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RESEARCH ARTICLE

The aliphatic hydrocarbon distributions of terrestrial plants around an alpine lake: a pilot study from Lake Ximencuo, Eastern Qinghai-Tibet Plateau

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Abstract As part of an investigation of the sources of aliphatic hydrocarbons to the sediments of alpine Lake Ximencuo, leaves of the eight dominant vascular plants were collected and their hydrocarbon contents were analyzed. A series of unsaturated aliphatic hydrocarbons were identified in the plant leaves; in particular, *Festuca* sp. contain a series of *n*-alkadienes that have rarely been reported in previous studies. The comparison of *n*-alkane proxies (ACL_{27-33}, ACL_T, P_{aq}, and CPI) and $\delta^{13}C_{org}$ among plant leaves, surface soils, and lake sediments suggests that organic proxies have been altered to varying degrees during the transport and burial process of organic materials. It is believed that microbial reworking and source changes have great impacts on organic proxies in the alpine lake system. In addition, the cluster analysis for plant leaves depending on *n*-alkane compositions and the ACL_T proxy generates similar results. Accordingly, we postulate that the average chain length of plant waxes might be a potential indicator of plant classification in regions such as the Qinghai-Tibet Plateau.

Keywords plant leaves, alpine lake, *n*-alkanes, *n*-alkadienes, Qinghai-Tibet Plateau (QTP)

1 Introduction

The highland core of Asia — the Qinghai-Tibet Plateau (QTP) and the mountain ranges that surround it — has a large and complex cryosphere, which alone would earn it the title of the “Third Pole” and justify the greater attention in recent decades (Yao et al., 2007, Fig. 1(a)). There are many small glacial lakes broadly distributed in the QTP area, representing the enormous amount of glacier movement in ancient and modern times (Wang et al., 2013). It is interesting to note that this type of lake commonly exists in cirques or trough valleys that are characterized by steep slopes that encourage land runoff (Fig. 1(b)). Both glacial meltwater and local precipitation have strong scouring effects on the slope vegetation and soil, delivering large amounts of terrigenous material into the lakes (Pu et al., 2013). Thus, the investigation of plants living around such alpine lakes is of great importance for the exploration of sedimentary environments and material sources.

Aliphatic hydrocarbons, which are ubiquitously present in lake systems, are believed to be produced mainly by aquatic algae and subaerial vascular plants living near the lakes (Meyers, 2003 and references therein). They are easily examined by GC-MS instruments and are suggested to be important biomarkers in recording the original plant assemblages and corresponding paleoenvironmental conditions (e.g., Aichner et al., 2012; Pu et al., 2013; Tarasov et al., 2013; Wang et al., 2014; Peng et al., 2016). In addition, some scholars in recent studies believe that the aliphatic hydrocarbons in plants have important classification functions (Li et al., 2012; Bush and McInerney, 2013). However, information about the hydrocarbon biomarkers in plants living on the QTP is scarce. Liu and Liu (2016) is one of the few studies that provides such information, yet even this study considered only a variety of unidentified shrubs and grasses. Thus, we know less about the characteristics of aliphatic hydrocarbons in the QTP plants, most of which survive in an extreme environment characterized by low temperatures, limited water supplies, high levels of radiation exposure, low atmospheric pressure, and oxygen-poor conditions.

Herein, we focus on hydrocarbon homologs in plant leaves living around Lake Ximencuo by using multivariable statistics. Additionally, novel compounds found in plant leaves were observed. Furthermore, the varying

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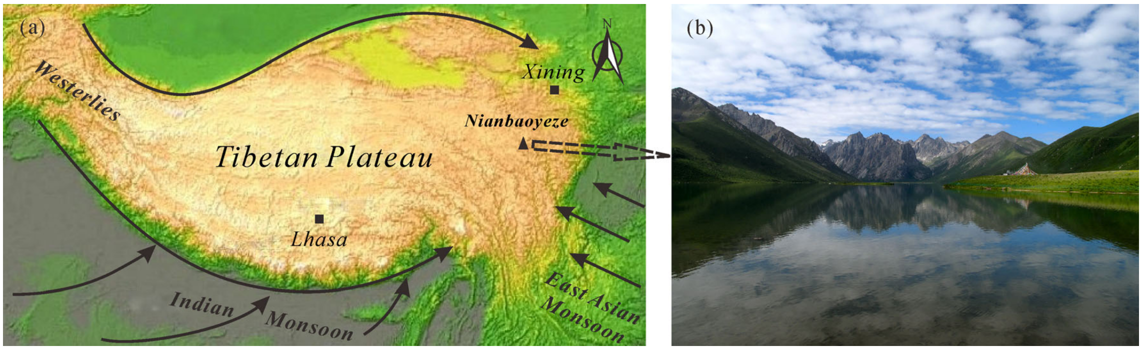


Fig. 1 Location of the Nianbaoyeze area on the eastern Qinghai-Tibet Plateau (a) and the setting of Lake Ximencuo (b). The extensive areas west and north of the Plateau are dominated by westerlies and the summer monsoons, including the East Asia monsoon and Indian monsoon.

pattern of the organic proxies, including *CPI*, ACL_T, $ACL_{27\text{–}33}$, P_{aq}, and $\delta^{13}C_{org}$, in the alpine lake system is presented.

2 Background and methods

Lake Ximencuo (33.38°N, 101.10°E, 4020 m above sea level) is a typical alpine lake in the Nianbaoyeze Mountain area of the eastern QTP (Fig. 1(a)). The vegetation in the study area is mainly characterized by alpine meadows, including dwarf shrubs and high alpine cushion and rosette plants (Fig. 1(b)). Eight dominant alpine plant species were sampled in their natural habitats in the Lake Ximencuo watershed for leaf lipid analysis (Table 1) in July during the warmest season in the study area. The sampling locations include the mountainous slope, the transitional zone of the mountainous slope to lakeshore (piedmont), and near the lakeshore. These zones roughly encompass the entire ecosystem of the Lake Ximencuo watershed.

The measurement of aliphatic hydrocarbons in plant leaves has been previously introduced by Pu et al. (2017). For the organic carbon isotope determination of plant leaves, the eight samples were rinsed ultrasonically in distilled water for 10 min to remove possibly adsorbed dust, and consequently dried and powdered for $\delta^{13}C$ measurement. The organic carbon isotope composition ($\delta^{13}C_{org}$) was tested on an EA 1112 HT-MAT253 using a standard of V-PDB (Vienna PeeDee Belemnite). Glycine and collagen standards provided by SIGMA Company were used to test instrument conditions, and the total error was less than 0.155‰.

To further investigate the differences and similarities of the leaf hydrocarbon compositions between the eight plant species, we used the relative abundances of the *n*-alkane series ranging from C_{21} to C_{35} for cluster analysis. Hierarchical cluster analyses were calculated with the discriminant scores. Ward's partitioning and the squared Euclidean distance were used for the hierarchical cluster analysis. All statistics were performed with SPSS 22.

The *n*-alkanes proxies, including average chain length (*ACL*), carbon preference index (*CPI*), and P_{aq}, mentioned in the discussion, are based on Eq. (1) to Eq. (4):

$$ACL_T = (\Sigma[C_i]^*i)/\Sigma[C_i]$$

$$(\text{“}i\text{” is an odd carbon number from 21 to 35}), \quad (1)$$

$$ACL_{27-33} = (\Sigma[C_i]^*i)/\Sigma[C_i]$$

$$(\text{“}i\text{” is an odd carbon number from 27 to 33}), \quad (2)$$

Table 1 Detailed information about the 8 terrestrial plants collected from the Ximencuo region

No.	Species	Family	Plant Life-Form	Sampling Location
Plant-1	*Potentilla fruticosa*	Rosaceae	Deciduous Shrub	Hillside
Plant-2	*Salix oritrepha*	Salicaceae	Deciduous Shrub	Hillside
Plant-3	*Hippophae rhamnoides*	Elaeagnaceae	Deciduous Shrub	Piedmont
Plant-4	*Kobresia* sp.	Cyperaceae	Perennial Herb	Near the Lakeshore
Plant-5	*Ajuga ovalifolia*	Lamiaceae	Annual Herb	Near the Lakeshore
Plant-6	*Lancea tibetica*	Scrophulariaceae	Annual Herb	Near the Lakeshore
Plant-7	*Festuca* sp.	Gramineae	Perennial Herb	Piedmont
Plant-8	*Rumex acetosa*	Polygonaceae	Perennial Herb	Piedmont

$$CPI_{\mathrm{T}} = (\Sigma\mathrm{odd}(\mathrm{C}_{21}-\mathrm{C}_{33}) + \Sigma\mathrm{odd}(\mathrm{C}_{23}-\mathrm{C}_{35}))/2\Sigma\mathrm{odd}(\mathrm{C}_{22}-\mathrm{C}_{34}), \quad (3)$$

$$P_{aq} = (\mathrm{C}_{23} + \mathrm{C}_{25})/(\mathrm{C}_{23} + \mathrm{C}_{25} + \mathrm{C}_{29} + \mathrm{C}_{31}). \quad (4)$$

3 Results and discussion

3.1 The aliphatic hydrocarbon distributions in plant leaves

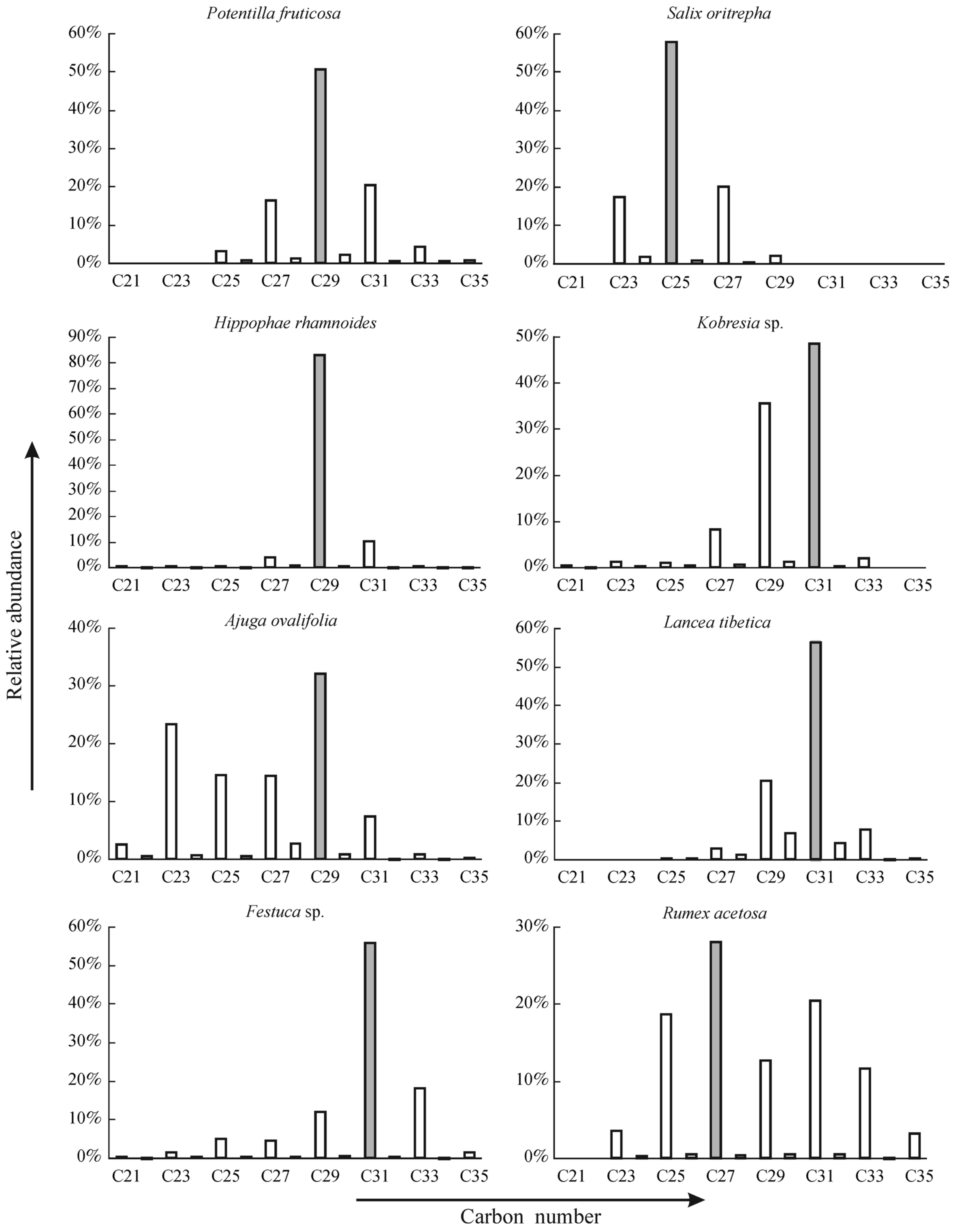
The *n*-alkane distributions in the eight plant leaves range from C_{21} to C_{35}, exhibiting strong odd-carbon-chain preferences that yield *CPI* values that range between 7 and 68 and average 36.6 (Pu et al., 2017). The maxima of *n*-alkane distributions were marked with shading in Fig. 2. Three of the plants are dominated by the C_{29} homolog, three others by the C_{31} homolog, and one each by either the C_{25} or C_{27} homolog, all of which are classical distributions of higher plant leaf waxes.

We have reported that different unsaturated hydrocarbon series were found in the leaf waxes of *S. oritrepha*, *A. ovalifolia*, and *Festuca* sp., all of which are widely present in the Lake Ximencuo watershed (Pu et al., 2017). In detail, *S. oritrepha* is dominated by even-carbon homologs ranging from *n*-$\mathrm{C}_{24:1}$ to *n*-$\mathrm{C}_{30:1}$, and the *n*-alkene series in *A. ovalifolia* and *Festuca* sp. have significant odd-carbon preferences. Interestingly, very low amounts of *n*-alkadienes with equal intervals, including *n*-$\mathrm{C}_{25:2}$, *n*-$\mathrm{C}_{27:2}$, and *n*-$\mathrm{C}_{29:2}$, were identified by their mass spectra in the leaves of *Festuca* sp. (Fig. 3). These homologs eluted prior to the corresponding alkene/alkane doublet, and their molecular ions are m/z 348, 376, and 404, respectively (Fig. 4). *n*-Alkadienes have been previously reported in algae living in lake systems by an analytical method different from ours (Weete, 1976). They are postulated to be diagenetically reduced to saturated hydrocarbons during incorporation into lake sediments (Lichtfouse et al., 1994). A more recent study has identified a series of *n*-alkadienes in the pyrolysates of leaf cuticles (Finch and Freeman, 2001). Nonetheless, reports of *n*-alkadienes series in living vascular plants remain rare. We have found only two reports of alkadienes in extractable plant lipid analyses similar to those we have conducted: a conjugated alkadiene series found in the flowers of *Rosa damascena* by means of thin-layer chromatography (Stoianova-Ivanova et al., 1971) and the *n*-alkane, *n*-alkene, and *n*-alkadiene series identified in the flowers of *Ophrys* plants in which the dienes were mainly the C_{27}, C_{29}, and C_{31} alkadienes with unknown double-bond positions (Stökl et al., 2005). The detection of *n*-alkadienes in *Festuca* leaves is the first time that a diene lipid has been identified from an alpine plant. The absence of recent reports of *n*-alkadienes in living plants suggests that these compounds are unusual lipids in vascular plants, in spite of being ubiquitous in aquatic environments, where they are postulated to be derived from *Botryococcus* algae (Metzger et al., 1985, 1986). It is believed that the higher plants, such as certain *Festuca* sp., could contribute diene lipids as well.

We summarized the characteristics of unsaturated hydrocarbons series mentioned in this study (Table 2). It is curious to note why the unusual alkadiene series might be present in the *Festuca* sp. perennial grass living around Lake Ximencuo. Additionally, why do the odd and even series of *n*-alk-1-ene appear simultaneously in the leaves of three of eight plants around this lake? We note that the proportions of unsaturated hydrocarbons present in plant leaves can greatly change with the seasons due to changes in the ambient temperature; low temperatures encourage plants to biosynthesize more unsaturated lipids to maintain the fluidity of their cell membranes (Nishida and Murata, 1996; Cui et al., 2008). The *n*-alkadienes and series of *n*-alk-1-enes identified in plant leaves in this study imply the physiological adaptation of the subaerial vascular plants to this harsh alpine environment. The cool conditions may force the alpine plants to biosynthesize the unsaturated hydrocarbon series that is less observed in vascular plants, most of which have been collected at lower elevations. Our findings should encourage the study of more alpine plants to confirm this assumption.

3.2 *n*-Alkane proxies and $\delta^{13}\mathrm{C}_{\mathrm{org}}$ in plant leaves vary in alpine lake system

The *n*-alkane proxies and $\delta^{13}\mathrm{C}_{\mathrm{org}}$ in plant leaves will be discussed in this section. The *CPI* values of eight plant leaves were introduced in Pu et al. (2017). For the P_{aq} index, which is a classic paleoenvironmental indicator, it changes in plant leaves with a wide range from near zero to 0.97, with a mean value of 0.25. We note that the *n*-alkane distribution in the leaves of *Salix oritrepha*, which is a widespread deciduous shrub species on the eastern QTP, maximizes at C_{25}, showing the highest P_{aq} value of all the plant samples. The distributions of the *Salix* sp. in prior analyses have always had their main peaks at *n*-C_{27} (e.g., Hietala et al., 1995; Tarasov et al., 2013), and therefore, the *n*-alkane distribution of *S. oritrepha* in this study is unusual. We also note that the *n*-alkane distribution of the herb *Ajuga ovalifolia* contains abundant C_{23} and exhibits the second highest P_{aq} value. Previous studies have reported that *n*-alkane distributions in herb and shrub leaves commonly maximize at C_{27}, C_{29}, or C_{31} (e.g., Vogts et al., 2009; Bush and McInerney, 2013; Tarasov et al., 2013). However, the *n*-alkane *n*-C_{23} and *n*-C_{25} abundances in the leaves of *S. oritrepha* and *A. ovalifolia* plants are instead more similar to those found by Ficken et al. (2000) as being distinctive of submerged and floating aquatic plants. Both of them showed relatively high P_{aq} values that were significantly greater than those of other plant species. However, previous studies have demonstrated that terres-



Potentilla fruticosa

Salix oritrepha

Hippophae rhamnoides

Kobresia sp.

Ajuga ovalifolia

Lancea tibetica

Festuca sp.

Rumex acetosa

Fig. 2 Distributions of the *n*-alkanes in the leaves of eight dominant plants around Lake Ximencuo (the gray bars emphasize the dominant carbon numbers).

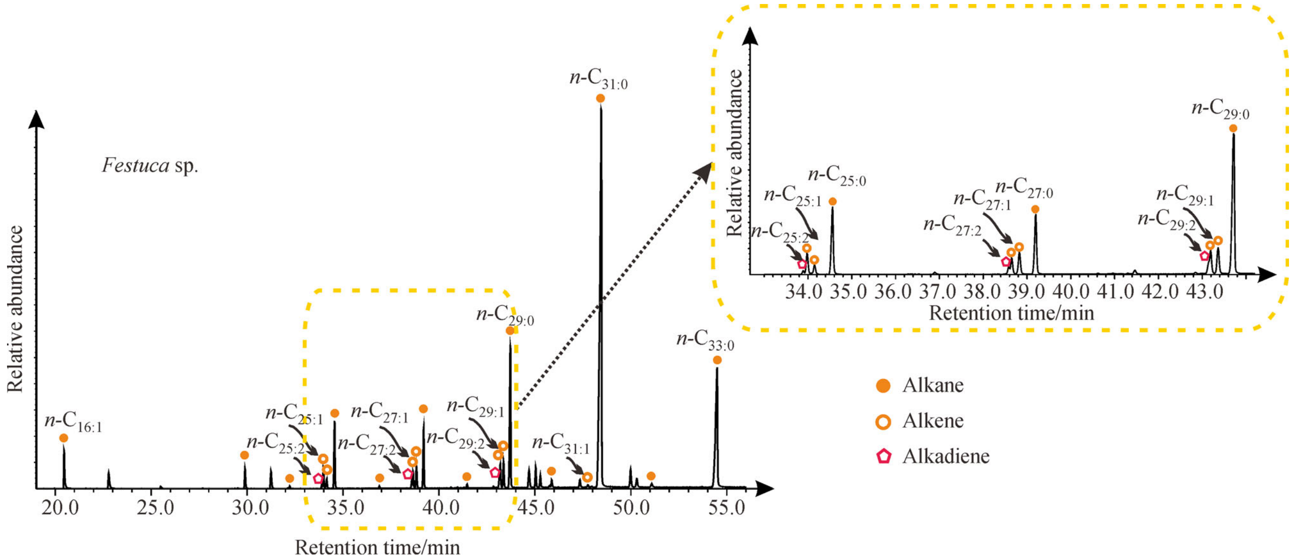


Fig. 3 Chromatograms of the *n*-alkene and *n*-alkadiene distributions in leaves of *Festuca* sp.

Table 2 General information of the unsaturated hydrocarbon series identified in eight plant leaves

Name	Carbon range	Carbon maximum	Carbon preference	Type of double-bond
Salix oritrepha	C_{24}–C_{30}	C_{26}	Even Preference	Monoalkene
Ajuga Ovalifolia	C_{27}–C_{31}	C_{29}	Odd Preference	Monoalkene
Festuca sp.	C_{25}–C_{31}	C_{29}	Odd Preference	Monoalkene
	C_{25}–C_{29}	–	Odd Preference	Dialkene

trial plants biosynthesize shorter chain compounds for their waxy coatings under colder conditions; this response is likely to decrease the proportions of odd-carbon *n*-alkanes from C_{21} to C_{35} that are produced by higher plants (e.g., Poynter et al., 1989). Consequently, the possibility of a typical hydrocarbon distributions in alpine plants such as these two should be taken into account during interpretations of the *n*-alkane origins in alpine lake sediments.

To summarize their distributions, we calculated the average chain length (*ACL*) values for the plant *n*-alkanes over the classical chain length range of C_{27} to C_{33} ($ACL_{27–33}$), and the broader range of C_{21} to C_{35} (ACL_T). The respective ranges of the $ACL_{27–33}$ and the ACL_T values are 27.2 to 30.9 and 25.1 to 30.6. In particular, the average value of $ACL_{27–33}$ is approximately 29.7, which is very close to the $ACL_{27–33}$ average value of 29.4 for Ximencuo sediments, suggesting that the land plants around the lake are major contributors of aliphatic hydrocarbons to the lake sediments and that the *n*-alkane distributions appear to be well preserved. The *ACL* is considered to mainly respond to temperature fluctuation and has been applied as a paleotemperature proxy in a number of studies (e.g., Zhou et al., 2005; Pu et al., 2013; Bush and McInerney, 2015). However, the individual $ACL_{27–33}$ values, and especially the ACL_T values, of the leaf waxes of the eight plants differ significantly despite the plants having originated from a common location and very similar growth conditions. This variability is reminiscent of the *ACL* variations noted by Feakins et al. (2016) in their multi-plant elevation transect in the Peruvian Andes. These researchers postulated that intraspecific variability was responsible for much of the *ACL* variation that they observed, but because we pooled leaves from ten or more plants, this would eliminate such a possibility. Instead, we are left with interspecific variability as the most likely explanation.

In their recent study of the *n*-alkane distributions of 13 terrestrial plant samples collected from 6 alpine lakes on the QTP, Liu and Liu (2016) report *ACL* values that are generally lower than those of our study. In particular, the seven grasses collected from the northern QTP show *n*-nonacosane as the main peak and have *ACL* values that average one-unit less than the values of the plants from around Lake Ximencuo. Previous studies have demonstrated that *n*-alkane distributions correlate with source plant groups and climate factors such as temperature and aridity. Therefore, the differences in the QTP plant *ACL* values may arise from differences in the plant groups in different parts of the Plateau. In addition, the locations of the lake areas studied by Liu and Liu (2016) are 2° to 5° farther north than Lake Ximencuo, and both the annual mean temperatures and extreme low temperatures of these areas are significantly lower than those in the Ximencuo

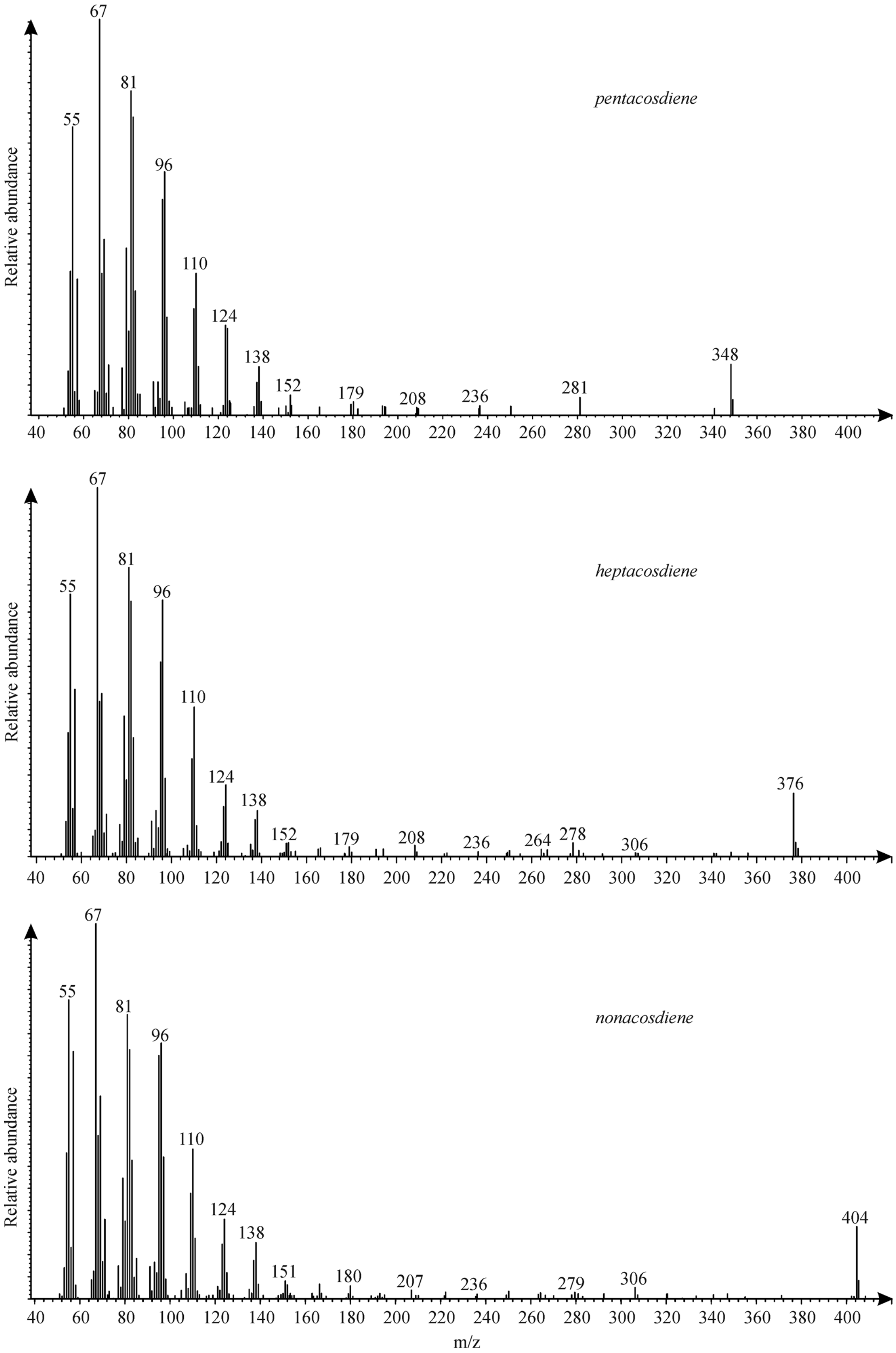


Fig. 4 Mass spectra of the *n*-alkadiene series identified in leaves of *Festuca* sp.

area. To maintain a plant's moisture balance and to protect its leaf membranes, the leaf epicuticular wax composition of higher plants changes significantly in response to ambient temperature changes. In warmer tropical climates, land plants are postulated to biosynthesize longer chain compounds for their waxy coatings and vice versa (Poynter et al., 1989). Thus, ambient temperatures might be another important factor to make the terrestrial plant *ACL* values in the Ximencuo area greater than those of the plants presented in Liu and Liu (2016). In addition to temperature, aridity has also been proposed as a driver of chain length, where drier conditions promote longer chain lengths and vice versa (Andersson et al., 2011). Typically, the relative humidity in the northern QTP is lower than that of the eastern QTP, which is influenced by the Indian Ocean Monsoon (Wang et al., 2010). This factor would be expected to encourage plants on the northern QTP to preferentially synthetize longer-chain length *n*-alkanes and therefore exhibit larger *ACL* values, not smaller ones. Because this behavior is not observed in the comparison of the *ACL* proxies between the northern and eastern QTP, aridity appears to not be the dominant factor in this high-altitude region.

Instead, the differences in chain length distributions in plants from a common location, as found in our study, underscore the potential importance of changes in plant assemblages, and in addition to environmental conditions, affecting *ACL* values in geological samples (Bush and McInerney, 2013; Feakins et al., 2016). The importance of plant community compositions is further underscored by the $ACL_{27–33}$ values of *S. oritrepha*, *A. ovalifolia*, and *R. acetosa* that are 1 to 2 units smaller than the ACL_T values because of the significant proportions of C_{23} and C_{25} *n*-alkanes in their wax distributions (Fig. 2).

The $\delta^{13}C_{org}$ proxy has been used as an authentic indicator to evaluate ecosystem responses to climate change (Kaplan et al., 2002). In this study, the $\delta^{13}C_{org}$ values of the eight plants ranged from –29.9 ‰ to –25.9 ‰, with an average of –27.5 ‰, which signifies that all the tested plants are representative C3 plants. However, the $\delta^{13}C_{org}$ values in the surface soils sampled from the Ximencuo watershed range from –26.0 ‰ to –26.8 ‰ (mean value = –26.4 ‰), and the $\delta^{13}C_{org}$ values in Ximencuo sediments range from –24.7 ‰ to –23.3 ‰ (mean value = –23.8 ‰) (Pu et al., 2011). As seen from Fig. 5, the $\delta^{13}C_{org}$ values in lake sediments show significantly more positive excursion than those of plant leaves, as well as surface soils. While the $\delta^{13}C_{org}$ values in soils and leaves are essentially similar, the mean value of $\delta^{13}C_{org}$ in surface soil is approximately 1.1‰ greater than that of plants, indicating that the organic matter in soil is primarily derived from terrestrial plants with minor degradation.

By extension, we compare the *CPI*, ACL_T, $ACL_{27–33}$, P_{aq}, and $\delta^{13}C_{org}$ values between the plant leaves, surface soils, and lake sediments to tentatively analyze and explore

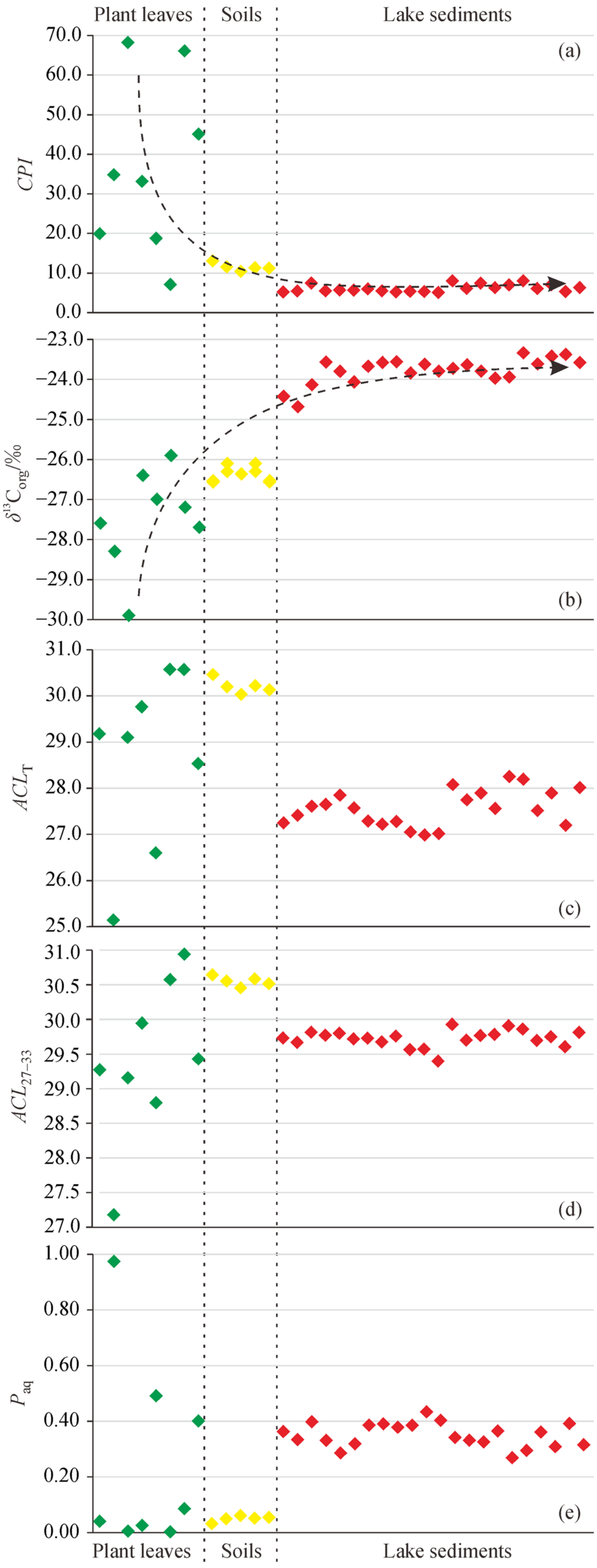


Fig. 5 The comparison of *n*-alkane indexes (*CPI*, ACL_T, $ACL_{27–33}$, P_{aq}, and $\delta^{13}C_{org}$) between plant leaves, surface soils, and lake sediments. The dotted lines denote the monotonic trend of organic proxies.

organic proxy shifts in the alpine lake system. *CPI* values continuously decrease from plant leaves to surface soils and then to lake sediments (indicated with dotted lines in Fig. 5(a)). It is suggested that the *n*-alkanes derived from terrestrial plants were degraded by microbial reworking in the delivery route from plant to soil and subsequently deposited in the lake. The odd-carbon *n*-alkane homologues are suggested to be preferentially degraded by microbial activities that led to the *CPI* proxy being significantly decreased in the transport process. Another possibility is that the potential *n*-alkane contributions from submerged plants, algae, and fungi living in alpine lakes with comparatively lower odd-carbon preferences might reduce the *CPI* values in lake sediments.

As for the $\delta^{13}C_{org}$ proxy, a similar monotonic trend could also be observed (Fig. 5(b)). Microbial reworking of plant-derived materials during early diagenesis can gradually increase its carbon isotopic content of ^{13}C owing to the lighter carbon atoms that are preferentially utilized by microbial degradation (Meyers and Ishiwatari, 1993). Simultaneously, the autochthonous contributions in the lake with more enriched $\delta^{13}C_{org}$ values, such as the submerged plants, algae, fungi, and so forth, probably lead to the positive shift in lake sediment. Taken together, the microbial reworking and sources change are presumed to be dominant factors for $\delta^{13}C_{org}$ proxy variations in alpine lake systems.

However, the comparable trend could not be observed from other organic proxies in Lake Ximencuo. In detail, both the ACL_T and ACL_{27-33} did not show significant decreases in the delivery route, and their mean values in soil and lake sediment are roughly in the range of the *ACL* values in plant leaves (Fig. 5(c) and Fig. 5(d)). In particular, the ACL_T and ACL_{27-33} values in soils are close to the ACL_T and ACL_{27-33} values in *Kobresia* sp., *Lancea tibetica*, and *Festuca* sp. which are dominant grasses in the Ximencuo region, indicating that the ACL_T and ACL_{27-33} in soils are dominated by certain local herbs. Similarly, the P_{aq} values in soil were also determined by some specific plants, which have P_{aq} values less than 0.1 as shown in Fig. 5(e). Nevertheless, the organic material from aquatic plants might raise the P_{aq} values in Lake Ximencuo sediments.

As mentioned above, both glacial meltwater and local precipitation have a strong scouring effect on the slope vegetation and soil, transporting terrigenous material such as aliphatic hydrocarbons into Lake Ximencuo. Thus, it is assumed that the surface soils in the watershed contribute amounts of aliphatic hydrocarbons into the lake, which were derived from vascular plants living around the lake. Nevertheless, the ACL_T and ACL_{27-33} values in lake sediments were generally lower than those in soils (Fig. 5(c) and Fig. 5(d)), and P_{aq} values are generally higher than those in soils (Fig. 5(e)). These results suggested that, except for soils and plants, other sources might contribute the aliphatic hydrocarbons to lake sediments. In light of the local conditions, we suppose that the aquatic organisms living in the lake, probably including submerged plants, algae, cyanobacteria, fungi, and microbes, most likely contribute a certain amount of *n*-alkanes with low or middle chain lengths to lake sediments, which resulted in the shifts of the ACL_T, ACL_{27-33}, and P_{aq} proxies (Fig. 5).

Overall, it is highlighted that the organic proxies have been altered at varying degrees during the transport and burial process of organic material in alpine lake sediments. The ACL_T and ACL_{27-33} proxies are considered to maintain the relatively pristine signals of local vegetation, whereas *CPI*, P_{aq}, and $\delta^{13}C_{org}$ proxies might be significantly altered by the factors of microbial reworking and sources change in alpine regions.

3.3 The cluster analysis of eight plant leaves on the basis of *n*-alkane distributions

In the dendrogram of the cluster analysis based on the relative abundances of *n*-alkanes (Fig. 3(a)), the *n*-alkane distributions of the three herb species *Kobresia* sp., *Lancea tibetica*, and *Festuca* sp. are clustered as one group (marked by a dashed box), all of which are characterized by a main peak at *n*-C_{31} and a significant odd-carbon preference (Fig. 2). The distributions of two of the dominant deciduous shrubs surrounding Lake Ximencuo, *Potentilla fruticosa* and *Hippophae rhamnoides*, are clustered into another group, reflecting their similar leaf *n*-alkane distributions (Fig. 6(a)). In a somewhat similar fashion, the distributions of the deciduous shrub *S. oritrepha* and the annual herb *A. ovalifolia* are clustered into one group because they have high abundances of mid-chain *n*-alkanes (*n*-C_{23} and *n*-C_{25}), even though they are in totally different categories of plants, and the perennial herb *R. acetosa* is distantly linked to this cluster on the basis of its broad *n*-alkane distribution (Fig. 6(a)).

It is worth noting that the ACL_T values agree with the relative abundance cluster results as presented in Fig. 6(b). Plants in the same group or showing comparatively close distances also have approximately the same ACL_T values. For instance, *Kobresia* sp., *Festuca* sp., and *L. tibetica,* as well as *P. fruticosa* and *H. rhamnoides*, all of which show near distances within their groups, also have roughly comparable *ACL* values. In fact, a cluster analysis for the eight plant samples using the ACL_T proxy yields a classification result similar to the one obtained with *n*-alkane distributions (Fig. 6(b)). We therefore suggest that the ACL_T values in plant leaves could be used as an indicator for plant classification in regions such as the QTP. However, the carbon preference index (CPI_T) values, which are commonly employed as a measure of the degree of *n*-alkane alteration, are irregular in different plant species and are inconsistent with the cluster result. This disparity indicates that the *ACL* proxy is more useful for plant classification than the *CPI* proxy.

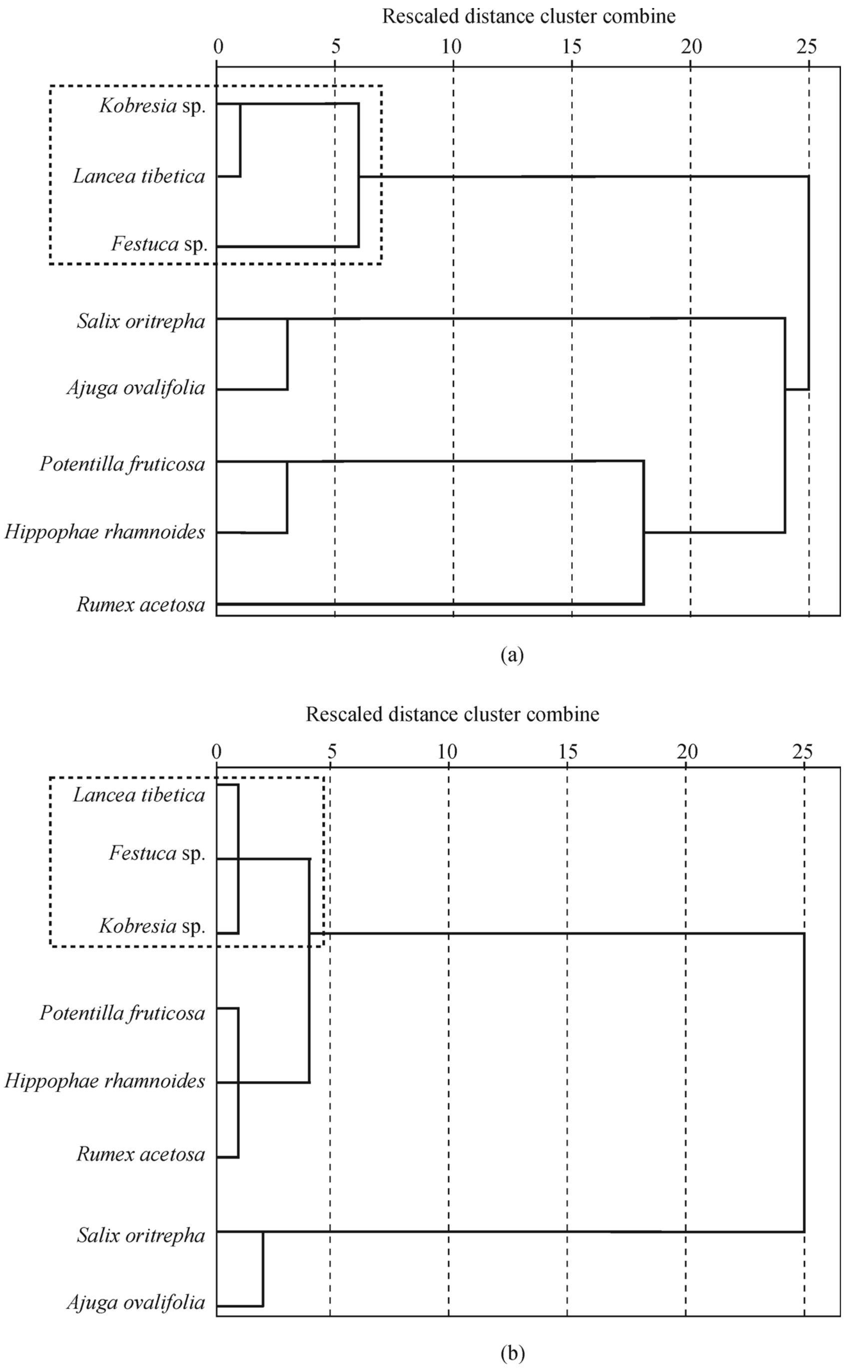


Fig. 6 Cluster analysis showing affinities between the eight terrestrial plants in this study, presented in terms of squared Euclidean distances that depended on their leaf wax *n*-alkane compositions (a) and ACL_T (b).

4 Conclusions

1) The aliphatic hydrocarbons of dominant plant species around Lake Ximencuo were presented. Some series of unsaturated hydrocarbons were found in alpine plant leaves. Notably, an unusual series of *n*-alkadiene homologs was identified in *Festuca* sp. leaves. These hydrocarbon waxes have rarely been reported in vascular plants living in alpine regions. Their presence could be interpreted as a physiological adaptation of the terrestrial plants to severe environments.

2) The comparison of hydrocarbon proxies and $\delta^{13}C_{org}$ between plant leaves, soils, and lake sediments suggests that the ACL_T and ACL_{27-33} proxies in alpine lake sediments could broadly reflect the conditions of local terrestrial plants, while CPI, P_{aq}, and $\delta^{13}C_{org}$ might be impacted by microbial reworking and sources change during the transport and burial processes of organic

materials.

3) The *n*-alkane compositions could roughly divide the plant samples into three different groups by using cluster analysis, which are coincident with the cluster result based on ACL_T values, illustrating that the ACL_T proxy is perhaps a potential proxy for plant classification in alpine regions such as the QTP.

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