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Distribution of carbon isotope composition of modern soils on the Qinghai-Tibetan Plateau

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Abstract. This paper presents a large data set on carbon isotope composition ($\delta^{13}C$) of modern soils which were collected under the main vegetation communities along an altitude of 1250–5500 m above sea level in the Qinghai-Tibetan Plateau. The $\delta^{13}C$ values of 198 samples range from −28.6 to −15.1‰ versus PDB and exhibit a clean relation to different vegetation communities from forest (−25.9 ± 1.2‰) to shrub (−24.7 ± 1.4‰), steppe (−23.1 ± 1.3‰), alpine meadow (−23.6 ± 0.7‰), alpine desert steppe (−21.3 ± 1.6‰), and alpine desert (−18.9 ± 2.5‰). We attributed the observed variability in $\delta^{13}C$ values to that the mean annual precipitation (MAP) and the mean annual temperature (MAT) are the main factors controlling the distribution of vegetation types in the Tibetan Plateau, which causes the change in carbon isotope composition of modern soils at any given altitude. The result of both linear and nonlinear regression analyses also confirms that MAP and MAT are the major factors affecting the $\delta^{13}C$ values of surface soils. In the absence of favorable moisture and temperature conditions, low pCO_2 alone is not sufficient to cause the distinct changes in carbon isotope composition of modern soils in the Tibetan Plateau. This study provides some fundamental information on the carbon isotope composition of terrestrial carbon pools and bears some practical significance for the use of carbon isotope data to document vegetation changes and environmental conditions of the high plateau in the past.

Introduction

The stable isotope composition of carbon ($\delta^{13}C$ values) of soil organic carbon reflects the relative contribution of plant species with C3, C4, and CAM photosynthetic pathways (Denis 1980; O'Leary 1988; Boutton et al. 1998). The $\delta^{13}C$ value has been widely used to address the origin of carbon in soil organic matter (Cerri et al. 1985; Balesdent et al. 1987; Krishnamurthy and Bhattacharya 1989; Bernoux et al. 1998), to document vegetation change, and to reconstruct the history of climate changes (e.g., Cerling et al. 1989; Gu 1991; Boutton et al. 1994, 1998; Humphrey and Ferring 1994; Lu et al. 2000). The carbon isotope composition of soils at high altitudes are influenced by a number of factors, including species composition, temperature, light level, moisture availability, partial pressure of CO_2 and O_2, and the source of CO_2 assimilated during photosynthesis (Teizen et al.

1979; Körner et al. 1988, 1991; Bird et al. 1994; Li et al. 1999). However, the effect of changing altitude and vegetation types on the carbon isotope composition of modern soils in the Qinghai-Tibetan Plateau, the highest plateau in the world, is still poorly known. In this study, we focus on the effect of altitude (i.e., decreasing temperature and atmosphere pressure) and precipitation (moisture) on carbon isotope composition of soil organic carbon in the Qinghai-Tibetan Plateau. The aim of this study is to investigate how the $\delta^{13}C$ value of surface soil organic matter varies with vegetation-soil types and regional climatic conditions.

Material and methods

Study area

The Qinghai-Tibetan Plateau, known as The roof of the world with an average altitude of over 4000 m above sea level (m a.s.l.), is the highest and largest plateau on the earth with unique environment and climate characteristics. It also greatly influences the natural environment and climate of adjacent regions. The study region covers a vast area between latitudes 25° and 42.34° E, and longitudes 77.8° and 104.1° E, over a large altitudinal range from 1250–5500 m a.s.l. (Figure 1). This area experiences drastic climate and environmental changes from north to south and from east to west, spanning several climatic zones from alpine temperate extreme dry zone in the north to alpine sub-temperate, alpine sub-cold in the middle, and alpine temperate zones in the south (Institute of Geography 1990, 1999). An extreme dry climate occurs in the northern margin with mean annual precipitation (MAP) about 30 mm. The main part of the plateau with an elevation of more than 4500 m is characterized by cold and dry winters and cool-humid summers with mean annual temperature (MAT) of -8 to 8 °C (Figure 2(a)). Low temperatures usually last for 7–8 months. To the south and southeast are relatively high rainfall regions with MAP from 370 mm to over 800 mm (Figure 2(b)).

Vegetation distribution in the Qinghai-Tibetan Plateau is largely controlled by rainfalls from the southeast and southwest monsoons. It is characterized by a zonal pattern from the southeast to northwest following a gradient of decreasing moisture (precipitation), ranging from forest, shrub, alpine meadow, steppe, desert steppe, alpine desert (Investigation Team of Chinese Academy of Science 1988a; Institute of Geography 1990, 1999). Coniferous and broadleaf forests, consisting mainly of *Picea, Abies, Pinus, Tsuga, Betula, Populus,* and *Quercus*, grow in valleys and mountain slopes below 4000 m. Mountain dark coniferous forests are mainly distributed in the northern slopes of some mountains at an elevation of about 3100–3500 m in the southeast, 3500–4100 m in the west, and 2800–3800 m in the northwest. Shrubs, generally including evergreen sclerophyllous, evergreen coniferous, deciduous and broadleaf, and succulent plants, are distributed at different elevations of the plateau. Alpine meadow occupies the main part of the plateau over 4000 m in altitude. It consists mainly of sedge and grass communities such as *Carex, Kobresia, Stipa, Festuca, Poa, Roegneria,* and *Koeleria*, together with some

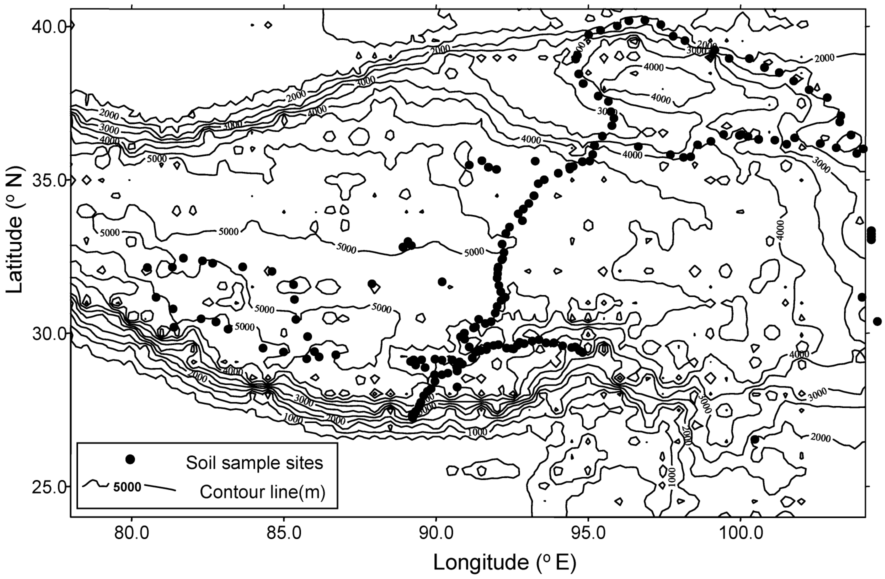

Figure 1. Map of study area showing sampling locations of soils in the Qinghai-Tibetan Plateau.

species of Compositae, Chenopodiaceae, Rannuculaceae, Polygonaceae, and Leguminosae. Alpine steppes occupy a vast region at elevation of 4400–5400 m in the interior of the plateau. *Stipa purpurea, S. basiplumosa, Carex moorcroftii* and *Artemisia wellbyi* are dominants of steppes. Usually there are some cushion plants (e.g., *Arenaria musciformis, Androsace stapete*) and succulent plants (CAM plants: *Rhodiola* sp.; *Sedum* sp.) (Investigation Team of Chinese Academy of Science 1988a; Chang 1981; Wang 1988). Alpine desert is found in the western part of the Tibetan Plateau, where the elevation of the plateau plain and lake basins is over 4500 m. The dominants of this vegetation type are cushion minor semi-shrubs adapted to extremely cold and dry climate. The representative community is composed of *Ceratoides compacta*, *Rhodiola* sp., *Sedum* sp. Companion species are few high mountain plants including *Ajania trilobata, Arenaria monticola, Carex moorcroftii, Hedinia tibetica*, *Oxytropis densa, Pegaeophyton scapiflorum, Stipa basiplumosa* and *Thylacospemum caespitosum* (Chang 1981; Wang 1988; Investigation Team of Chinese Academy of Science 1988a; Institute of Geography 1990,1999).

In the Tibetan Plateau, a markedly different altitudinal vegetation zonation occurs between the northern part and southern part. In the southern part, for example, Yadong region, the zone of mountain coniferous-broadleaf mixed forest below 3000 m is dominated by *Picea*, *Pinus, Sabina, Tsuga, Betula, Populus, Quercus*, together with *Tilia, Acer,* and *Hippophae*. From 3000 to 3500 m, *Picea* and *Abies* dominate the vegetation, mixed with *Quercus* and *Betula*. The zone between 3500 and 4000 m is occupied by subalpine shrub-meadow, composed mainly of

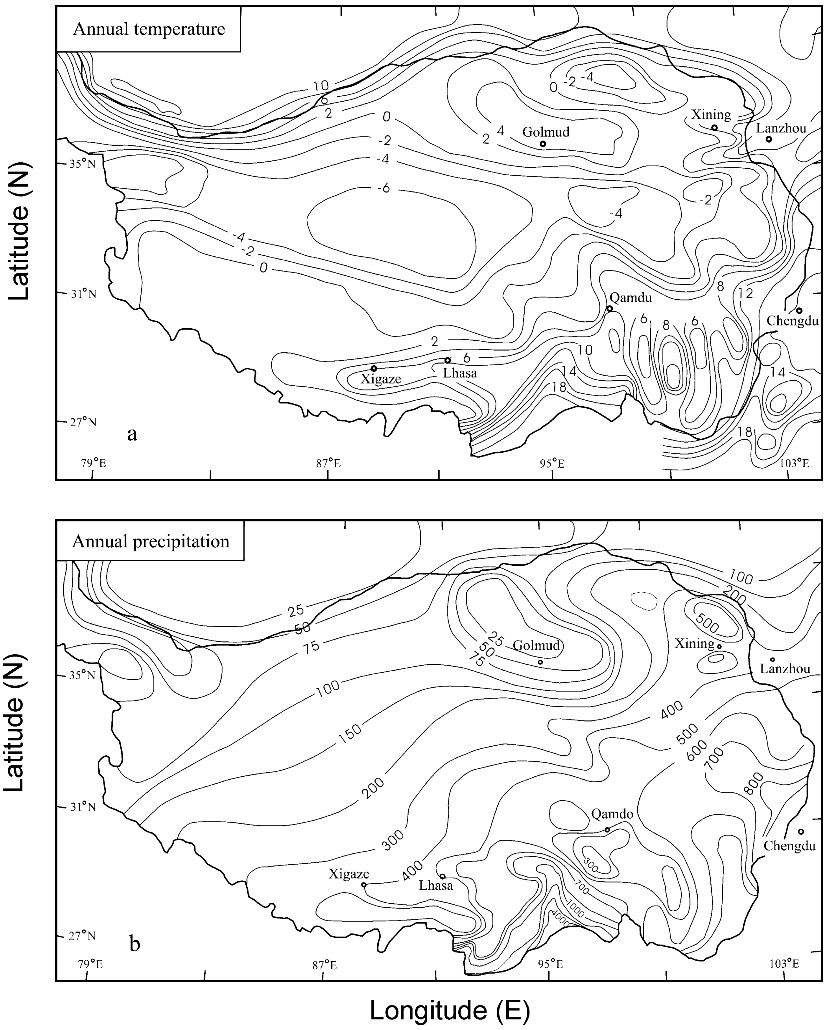

Figure 2. (a) MAT of the Qinghai-Tibetan (°C); (b) MAP of the Qinghai-Tibetan (mm) (modified from Institute of Geography 1990).

Rhododendron, Potentilla, Caragana, Salix, Kobresia, Carex, and *Stipa.* Alpine meadow and desert steppe exist from 4000 to 4600 m, which is dominated by *Carex, Androsace, Stipa,* and *Saussurea.* In the northern plateau part, for example, Qilian mountains, the zone of mountain broadleaf trees composed of *Quercus* and *Populus* is distributed in river basins and oasis at an elevation of 1800–2500 m. Scattered mountain coniferous and broadleaf forests composed of *Pinus, Picea, Sabina, Quercus*, and *Populus* etc. grow on the northern slopes at an elevation of 2000–3600 m. The coniferous forests dominated by spruce trees are located at an altitude of 2500–4100 m. Subalpine shrub and grassland lie above the forest line at an

Table 1. Relationship between vegetations and soil types in Qinghai-Tibetan Plateau (Investigation Team of Chinese Academy of Science 1985, 1988a; Institute of Geography 1999).

Vegetation types	Tibetan classification – Soil types	WRB classification
Alpine desert	Frigid desert soils, Cold desert soils	Calcic Xerosol, Takyric Xerosol
Desert steppe	Morga soils	Haplic Xerosols,
Alpine meadow	Felty sod soils, Black felty soils	Humic Cambisol
Steppe	Baga soils, Saga soils	Haplic Xerosols,
Shrub	Brow felty soils	Haplic Xerosols,
Forest	Burozems, yellow-brown earths, cinnamon soils, Bleached gray soils	Humic Cambisol, Orthic Luvison, Dystric Podzoluvisols

elevation of 3200–4000 m. Mountain desert steppe and alpine steppe dominated by *Stipa, Festuca, Artemisia,* and *Krascheninnikovia*, as well as alpine meadow with *Kobiresia, Potentilla,* Polygonum, and *Carex*, occur between 3200 and 4700 m.

Material and methods

Soil samples used in this study were collected under the main vegetation communities mainly from a northeast–southwest transect that runs along the elevation from 1250 to 5500 m a.s.l. (Figure 1). This transect covers a broad gradient in climate and a variety of vegetation communities including forest, shrub, steppe, alpine meadow, desert steppe, desert and alpine desert. The variety of main vegetation types covers a mosaic of soil types in these study regions (Table 1). (Investigation Team of Chinese Academy of Science 1985, 1988a, b).

A total of 209 samples were collected from 0 to 3 cm depth along the transects (Figure 1) at approximately 50–70 km sampling intervals in the summer to autumn of 1999. Leaves, grass roots, and litter were removed prior to sampling. Longitude, latitude, and altitude of the sites were measured using a GPS 12 (GARMIN). The altitude of each sampling site was also determined using a Pocket-Altimeter Barometer, which was calibrated at locations of known altitude during the course of sampling each day. Diurnal pressure variations reduce the accuracy of the absolute altitude determination to approximately ± 30 m. The modern climatic parameters for spatial interpolation used in this paper (Table 1) are from a database of the MAP and MAT in the past 40 years from Chinese National Meteorological Bureau (Lin et al. 2002). The pCO_2 (partial pressure of atmospheric carbon dioxide) of each sampling site was estimated based on a relationship between the altitude and atmospheric pressure in the standard atmosphere (Zhou 1997). The pCO_2 would decrease from its present value of 36 Pa at sea level to 25.7 Pa at 3000 m, and to 19.1 Pa at 5000 m with decreasing atmospheric pressure (Zhou 1997; Boom et al. 2002).

Among the 209 samples obtained, 198 samples were analyzed for this study, the remaining 11 samples are all from desert sand and contain inefficient quantities of organic matter for the analyses. All the soil samples were dried at 60 °C, and then ground to less than 250 μm. The <250 μm fraction was treated with 1 N HCl at room temperature overnight to remove carbonates, then washed to neutrality with distilled water, and dried at low temperature (50 °C) (Bird et al. 1994). About 50 mg samples prepared were measured for carbon isotope ratios using an NC2500 (EA-IRMS) mass spectrometer. All results are reported in δ notation versus PDB standard. Overall analytical precision is less than 0.1‰. Twenty-eight duplicate samples from different soil sediments were measured repeatedly with an average deviation of ±0.23‰.

Results

Table 2 shows the results of 198 samples for their carbon isotope composition of soil organic matter with the MAP and MAT from the Qinghai-Tibetan Plateau, spanning an overall altitudinal range from 1250 to 5500 masl. Figure 3 shows the variations in $\delta^{13}C$ values of all soils for this study as a function of changing elevations, in a range of −28.6 to −15.1‰, averaging −23.3 ± 2.2‰. Though no all of $\delta^{13}C$ values of soils show a clear relationship with altitude, however, below 3500 m, the $\delta^{13}C$ values of soils from forest and steppe are distributed in a wider range, a general trend of gradual decrease is apparent with increasing altitude, ranging from −20.5 to −28.5‰. Above this height, the $\delta^{13}C$ values are more scattered, specifically the soils from desert and alpine desert sites (Figures 3 and 4(f)) show that a significant positive shift with increasing altitude is observed, varying from −23.5‰ to −15.1‰ (Figures 3 and 4).

Soils under different vegetation types show visibly different extents of $\delta^{13}C$ values. For example, soils under desert and alpine desert are characterized by the most positive $\delta^{13}C$ values from −22.5 to −15.1‰, averaging −18.9 ± 2.5‰, and desert steppe from −23.9 to −18.5‰, averaging −21.3 ± 1.6‰. Alpine meadow ranges from −25.2 to −22.4‰, averaging −23.6 ± 0.7‰. Steppe have similar $\delta^{13}C$ values to alpine meadow ranging from −25 to −19.6‰, averaging −23.1 ± 1.3‰, shrub from −27.3 to −19.6‰, averaging −24.7 ± 1.4‰, and forest from −28.6 to −23.9‰, averaging −25.9 ± 1.2‰.

Comparison of the carbon isotope values of soils under each vegetation type versus MAP, MAP and *p*CO2 (Pa) demonstrates that both the MAP and MAT are nonlinear negatively correlated with $\delta^{13}C$ at higher correlation coefficients ($R^2_{MAP} = -0.86$, n = 198 data set; $R^2_{MAT} = -0.91$, n = 198 data set). The *p*CO2 is not significantly correlated ($R^2_{pCO2} = 0.024$, n = 198 data set) to $\delta^{13}C$ (Figure 5).

In this study, we also used the methods of linear regression analyses to explore the effect of environmental factors on the $\delta^{13}C$ of soils from all of sets. First, we use a linear regression method to explore the effect of MAP, MAT, and *p*CO2 on the $\delta^{13}C$ based on the data of 198 samples (Table 3). Considering the effect of local soil solution water and groundwater on $\delta^{13}C$ values (Feng et al. 2000), we excluded 24 samples from these analyses. Among them, five samples (sample nos. 119–123, see Table 2) were collected from the margin of saline lakes in the Qiadam Basin, and nineteen surface samples (sample nos. 14,17, 124–139, see Table 2) from the areas of oasis along the ancient Silk Road. Then, we perform this method on the data sets of 198 and 174 samples, respectively, to compare the results of regression analyses.

Table 2. Carbon isotope composition of modern soils and some associated plants from the Qinghai-Tibetan Plateau.

Sample no.	Latitude (N)	Longitude (E)	Altitude (m)	$\delta^{13}C$ (‰)	MAP (mm)	MAT (°C)	Vegetations***	Associated plants****
1	36°09.060′	103°25.333′	1730	−20.91	316	9.5	G	No record
2	36°20.720′	102°45.520′	1830	−22.75	329	8.8	S	No record.
3	36°28.755′	102°14.202′	2030	−24.96	346	7.5	G	No record
4	36°40.127′	101°24.130′	2650	−23.17	351	3.4	Gs	No record
5	36°27.844′	101°08.548′	3300	−24.70	356	2.8	Gs	No record
6	36°35.584′	100°45.286′	3400	−24.66	377	1.9	Gs	No record
7	36°37.198′	100°13.636′	3350	−27.75	448	1.3	F	No record
8	36°47.115′	99°40.113′	3438	−24.20	327	1.0	G	*Stipa purpurea*
9	36°45.160′	99°36.260′	3817	−24.45	335	0.3	Am	*Carex* sp.
10	36°47.009′	99°04.798′	3145	−22.86	270	2.0	G	No record
11	36°33.324′	98°40.245′	3550	−20.94	251	0.8	Ds	*Artemisia gmelinii, Kalidium gracile, Stipa* sp.,
12	36°26.678′	98°14.073′	3243	−22.51	210	0.8	Ds	*Nitraria tangutorum, Atriplex centralasiatica, Heteropappus semiprostratus, Astragalus* sp., *Lepidium apetalum, Stipa* sp., *Achnatherum splendens*
13	36°02.780′	98°00.827′	3210	−23.05	190	1.5	Ds	*Neopallasia pectinata, Stipa* sp., *Achnatherum splendens*
14*	36°01.509′	97°46.705′	3113	−25.70	105	2.2	S	*Salix cheilophila, Phagmites communis*
15	36°06.920′	97°21.034′	2923	−22.53	82	3.5	Dg	Sympegma regelii, Asterothamnus centrali−asiaticus
17*	36°25.299′	94°52.227′	2890	−24.81	58	4.1	S	*Salix cheilophila, Phagmites communis*
18	36°07.215′	94°48.954′	3201	−20.85	80	3.8	Dg	No record
19	35°54.459′	94°42.978′	3420	−22.30	85	3.5	Ds	*Leymus angustus, Verbascum thapsus, Pennisetum centrasiaticum, Eragrostis nigra, Roegneria nutans, Elymus sibiricus*
20	35°52.940′	94°28.830′	3660	−16.46	90	−0.8	Dad	No record
21	35°43.650′	94°10.497′	4340	−23.19	186	−1.2	Ag	*Roegneria nutans*
22	35°42.624′	94°03.608′	4610	−22.80	197	−2.1	Ag	*Littledalea przevalskyi, Kobresia humilis, Roegneria nutans, Trisetum spicatum*

Table 2. (continued)

Sample no.	Latitude (N)	Longitude (E)	Altitude (m)	$\delta^{13}C$ (‰)	MAP (mm)	MAT (°C)	Vegetations***	Associated plants****
23	35°38.443′	94°04.078′	4767	−23.46	207	−2.6	Ag	*Saussurea gnaphalodes, Poa* sp.
24	35°30.143′	93°41.448′	4540	−25.15	280	−2.7	Am	*Oxytropis falcate, Poa* sp., *Kobresia schoenoides*
25	35°17.005′	93°14.000′	4650	−22.95	274	−3.1	Am	*Festuca coelestis, Carex* sp, *Stipa purpurea, Kengyilia hirsuta*
26	35°09.410′	93°02.311′	4720	−22.82	283	−3.8	Am	*Kobresia schoenoides, Ptilagrostis concinna, Poa poophagorum*
27	35°54.053′	92°56.335′	4600	−25.05	285	−4.0	Am	*Leontopodium pusillum, Poa perennis, Trisetum spicatum, Littledalea przevalskyi*
28	34°45.410′	92°54.025′	4750	−24.46	285	−4.7	Am	*Kobresia* sp., *Stipa purpurea, Leontopodium nanum, Potentilla bifurca*
29	34°30.028′	92°43.755′	4640	−17.47	280	−4.6	Dg	*Stipa purpurea*
30	34°18.823′	92°32.895′	4640	−24.72	328	−4.3	Am	No record
31	34°09.759′	92°23.277′	4660	−24.94	336	−4.2	Am	*Kobresia* sp., *Elymus* sp.
32	33°55.995′	92°31.136′	4660	−20.23	331	−4.0	Ds	*Carex* sp., *Stipa purpurea*
33	33°43.283′	92°05.913′	4700	−25.09	336	−3.9	Am	*Kobresia pygmaea, K. capillifolia, Stipa purpurea, Trisetum spicatum*, *Festuca ovina, Potentilla bifurca*
34	33°30.830′	91°58.846′	4780	−24.33	341	−4.1	Am	No record
35	33°09.491′	91°51.571′	4915	−22.85	345	−4.6	Am	*Kobresia pygmaea, Leontopodium pusillum, Roegneria nutans, Poa poophagorum, Trisetum spicatum, Festuca ovina*
36	32°52.948′	91°55.133′	5231	−24.36	420	−4.8	Am	*Deyeuxia grata*
37	32°40.488′	91°52.332′	5000	−22.85	424	−3.6	Am	*Kobresia schoenoides, K. humilis, Festuca* sp., *Deschampsia littoralis*
38	32°38.241′	91°51.200′	5050	−24.79	430	−3.8	S	*Potentilla parvifolia, Leontopodium nanum, Meconopsis horridula, Festuca* sp., *Trisetum spicatum, Poa poophagorum*
39	32°23.927′	91°44.089′	4820	−22.59	435	−2.6	Am	*Kobresia capillifolia, Elymus nutans, Stipa purpurea, Iris potaninii*
40	32°20.076′	91°43.077′	4775	−23.71	476	−2.3	Am	No record

41	32°10.844′	91°42.884′	4910	−22.91	401	−2.8	Am	*Kobresia pygmaea, K. schoenoides*
42	32°10.844′	91°42.884′	4925	−22.42	403	−2.9	Am	No record
43	32°02.102′	91°41.497′	4755	−23.39	418	−2.0	Am	No record
44	31°47.324′	91°45.333′	4800	−23.65	422	−2.0	Am	No record
45	31°34.943′	91°48.702′	4600	−23.19	444	−1.0	Am	*Kobresia pygmaea, K. schoenoides, Poa* sp.
46	29°39.483′	91°06.907′	3738	−23.68	432	4.4	S	No record
47	29°39.483′	91°06.907′	3728	−23.00	433	4.5	S	No record
48	29°40.347′	91°21.066′	3680	−22.49	413	4.6	G	*Elymus nutans*
49	29°46.616′	91°22.418′	3700	−19.56	415	4.5	G	*Eragrostis nigra, Pennisetum centrasiaticum, Pertya uniflora*
50	29°49.929′	91°44.538′	3780	−22.17	413	4.1	S	*Potentilla parvifolia, Stipa krylovii, Pennisetum centrasiaticum*
51	29°43.049′	92°00.343′	4025	−25.14	433	3.1	S	*Potentilla parvifolia, Chenopodium foetidum, Elymus sibiricus, Aristida triseta, Carex atrofusca, Kobresia kansuensis, Stipa capillacea, Bromus tectorum, Agrostis schneideri*
52	29°42.297′	92°10.449′	4220	−23.28	391	2.2	Am	*Kobresia humilis, Stipa purpurea, Anaphalis lacteal, Elymus sibiricu, Oxytropis* sp.
53	29°49.492′	92°21.710′	4840	−23.56	375	−0.7	Am	No record
54	29°54.506′	92°25.881′	4390	−24.43	412	1.2	S	*Rhododendron* sp., *Rosa sericed, Berberis angulosa, Leymus secalinus, Poa psilolepis, Polygonum macrophyllum*
55	29°52.073′	92°34.572′	4170	−25.73	434	2.3	S	*Caragana* sp., *Rosa sericed, Spiraea* sp., *Sibiraea angustata, Gentiana officinalis, Kobresia capillifolia, Arundinella yunnanensis, Agrostis hugoniana, Koeleria argentea, Polygonum viviparum, Festuca nitidula, Deyeuxia* sp., *Roegneria nutans, Stipa capillacea*
56	29°57.096′	92°50.691′	3850	−25.71	466	3.7	S	*Rosa sericed, Spiraea* sp., *Kobresia filifolia, Agrostis hugoniana, Trisetum spicatum, Festuca* sp., *Pennisetum centrasiaticum, Roegneria parvigluma, R. nutans, Elymus nutans, Koeleria cristata, Poa crymophila*
57	29°59.765′	93°03.565′	3670	−28.57	686	4.4	F	*Picea likiangensis* var. *balfouriana, Carex* sp., *Agrostis muliensis, Stipa* sp.

Table 2. (continued)

Sample no.	Latitude (N)	Longitude (E)	Altitude (m)	$\delta^{13}C$ (‰)	MAP (mm)	MAT (°C)	Vegetations***	Associated plants****
58	29°34.283′	94°29.278′	3115	−25.01	675	7.3	F	*Quercus aquifolioides, Betula platyphylla, Verbascum thapsus, Kobresia schoenoides, Carex* sp., *Arundinella yunnanensis*
59	29°34.687′	94°28.574′	3120	−23.87	672	7.2	F	*Quercus aquifolioides, Eragrostis nigra*
60	29°37.747′	94°23.244′	3100	−26.57	661	7.3	F	No record
61	29°45.064′	94°15.280′	3110	−25.47	637	7.2	F	No record
62	29°45.199′	94°14.533′	3150	−24.30	632	7.0	F	*Pinus densata, Quercus aquifolioides, Arundinella yunnanensis, Kobresia capillifolia*
63	29°44.209′	94°07.594′	3150	−25.68	622	7.0	F	*Quercus aquifolioides, Populus* sp., *Carex* sp., *Plantago depressa, Artemisia* sp., *Eragrostis ferruginea*
64	29°47.787′	93°50.115′	3250	−25.39	578	6.5	S	*Sabina* sp., *Cotoneaster* sp., *Arundinella yunnanensis, Bromus tectorum, Puccinella pamirica, Roegneria* sp.
65	29°53.627′	93°33.085′	3360	−25.55	532	5.9	S	*Sabina* sp., *Cotoneaster* sp., *Roegneria* sp., *Pennisetum centrasiaticum*
66	29°53.408′	93°17.697′	3480	−25.26	495	5.4	S	*Rosa sericed, Berberis angulosa, Artemisia* sp., *Pennisetum centrasiaticum, Eragrostis nigra*
67	29°48.634′	92°21.107′	4870	−23.76	373	1.0	Ag	No record
68	29°35.123′	90°59.455′	3620	−17.61	224	4.7	Dad	*Elymus nutans, Trisetum spicatum, Poa* sp., *Ligusticum thomsonii*
69	29°23.535′	90°53.192′	3590	−19.44	220	5.7	Ds	*Artemisia* sp., *Pertya phylicoides, Aristida scabrescens, Orinus thoroldii, Pennisetum centrasiaticum*
70	29°15.538′	90°28.483′	3630	−19.23	300	5.3	Ds	*Elymus* sp., *Eragrostis nigra, Pennisetum centrasiaticum*
71	29°19.897′	90°13.754′	3705	−18.73	238	5.1	Dad	*Oxytropis ochrantha, Orinus thoroldii, Aristida triseta*
72	29°19.199′	89°53.900′	3750	−22.49	387	5.0	G	*Orinus thoroldii*
73	29°21.257′	89°40.213′	3780	−20.57	383	4.9	Ds	*Orinus thoroldii, Oxytropis ochrantha, Pennisetum centrasiaticum*
74	29°20.022′	89°14.085′	3820	−18.57	267	4.1	Ds	*Chloris virgata, Oryzopsis* sp.

75	29°19.930′	88°58.475′	3850	−23.45	363	4.0	Am	*Pennisetum centrasiaticum, Orinus thoroldii, Oxytropis* sp.
76	29°16.54′	88°52.66′	3890	−18.54	351	3.9	Ds	No record
77	29°09.711′	89°02.393′	3870	−24.88	364	4.0	S	*Caragana* sp., *Pennisetum centrasiaticum*
78	29°04.265′	89°20.978′	3910	−23.45	368	3.9	G	*Elymus sibiricus, Carex* sp.
79	28°50.165′	89°39.196′	4070	−24.40	376	4.4	G	*Artemisia desertorum*
80	28°37.361′	89°40.089′	4230	−21.28	252	4.1	Ds	*Artemisia desertorum, Stipa purpurea, Pennisetum centrasiaticum*
81	28°22.484′	89°32.329′	4410	−23.91	325	3.0	Ds	*Artemisia demissa, Oxytropis ochrocephala, Bassia dasyphylla*
82	28°17.065′	89°25.219′	4430	−22.35	317	2.8	G	*Stipa purpurea, Oxytropis* sp., *Artemisia desertorum, Elymus nutans, Stipa basiplumosa*
83	28°08.561′	89°18.264′	4470	−23.89	365	2.7	G	*Lepidium apetalum, Artemisia desertorum*
84	28°08.561′	89°18.264′	4480	−24.12	365	2.7	G	*Stipa purpurea, Artemisia desertorum, A.* sp., *Leymus secalinus*
85	27°55.444′	89°12.524′	4525	−24.39	378	2.2	G	No record
86	27°49.898′	89°10.058′	4540	−23.16	376	2.2	Am	*Carex* sp., *Koeleria litwinowii, K. cristata, Stellaria arenaria, Anaphalis lacteal, Elymus sibiricus*
87	27°45.935′	89°08.861′	4396	−23.27	399	2.9	Am	*Carex* sp., *Stipa capillacea*
88	27°37.722′	89°02.291′	4160	−25.00	437	4.1	G	*Stipa purpurea, Oxyria digyna, Artemisia macrocephala, Trisetum spicatum, Polygonum tenuifolium, Ranunculus tanguticus, Saxifraga tangutica, Festuca* sp., *Iris* sp.
89	27°36.254′	89°02.349′	4070	−26.57	510	4.5	F	No record
90	27°35.794′	89°02.048′	3900	−26.89	552	5.3	F	*Betula utilis, Leontopodium leontopodioides, Ligusticum thomsonii, Anaphalis nepalensis, A. flavescens , Rumex nepalensis, Epilobium palustre, Trisetum clarkei*
91	27°34.238′	89°00.440′	3725	−25.79	594	6.1	F	*Abies spectabilis, Picea spinulosa, Plantago* sp., *Pimpinella diversifolia, Trisetum clarkei, Agrostis* sp., *A. muliensis, Festuca brachyphylla, F. rubra, Poa pratensis, Cerastium caespitosum*

Table 2. (continued)

Sample no.	Latitude (N)	Longitude (E)	Altitude (m)	$\delta^{13}C$ (‰)	MAP (mm)	MAT (°C)	Vegetations***	Associated plants****
92	27°32.450′	88°59.669′	3490	−25.39	631	7.2	F	*Abies spectabilis, Picea spinulosa, Rosa swegingowii, Potentilla fulgens, Pteridium aquilinum* var. *Latiusculum, Agrostis muliensis*
93	27°30.339′	88°56.937′	3300	−25.69	667	8.1	F	*Abies spectabilis, Picea spinulosa, Kobresia filifolia, Bromus tectorum, Eragrostis ferruginea*
94	27°30.008′	88°55.777′	3100	−26.77	725	9.0	F	*Tsuga dumosa, Pinus armandi, Quercus semecarpifolia, Anaphalis margaritacea, Calamagrostis flaccida, Roegneria tibetica*
95	27°25.057′	88°56.308′	2870	−26.90	751	10.1	F	*Tsuga dumosa, Pinus armandi, Quercus semecarpifolia, Halenis elliptica, Agrostis hugoniana, Isodon* sp., *Eragrostis ferruginea, Trisetum clarkei*
96	28°50.419′	89°53.612′	4290	−22.72	373	3.9	Ds	*Pennisetum centrasiaticum*
97	28°53.526′	90°05.299′	4635	−23.35	346	3.1	Am	No record
98	28°57.591′	90°23.624′	4560	−23.24	359	3.2	Am	*Carex* sp., *Elymus nutans*
99	28°25.739′	90°23.603′	4520	−23.59	373	2.7	Am	*Carex* sp., *Pennisetum centrasiaticum*
100	28°25.739′	90°23.603′	4500	−24.66	375	2.7	Am	*Elymus sibiricus, Artemisia* sp.
101	29°02.056′	90°23.863′	4530	−21.46	310	3.3	Ds	No record
102	29°05.952′	90°22.585′	4530	−17.23	308	3.3	Dad	No record
103	29°11.306′	90°33.730′	4510	−25.19	363	3.7	S	No record
104	29°38.142′	91°09.771′	3760	−19.50	312	4.4	Ds	No record
105	29°45.512′	90°47.163′	3900	−16.96	308	4.4	Dad	*Pennisetum centrasiaticum, Chenopodium* sp.
106	30°00.888′	90°38.145′	4115	−22.74	321	4.3	Ds	*Artemisia* sp., *Pennisetum centrasiaticum*
107	30°05.524′	90°32.621′	4335	−25.03	359	3.9	S	*Potentilla* sp., *Orinus thoroldii, Artemisia* sp., *Elymus nutans*
108	30°05.541′	90°29.898′	4360	−18.40	321	3.4	Dad	No record
109	30°05.541′	90°29.898′	4400	−20.45	311	3.2	Ds	No record
110	30°12.951′	90°37.669′	4640	−23.94	334	2.2	Am	No record
111	30°23.092′	90°55.611′	4305	−25.27	367	2.9	S	*Potentilla* sp., *Sabina* sp., *Elymus nutans, P. crymophila, P. poophagorum*

112	30°25.280′	90°59.505′	4310	−19.95	347	1.3	Ds	No record
113	30°31.966′	91°18.641′	4430	−23.85	364	1.2	Am	No record
114	30°35.727′	91°30.177′	4700	−23.35	347	0.2	Am	*Kobresia robusta, K. filifolia, K. Schoenoides, Elymus atratus, Roegneria nutans, Koeleria cristata*
115	30°52.666′	91°38.089′	4780	−23.01	338	−1.2	Am	*Koeleria cristata, Roegneria nutans, Elymus cylindricus*
116	31°05.880′	91°41.796′	4810	−24.57	383	−1.6	Am	No record
117	31°17.941′	91°49.858′	4710	−24.59	391	−1.3	Am	No record
118	31°24.090′	91°57.585′	4600	−23.95	352	−0.8	Am	No record
119**	36°43.690′	95°07.552′	2785	−21.67	49	4.2	Ds	No record
120**	37°04.264′	95°26.448′	2730	−26.25	165	4.1	S	No record
121**	37°18.991′	95°30.369′	3065	−23.25	117	3.4	Gs	*Salsola* sp., *Bassia dasyphylla, Calligonum* sp., *Reaumuria kaschgarica*
122**	37°32.354′	95°24.302′	3220	−23.45	72	3.1	Gs	No record
123**	37°52.448′	95°19.614′	3210	−22.72	69	2.0	Ds	*Achnatherum splendens, Leymus secalinus, L.* sp.
124*	38°03.079′	94°59.839′	3250	−23.31	69	1.8	Gs	*Ceratoides latens, Reaumuria soongarica, Salsola abrotanoides, Artemisia rutifolia, Nitraria sibirica*
125*	38°27.912′	94°30.120′	3300	−23.71	69	1.5	Ds	No record
126*	38°47.020′	94°21.589′	2925	−27.32	50	1.3	S	*Salsola abrotanoides, Artemisia minor*
127*	39°16.507′	94°15.783′	3370	−23.79	55	3.0	Ds	*Artemisia sieversiana, Salsola ruthenica, Achnatherum splendens*
128*	39°23.765′	94°18.591′	2820	−24.88	65	4.2	G	No record
129*	40°05.079′	94°40.587′	1450	−22.39	82	8.5	Dg	No record
130*	40°13.445′	95°04.306′	1255	−22.39	120	8.8	Ds	*Achnatherum splendens, Nitraria tangutorum*
131*	40°22.217′	95°36.850′	1260	−25.2	140	7.7	S	*Nitraria sibirica*
132*	40°32.398′	95°59.881′	1340	−21.71	145	7.1	Dg	No record
133*	40°34.131′	96°30.971′	1440	−20.83	143	6.4	Dg	Kalidium gracile
134*	40°25.061′	97°01.976′	1525	−23.22	150	7.1	G	No record
135*	40°01.746′	97°26.363′	1735	−23.315	160	7.1	G	No record
136*	39°53.123′	97°49.274′	1945	−25.16	180	6.8	F	*Glycyrrhiza uralensis, Achnatherum splendens, Nitraria sibirica*
137*	39°34.409′	98°47.959′	1590	−24.39	190	6.9	S	*Hippohae* sp., *Artemisia* sp.
138*	39°17.891′	99°15.793′	1870	−22.3	210	6.6	Ds	*Kalidium foliatum, Sympegma regelii, Nitraria* sp.
139*	39°17.557′	99°55.349′	1500	−24.56	220	6.5	S	*Salix* sp., *Phragmites australis*

Table 2. (continued)

Sample no.	Latitude (N)	Longitude (E)	Altitude (m)	$\delta^{13}C$ (‰)	MAP (mm)	MAT (°C)	Vegetations***	Associated plants****
140	38°59.685′	100°25.041′	1585	−25.11	230	6.4	F	*Sympegma regelii, Artemisia* sp., *Phragmites australis*
141	38°49.801′	100°53.863′	1760	−21.82	240	5.8	Ds	No record
142	38°33.246′	101°22.225′	2200	−24.1	312	4.9	G	*Achnatherum splendens, A.* sp.
143	38°15.816′	101°52.428′	2110	−23.17	373	4.4	G	*Poa* sp., *Stipa bungeana, Achnatherum splendens, A.* sp., *Peganum multisectum*
144	38°00.186′	102°28.117′	1750	−25.16	300	5.4	S	*Caragana jubata, Achnatherum splendens, Elymus cylindricus, Artemisia* sp.
145	37°24.086′	102°54.559′	2270	−23.61	269	3.9	G	*Achnatherum splendens, A.* sp.
146	37°11.821′	102°52.172′	3060	−24.45	357	0.4	Am	*Kobresia humilis, Achnatherum* sp.
147	36°46.014′	103°14.142′	2210	−25.05	311	5.7	S	*Hippohae* sp., *Festuca sp., Pennisetum centrasiaticum, Elymus* sp., *Achnatherum splendens, Pennisetum centrasiaticum, Leymus secalinus*
148	36°18.270′	103°38.398′	1870	−23.535	334	8.3	G	No record
149	35°37.8′	91°40.6′	4820	−22.43	199	−6.7	Ds	No record
150	35°46.140′	90°47.194′	5100	−20.85	179	−8.5	Dad	No record
151	35°55.00′	91°11.90′	4750	−21.31	149	−6.5	Ds	No record
152	35°42.00′	91°24.800′	4870	−21.36	187	−7.1	Ds	No record
153	26°42.00′	100°06.00′	2600	−24.45	672	12.5	S	No record
154	30°40.272′	91°05.806′	5021	−22.08	308	−0.2	Ds	No record
155	33°14.322′	88°47.405′	5145	−23.16	319	−5.3	Am	No record
156	33°02.968′	88°38.110′	4980	−23.00	313	−3.9	Am	No record
157	31°50.852′	87°37.015′	4505	−15.99	214	−2.8	Dad	No record
158	31°54.633′	89°54.11′	4583	−25.62	455	−1.1	S	No record
159	33°06.484′	88°54.150′	5003	−23.61	321	−4.2	Am	No record
160	33°03.504′	88°37.544′	5426	−15.08	291	−6.9	Dad	No record
161	33°03.381′	88°37.835′	5302	−23.88	311	−6.0	Am	No record

162	29°41.68′	92°14.27′	4460	−23.96	412	3.6	G	No record
163	29°48.24′	91°34.95′	3766	−19.19	303	3.4	Ds	No record
164	29°29.80′	86°26.18′	4809	−23.98	326	1.4	Am	No record
165	29°25.58′	85°53.38′	4892	−23.52	320	1.4	Am	No record
166	29°36.09′	85°44.65′	5000	−23.87	311	1.8	Am	No record
167	30°05.90′	85°31.16′	3510	−26.61	381	2.8	F	No record
168	30°39.92′	85°08.06′	4744	−23.65	308	−4.2	Am	No record
169	31°19.78′	85°05.38′	4689	−20.52	184	−4.7	Ds	No record
170	31°48.69′	85°03.34′	4848	−23.24	173	−2.8	Am	No record
171	32°15.26′	84°21.35′	4506	−23.36	176	−1.3	Am	No record
172	32°24.36′	83°23.75′	4620	−22.89	166	−0.9	Am	No record
173	32°31.66′	82°25.14′	4386	−23.38	150	−0.1	Am	No record
174	32°36.38′	82°05.33′	4398	−23.12	145	1.6	Am	No record
175	32°41.68′	81°27.97′	4492	−22.68	98	0.5	Am	No record
176	32°23.70′	81°06.34′	4701	−23.74	110	1.0	Am	No record
177	32°22.99′	80°17.11′	4200	−23.36	75	1.3	Am	No record
178	31°24.13′	80°34.30′	4725	−23.69	155	1.7	Am	No record
179	31°00.91′	81°07.38′	4785	−25.53	270	1.6	S	No record
180	30°24.53′	81°09.32′	4343	−24.465	225	1.5	G	No record
181	30°41.42′	82°02.73′	4800	−23.64	212	−0.5	Am	No record
182	30°35.00′	82°31.61′	4957	−22.98	200	−2.4	Am	No record
183	30°20.80′	82°55.42′	4643	−22.85	250	−0.3	Am	No record
184	29°43.05′	84°03.75′	4564	−24.05	257	0.0	Am	No record
185	29°35.68′	84°43.77′	4664	−19.06	276	−1.1	Dad	No record
186	29°21.88′	85°29.09′	4661	−23.32	276	−1.1	Am	No record
187	31°24.00′	103°36.00′	2700	−24.52	763	15.8	S	No record
188	30°36.00′	104°06.00′	3000	−24.35	653	16.0	F	No record
189	33°36.00′	103°54.00′	3150	−25.55	694	13.7	F	No record
190	33°30.00′	103°54.00′	3000	−24.45	688	13.2	F	No record
191	33°18.00′	103°54.00′	2450	−26.50	653	13.1	F	No record
192	33°24.00′	103°54.00′	2550	−26.42	665	12.7	F	No record

Table 2. (continued)

Sample no.	Latitude (N)	Longitude (E)	Altitude (m)	$\delta^{13}C$ (‰)	MAP (mm)	MAT (°C)	Vegetations***	Associated plants****
b1	36°39.00′	101°31.20′	2500	−22.20	281	4.4	G	No record
b3	36°39.00′	101°31.20′	2500	−22.50	281	4.4	G	No record
j1	37°00.00′	104°12.00′	1630	−21.90	222	7.1	G	No record
By5	36°19.80′	104°06.00′	1720	−21.70	285	9.1	G	No record
By6	36°19.80′	104°06.00′	1720	−20.10	285	9.1	G	No record
Sd1	38°09.60′	101°00.00′	1850	−21.00	245	5.3	G	No record
Zw1	37°27.00′	104°03.60′	1700	−21.90	194	6.3	G	No record

*Samples from the regions of saline lakes.

**Samples from oasis areas.

***Vegetation communities: Ag: Alpine grassland, Am: Alpine meadow, Dad: Desert and alpine desert, Dg: Desert, gobi, Ds: Desert steppe, F: Forest, G: Grassland, Gs: Grassland and steppe, S: Shrub. In the text, we divided these communities into six groups: (1) Forest (F); (2) Shrub(S) ; (3) Steppe (G, Gs, Ag); (4) Alpine meadow (Am); (5) Desert steppe (Ds); and (6) Desert and alpine desert (Dg, Dad).

****Associated plants around the sampling sites in the Tibetan plateau, all plant samples were preserved in Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. The order of arrangement of different plant species in the table is based on the order of field collection. No record means that we cannot select plant samples during the fieldwork due to the snow weather.

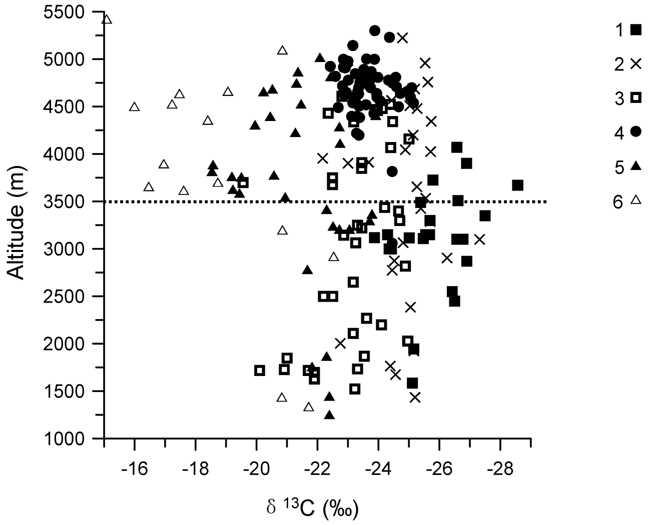

Figure 3. The $\delta^{13}C$ values of surface soil samples under different vegetation types from the Qinghai-Tibetan Plateau plotted against elevation. (1) Forest; (2) shrub; (3) steppe; (4) alpine meadow; (5) desert steppe; and (6) desert and alpine desert. Data use from Table 2.

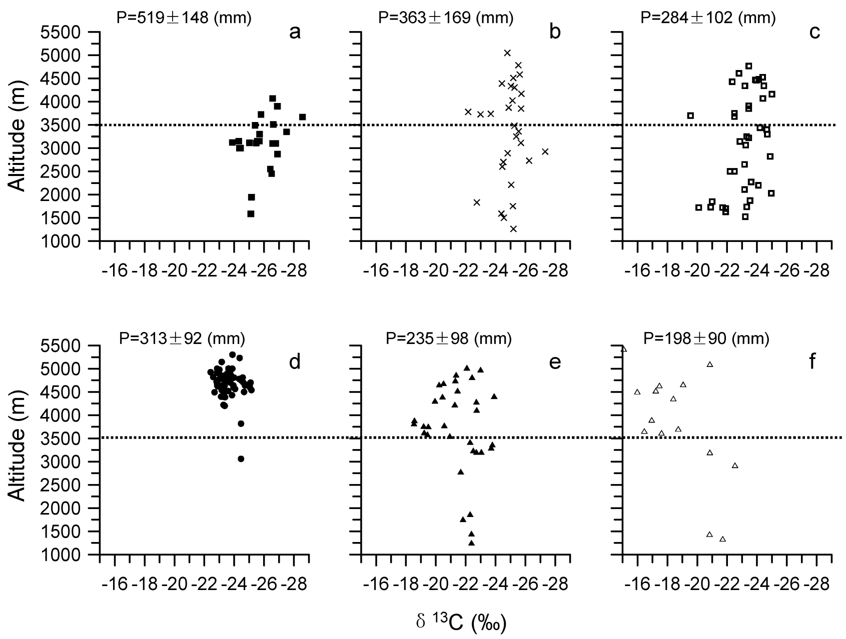

Figure 4. The $\delta^{13}C$ values of each vegetation type in the Qinghai-Tibetan Plateau against elevation showing visibly different extents of $\delta^{13}C$ values. Symbol P indicates MAP range for each vegetation type. (a) forest; (b) shrub; (c) steppe; (d) alpine meadow; (e) desert steppe; and (f) desert and alpine desert.

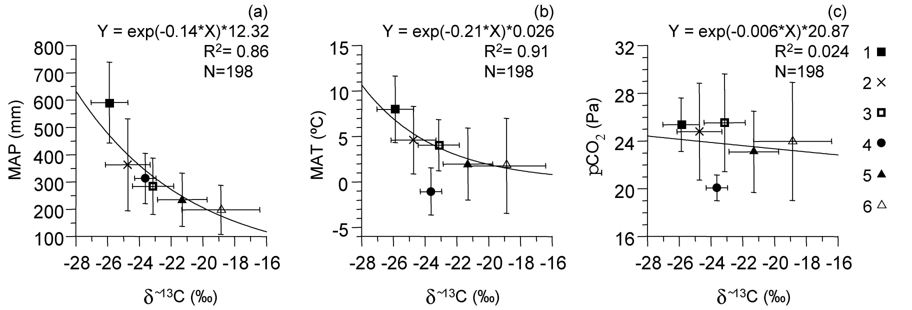

Figure 5. Relationship between $\delta^{13}C$ values of six vegetation types and their MAP (a), MAT (b) and pCO_2 (c) showing that both the MAP and MAT are nonlinear negatively correlated with $\delta^{13}C$, and pCO_2 is not significantly correlated. (1) Forest; (2) shrub; (3) steppe; (4) alpine meadow; (5) desert steppe; and (6) desert and alpine desert.

Table 3. Result of linear regression analyses for the relationships between the $\delta^{13}C$ and precipitation, Temperature, and pCO_2.

Regression equation		*r*	f	df	*p*
N = 198	$\delta^{13}C = -21.458$ (±0.336)–0.0055 (±0.0009) × MAP	−0.39	35.352	1.196	<0.0001
N = 174	$\delta^{13}C = -20.259$ (±0.393)–0.0082 (±0.0010) × MAP	−0.52	64.169	1.172	<0.0001
N = 198	$\delta^{13}C = -23.011$ (±0.177)–0.0956 (±0.0347) × MAT	−0.19	7.588	1.196	0.0064
N = 174	$\delta^{13}C = -22.956$ (±0.188)–0.1006 (±0.0372) × MAT	−0.20	7.315	1.172	0.0075
N = 198	$\delta^{13}C = -22.097$ (±0.957)–0.0495 (±0.0406) × *p*CO2	−0.08	1.487	1.196	0.2242
N = 174	$\delta^{13}C = -22.029$ (±1.196)–0.0507 (±0.0525) × *p*CO2	−0.07	0.931	1.172	0.3360

MAP: mean annual precipitation (mm/y).
MAT: mean annual temperature (°C).
pCO_2: the partial pressure of atmospheric carbon dioxide (Pa).

In the linear regression analysis, both the MAP and MAT are negatively correlated with $\delta^{13}C$ at the 0.0001 and 0.01 significance levels, respectively. The MAP has higher correlation coefficients ($r = -0.52$ (174 data set) > -0.39 (198 data set)) than MAT ($r = -0.20$ (174 data set) > -0.19 (198 data set)). The pCO_2 is not significantly correlated ($p > 0.05$) to $\delta^{13}C$ (Table 3).

As shown above, both of MAP and MAT are the primary factor affecting the $\delta^{13}C$ values of surface soils in the Tibetan Plateau. Figure 6 shows a trend analysis result that takes the nonlinear relation between $\delta^{13}C$ values and two climatic variables (MAP, MAT). A saddle-shaped response surface has two peaks: one in a warm and aridity–semi-aridity region with mean MAT > ca. 4 °C and MAP < ca. 400 mm; the other one, in a cold and aridity–semi-aridity region with mean MAT > ca. −4 °C and MAP < ca. 400 mm. However at range of MAT from ca. 4 °C to ca. −4 °C and MAP < 800 mm, the $\delta^{13}C$ values are clearly controlled by precipitation and increase $\delta^{13}C$ values with decrease MAP; The range of MAT ca. 4 °C to ca. −4 °C are cover mostly areas of Tibetan Plateau (Figure 2), imply that the MAP has more important effect on the $\delta^{13}C$ values of surface soils in the Tibetan Plateau.

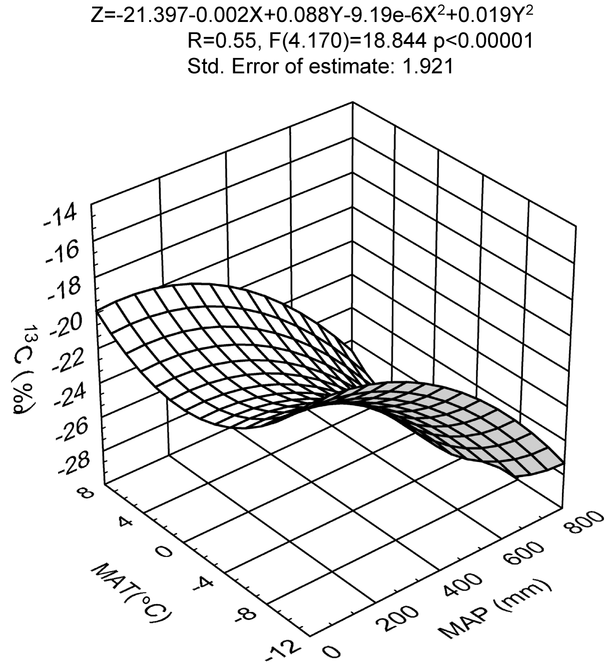

Figure 6. Trend analysis result of soil $\delta^{13}C$ values and climate variables (MAP, MAT) in three dimensions. $Z = \delta^{13}C$ values, $X = MAP$ (mm), $Y = MAT$ (°C).

Discussion

The organic matter of soils is principally derived from surface plants. The major factors that affect the composition of carbon isotope of plants include the pathways of photosynthesis, the pressure of atmosphere, the $\delta^{13}C$ values of atmosphere CO_2, temperature, precipitation, available soil moisture (e.g., Smith et al. 1976; Francey and Farquhar 1982; Körner et al. 1991).

Distributions of C3, C4 and CAM plants supports results of carbon isotope discrimination

Indeed, surveys of plant communities usually reveal a bimodal distribution of $\delta^{13}C$ values (C_3 plants typically in the rangeof −23 to −36‰, and C_4 and CAM plants in the rangeof −10 to −18‰ (e.g., Körner et al. 1988; O'Leary 1988; Griffiths 1993; Boutton et al. 1994; Sage et al. 1999). C3 plants, forest trees generally occur at elevations below ca. 4000 m in the Tibetan Plateau. Above 4000 m, meadow communities are dominated by almost all of C3 plants. Alpine deserts are dominated by xeric Chenopodiaceae (such as *Ceratoides lateens* and *C. compacta*).

Crassulacean acid metabolism (CAM plant) is a photosynthetic pathway usually associated with succulent plants in arid habitats (Drennan and Nobel 2000). More than 60 species of Crassulacean plants (such as *Rhodiola* sp., *Sedum* sp.) occur at deserts to Alpine deserts arid habitats above 3500–5500 m elevation in the Tibetan Plateau (Investigation Team of Chinese Academy of Science 1985, 1988a).

C4 plants composed mostly of Gramineae (such as *Imperata cylindrical* var. *major*, *Arundinella setosa*, *A. hirta*, *Themeda gigantea* var. *caudate*, *T. triandra* var. *japonica*, *Eeragrostis pilosa, Cynodon dactylon, Setaria viridis, S. geniculata, S. plicata*) and some species of Chenopodiacea occur only at lower elevations (below ca. 3500 m) and in some arid regions (Investigation Team of Chinese Academy of Science 1988a; Wu et al. 1992; Wang 2001). Similar distribution of C4 plants also occurs at below 3050 m in mountainous region of Kenya (Tieszen et al. 1979). The significance of temperature and precipitation in determining C4 occurrence has since been corroborated in several studies (e.g., Teeri and Stowe 1976; Rundel 1980; Hattersly 1983). The global distributions of grass genera according to photosynthetic type revealed that the most consistent criterion for the occurrence of C4 grass genera was mean temperature >22 °C and mean precipitation >25 mm for any month (Collatz et al. 1998). In the Tibetan Plateau regions, around above 3500 m, had no monthly temperature above 22 °C with >25 mm of precipitation even in July (Institute of Geography 1999).

Our study shows a general decrease in $\delta^{13}C$ values of forest and steppe soil organic matter with increasing altitude below ca. 3500 m (Figure 3), suggesting that may be related to the decrease in C4 plants with increasing altitude as discussed above. Above ca. 3500 m, the $\delta^{13}C$ values of soils from desert and alpine desert sites (Figures 3 and 4(f)) showed a significant positive might be related to the present CAM plants at high altitude.

The potential effect of CO_2 on carbon isotope

The discussion of potential effect of CO_2 on carbon isotope will focus on two aspects: firstly, are the $\delta^{13}C$ values of atmospheric CO_2 changing with elevation gradient? Levin (1984) and Körner et al. (1988) have demonstrated that atmospheric variations in $\delta^{13}C$ values are very smaller in the different elevations; for example, in central Europe $\delta^{13}C$ increases by 0.2‰ between 1200 and 3500 m, both in summer and winter (Körner et al. 1988). Thus over the range of sampling areas between 1250 and 5500 m in Tibetan Plateau encounter variations in atmospheric $\delta^{13}C$ one order of magnitude smaller than ca. 0.5‰, only a minor portion of the observed $\delta^{13}C$ values range from −28.6 to −15.1‰. Atmospheric variations in $\delta^{13}C$ values do not explain this large variation in $\delta^{13}C$ values of soils.

Secondly, though the $\delta^{13}C$ values of atmosphere has not a lager change along the different elevations, but at high elevation, the lowering of partial pressure of CO_2 and O_2 induced by the decreasing atmosphere pressure will lead to the decrease in the ratio of Pi/Pa (Ratio of intercellular to atmospheric CO_2 partial pressure) in plant leaves, causing lower rates of photosynthesis and heavier ^{13}C in plants

(Körner et al. 1988, 1991). There have been some studies of modern C3 plants and their carbon isotopic composition in the Qinghai-Tibetan Plateau. The results from both Li et al. (1999) and Luo (1998) together with ours (Wang et al. 2003) showed a steady increase in the $\delta^{13}C$ values of C3 plants with increasing altitude. The difference of mean $\delta^{13}C$ values per 1000 m increase in altitude is $1.14 \pm 0.76‰$, which is comparable to the value ($1.2 \pm 0.90‰$) obtained by Körner et al. (1988) based on a global survey of carbon isotope discrimination in plants. Although we accept that the $\delta^{13}C$ values of soils from different vegetations will response to pCO_2 change in the different elevation, however, this does not explain the generally decreases of $\delta^{13}C$ of soils under forest and steppe below ca. 3500 m and large increases of $\delta^{13}C$ of soils under desert and alpine desert above this height. Our regression analyses results also suggest that pCO_2 is not crucial factor affecting the $\delta^{13}C$ values of soils in the Tibetan Plateau. One of the causes may be that the effects of vegetations cover up the ones of pCO_2 on carbon isotope composition of modern soils at any given altitude.

Variations of carbon isotope of soils associated with MAP and MAT

It has become known that precipitation or moisture is an important factor affecting the ^{13}C values of plants. The different carbon isotope composition among C3 plants can be explained by different proportions of stomata and mesophyll resistance to CO_2 uptake (Farquhar 1980, O'Leary and Osmond 1980; Vogel 1980; Farquhar et al. 1982). Plants under different environmental stresses will alter the relative magnitude of the two resistance components (e.g., Mooney et al. 1974; Farquhar and Richards 1984). Low precipitation or humidity (both air and soil) and large ambient vapor pressure deficits would decrease stomatal conductance and reduce the ratios of Pi/Pa (e.g., Farguhar and Sharkey 1982; Farquhar et al. 1982), hence, heavier ^{13}C yields in plants (Farquhar et al. 1982). The decrease in temperature with increasing altitude will increase the ratio of internal to external partial pressure of CO_2 (Pi/Pa) in plants, and reduce the $\delta^{13}C$ values of plants (Farquhar and Wong 1984).

The variations in precipitation and temperature are a crucial factor not only affecting the $\delta^{13}C$ values of plants, but also controlling the vegetation distribution in the Tibetan Plateau. Studies of modern plant distributions indicate that crossover precipitation and temperature strongly affects the competitiveness of C3, C4 and CAM plants (Investigation Team of Chinese Academy of Science 1988a). Regional climate condition plays a key role in the distribution of vegetation communities. In the absence of favorable moisture and temperature conditions, low PCO_2 alone is not sufficient to cause the distinct change in carbon isotope composition of modern soils in the Tibetan Plateau. Huang et al. (2001) also indicate that in the absence of favorable climatic conditions, low pCO_2 alone is insufficient to control the distribution of vegetations.

Our results indicate that both of MAP and MAT are the primary factor affecting the $\delta^{13}C$ values of surface soils in the Tibetan Plateau, a saddle-shaped response surface of $\delta^{13}C$ values corresponding the variety of MAP and MAT. However, the generally positive $\delta^{13}C$ values of soils from alpine deserts in higher altitude, does not been explained this large shift by low pCO_2 and low precipitation, there, a contribution of CAM plants must be considered, suggest that carbon isotope is one of the most sensitive indicators of vegetations in Tibetan Plateau and its conditions may be determined largely by the climate of mountainous region.

In our study, 24 samples collected from the margin of saline lakes and oasis areas, where mean precipitation is less than 200 mm, show relatively light $\delta^{13}C$ (-23.8 ± 1.5‰) (Table 2). The large amplitude of negative shifts in the $\delta^{13}C$ values of soils may reflect an effect of soil solution water and groundwater.

In addition, Bird et al. (1994) discussed some other factors that might cause the change in carbon isotope composition of grassland soils due to changing altitude, such as the effects of decomposition, and the influence of wet condition and sampling locality. In our study, these influential factors may also play some role in determining the proportions of C3 and C4 grasses at any given altitude. For this, more work would be required to substantiate these relationships.

Conclusions

The data presented here for the changes of carbon isotope composition of soils under different vegetation communities along an altitude gradient in the Qinghai-Tibet Plateau demonstrate that the $\delta^{13}C$ values of soils exhibit significant positive shift with changing vegetation communities from forest to shrub, steppe, alpine meadow, alpine desert steppe, and alpine desert.

MAP and MAT are crucial factors not only controlling the vegetation distribution, but also affecting the $\delta^{13}C$ values of plants in the Tibetan Plateau, which causes the change in carbon isotope composition of modern soils at any given altitude. The results of both linear and nonlinear regression analyses also confirms that MAP and MAT are major factors affecting the $\delta^{13}C$ values of surface soils. In the absence of favorable moisture and temperature conditions, low PCO_2 alone is not sufficient to cause the distinct changes in carbon isotope composition of modern soils in the Tibetan Plateau.

There are many factors affecting the composition of carbon isotope of organic matter as mentioned above. Identification of the underlying cause, however, is more complicated because of many uncertainties such as the effect of soil solution water and groundwater, the degree of re-utilization of respired CO_2 during plant photosynthesis, the degree of decomposition of organic matter, and the age of the carbon. Therefore, accurate estimate for the contribution of these influential factors should be included in future investigation of this area. Our study only provides a preliminary framework of carbon isotope composition of soil organic matter in the Qinghai-Tibetan Plateau and some fundamental information on the carbon isotope composition of terrestrial carbon pools, which might have some significance for the use of carbon isotope data to reconstruct vegetation changes and environmental conditions of the high plateau in the past.

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