青藏高原高寒灌丛草甸花粉组合的植被指示性

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摘要 基于青藏高原泽库盆地31个样点表层苔藓样品孢粉组合分析和植被调查数据, 揭示了高寒灌丛草甸花粉组合特征及其花粉来源范围, 阐明了主要花粉类型对植被组成的指示意义. 结果显示: 研究区花粉组合以莎草科、紫菀属、毛茛科、蔷薇科和禾本科等为主, 其主要由样点周围40 km范围内植被产生(花粉贡献率83%); 花粉组合中出现的桦属、松属和云杉属等乔木类型花粉由风力远距离搬运而来. 0~100 m范围, 研究区各样点间植被组成差异显著, 与花粉组合的对应关系差; 0~3 km范围, 各样点间植被组成差异性减小、整体趋于均质化, 与花粉组合的对应关系逐渐提升; 据此认为, 考虑花粉组合贡献率和区域植被组成影响后的花粉-植被数量关系更能真实反映研究区花粉组合与区域植被组成的对应关系. 此外, 青藏高原灌丛草甸区湖泊表层花粉组合可能受区域外花粉或隐域性植被的影响较大, 花粉组合中出现的大量蒿属和藜科花粉并不真实地代表区域植被组成, 依据该区域湖泊沉积花粉组合变化推测区域植被演替及气候变化时应予以排除.

关键词 青藏高原, 高寒灌丛草甸, 花粉组合, 花粉来源, 区域植被

青藏高原是具有全球意义的脆弱生态系统^[1,2], 对全球气候变化和人类活动干预响应十分敏感^[3]. 现代观测证据显示, 20世纪80年代以来, 青藏高原生态环境变化显著^[4], 植被覆被表现出明显的区域性差异^[5,6]. 未来全球变暖将对青藏高原区域植被组成和空间格局产生怎样的影响, 其发展趋势如何, 是目前学界关注的热点科学问题. 从古生态学角度出发, 重建地质时期青藏高原植被演替历史及其空间格局变化, 可为准确评估和预测未来增温背景下区域生态环境变化提供科学依据.

20世纪80年代以来, 在国内外学者的共同努力下, 青藏高原地区积累了许多晚更新世以来的孢粉学记录^[7~12], 为恢复和重建青藏高原区域植被和气候变化奠定了基础. 如唐领余和李春海^[13]、Hou等人^[14]、Tian等人^[15]基于孢粉资料构建了青藏高原末次冰盛期以来典型时段区域植被格局变化, 为认识和评估不同气候背景下区域生态响应提供了重要参考. 但值得注意的是, 上述研究对化石孢粉数据的植被解释多基于主观经验性判断, 即根据花粉百分比来定性推测植物的多寡, 导致研究结果存在很大不确定性. 解决上述问题的关键

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突破点,就是开展青藏高原地区花粉现代过程研究,建立现代花粉组合与植被的数量关系。

20世纪70年代以来,现代花粉组合与植被关系的研究有了很大发展。其中校正系数 R 值模型自提出以来便广泛应用于花粉与植被关系的研究,随后相对花粉产量和线性模型^[16]、Prentice模型^[17-19]以及Prentice-Sugita模型^[20]的提出进一步修正了花粉与植被关系。另外,我国学者关于现代花粉组合与植被关系的研究涵盖了我国高山、森林、草原、荒漠和青藏高原等区域^[21-27]。然而,受青藏高原独特的地理位置和环境条件等因素限制,目前为止青藏高原地区花粉现代过程研究相对薄弱,且多集中于花粉-气候参数对应关系研究^[28-32],花粉-植被对应关系研究相对较少^[33-35]。此外,已有花粉-植被对应关系研究尚存在以下不足:(1)植被调查范围小,常局限于样点周围(小于20 m×20 m),忽略了区域植被和区域外植被对花粉组合的影响^[36,37];(2)缺乏系统详尽的植被调查数据^[33,34],导致建立的花粉-植被对应关系存在较大误差。因此,亟须开展青藏高原现代代表层花粉组合与植被数量关系研究,弥补现有资料的不足。

高寒灌丛草甸是青藏高原区广泛分布的地带性植被类型^[38](图1),多以莎草科(Cyperaceae)、毛茛科(Ranunculaceae)、菊科(Asteraceae)和蔷薇科(Rosaceae)等植物属种为建群种^[39]。本文选取青藏高原东北部泽库盆地作为研究区,基于详细的野外植被调查和表层苔藓样品花粉分析,旨在揭示高寒灌丛草甸表层花粉组合特征及其花粉来源范围,阐明主要花粉类型与植被组成的对应关系,为地层花粉组合解释和区域植被重建奠定基础。

1 研究区概况

研究区位于青藏高原东北部(34°31'~35°08'N, 101°08'~101°48'E, 3300~4000 m a.s.l.),区内地势开阔、起伏平缓;气候区划属高寒半湿润气候区,季节性特征明显,年均温在-3~3°C之间,气温年较差小,年降水量约400~700 mm,多集中在6~9月^[39,40]。

研究区植被区划属高寒草甸和高寒灌丛,区内植被组成以耐寒和喜冷湿的草本和灌木为主:其中高寒草甸以莎草科植物嵩草属(*Kobresia*)和薹草属(*Carex*)为优势种,伴生有菊科、毛茛科、禾本科(Poaceae)和

图1 研究区地理位置及样点分布图。(a) 高寒灌丛草甸植被带(蓝线)和研究区(红线),底图来源于 <https://maps.google.com>; (b) 研究区青藏高原高寒灌丛草甸主要植被类型,底图来源于中国1:100万植被图。1, 毛枝山居柳灌丛; 2, 毛枝山居柳、金露梅、箭叶锦鸡儿灌丛; 3, 积石山柳灌丛; 4, 金露梅灌丛; 5, 头花杜鹃、百里香杜鹃灌丛; 6, 高寒禾草、薹草草原; 7, 禾草、杂类草草甸和嵩草、杂类草草甸; 8, 小嵩草草甸和矮嵩草草甸; 9, 线叶嵩草草甸; 10, 西藏嵩草、薹草草甸; 11, 圆穗蓼、珠芽蓼草甸

Figure 1 Location of the study area. (a) The range of alpine shrub meadow (the blue line) and study area (the red line); (b) The main vegetation type in study area. 1, *Salix oritrepha* scrub; 2, *Salix oritrepha*, *Dasiphora fruticosa*, *Caragana jubata* scrub; 3, *Salix oritrepha* var. *amnematchinensis* scrub; 4, *Dasiphora fruticosa* scrub; 5, *Rhododendron capitatum*, *Rh. thymifolium* scrub; 6, Alpine Grass, *Carex* Steppe; 7, Grass and Forb meadow, *Kobresia* and Forb meadow; 8, *Kobresia pygmaea* meadow, *Kobresia humilis* meadow; 9, *Kobresia capillifolia* meadow; 10, *Kobresia tibetica*, *Carex* meadow; 11, *Polygonum macrophyllum*, *Polygonum viviparum* meadow. Satellite image (a) is from <https://maps.google.com>; Basemap (b) is from Vegetation Map of the People's Republic of China (1:1000000)

委陵菜属(*Potentilla*)等, 主要分布于盆地区域和山地阳坡; 高寒灌丛以金露梅(*Dasiphora fruticosa*)为主, 另有少量沙棘属(*Hippophae*)和高山绣线菊(*Spiraea alpina*), 多分布在坡度较大的山地阴坡。

2 研究方法

2.1 样品采集与植被调查

2017年4月, 根据青海省植被区划和Google卫星影像确定研究区范围, 采用随机布点法(参见Li等人^[41]和孙沅浩等人^[42]) 在研究区内选取31个代表性强、人类活动影响小的样点(图1(b))。

2017年7~8月, 课题组成员赴研究区开展样品采集和植被调查工作。首先利用GPS系统寻找随机样点, 采集苔藓样品并记录经纬度和海拔高程等信息; 然后按照Bunting等人^[43]提出的工作方法进行植被调查: 0~10 m范围采用1 m×1 m样方调查法; 10~100 m范围采用群落调查法; 100~3000 m范围主要针对百米范围内未出现的群落类型, 目测估算主要植物属种的盖度。

2.2 实验室处理及数据分析

花粉提取采用常规的酸-碱-重液浮选法^[44], 每个样品取干重5 g。花粉鉴定统计在OLYMPUS BX51光学显微镜下完成, 每个样品鉴定统计陆生植物花粉800粒以上, 花粉形态鉴定主要参考《中国植物花粉形态》^[45]和青藏高原东北部现代花粉形态^[46]。花粉百分比计算以陆生花粉总数为基数, 花粉图谱在Tilia 1.7.16软件中绘制^[47]。

野外获取的0~100 m植被调查数据采用Vegetation Survey Manager 2.0^[48]软件进行处理, 得到0~100 m距离加权植被盖度。100 m外植被数据在ArcGIS软件中利用最大似然分类法对研究区卫星影像数字化和赋值, 为保证各样点100 m外植物群落赋值的准确性, 参考各样点及其周围生境相似的3~4个样点植物群落的属种盖度均值、《青海植被》以及中国1:100万植被图对群落进行赋值, 最终得到研究区80 km×70 km范围的距离加权植被盖度。

此外, 为获得不同范围植被对花粉组合的影响, 本研究采用Prentice等人^[19,49]提出的花粉沉积散布模型计算主要花粉类型的贡献率(公式(1))。模型运算时主要参数设定如下: 沉积盆地半径0.5 m, 区域多年平均风速2.6 m/s, 花粉来源范围不限; 模型中使用的各花粉属种

沉降速率采用Gregory提出的Stoke和Falck方法计算^[50] 公式(2)和(3), 其中花粉大小由显微镜下实际测量得到(每个花粉形态测量100个):

$$g_i(z) = b_i \gamma z^{\gamma-1} e^{-b_i z^\gamma}, \quad (1)$$

$$v_s = 2r^2 \cdot \frac{g(\rho_0 - \rho)}{9\mu}, \quad (2)$$

$$v_e = v_s \cdot \sqrt[3]{\frac{a}{b}}, \quad (3)$$

其中, v_s 为球形花粉沉降速率(cm s^{-1}); v_e 为椭圆形花粉沉降速率(cm s^{-1}); r 为球形花粉粒半径(cm); a 为椭圆形花粉粒长轴长度(cm); b 为椭圆形花粉粒短轴长度(cm); g 为重力加速度(cm s^{-2})取 981 cm s^{-2} ; ρ_0 为花粉粒密度(cm^{-3})取 1 cm^{-3} ; ρ 为空气密度(cm^{-3})取 $1.27 \times 10^{-3} \text{ cm}^{-3}$; μ 为动力黏度($\text{cm}^{-1} \text{ s}^{-1}$)取 1.8×10^{-4} ; z 为距沉积盆地中心的距离; $g_i(z)$ 为距离沉积盆地中心 z 距离时, 属种 i 的花粉累积贡献率; b_i 为 $75.2v_i/v$, v_i 为属种 i 的花粉沉降速率, v 为当地平均风速; γ 为常数约等于 $1/8$ ^[19]。

3 研究结果

3.1 花粉组合特征

研究区31个样点共鉴定出37个科属孢粉类型。花粉组合中草本类型占绝对优势(平均81.80%), 莎草科含量最高(7.94%~44.68%, 平均27.05%), 其次为紫菀属(*Aster*, 1.76%~50.47%, 平均19.98%)、毛茛科(6.47%~40.54%, 平均15.39%)和禾本科(0~15.43%, 平均4.62%); 灌木类型以蔷薇科为主(金露梅, 2.59%~17.55%, 平均7.01%), 并出现有少量沙棘属(0~8.82%, 平均1.77%); 乔木类型主要为桦木属(*Betula*, 0~17.80%, 平均5.94%)、松属(*Pinus*, 0~5.99%, 平均1.72%)和云杉属(*Picea*, 0~5.39%, 平均1.04%)。研究区各样点主要花粉属种百分比见图2(a)。

3.2 植被组成特征

研究区植被调查共鉴定出39个植物属种, 区内平均植被盖度在90%以上。根据各样点0~100 m范围内植被组成, 可将31个样点划分为3个群落类型, 其中莎草群落21个、禾草群落5个和金露梅群落5个(图1(b))。0~100 m范围内, 不同群落植被组成差异明显: 莎草群落以莎草科(1.88%~15.63%, 平均38.27%)和紫菀属(2.52%~33.76%, 平均11.91%)为主, 其他植物属种含量

图2 研究区花粉组合及植被组成. (a) 花粉百分比(%); (b) 0~100 m植被组成($\text{m}^2/\text{m}^2 \times 100$); (c) 0~3000 m植被组成($\text{m}^2/\text{m}^2 \times 100$); A, 莎草群落; B, 禾草群落; C, 金露梅群落

Figure 2 Pollen assemblages and vegetation composition in the study area. (a) Pollen proportion (%); (b) vegetation composition within distance of 0–100 m ($\text{m}^2/\text{m}^2 \times 100$); (c) vegetation composition within distance of 0–3000 m ($\text{m}^2/\text{m}^2 \times 100$). A, Cyperaceae communities; B, grass communities; C, *Dasiphora fruticosa* communities

均较低(<10%); 禾草群落优势种为禾本科(6.54%~41.43%, 平均19.93%)、毛茛科(5.88%~34.99%, 平均17.46%)、紫菀属(4.45%~21.92%, 平均13.28%)和莎草科(3.47%~21.77%, 平均12.48%); 金露梅群落主要由蔷薇科(12.44%~25.46%, 平均21.07%)、莎草科(2.47%~33.33%, 平均16.06%)和毛茛科(7.36%~22.18%, 平均14.30%)组成. 0~3000 m范围内, 不同群落植被组成差异相对减小, 植被趋于均质化, 以莎草科(17.81%~37.99%, 平均30.49%)为优势, 伴生紫菀属(6.65%

~18.95%, 平均12.47%)、毛茛科(7.57%~17.70%, 平均10.85%)、蔷薇科(5.48%~13.61%, 平均8.92%)和禾本科(4.75%~15.77%, 平均8.45%)等. 研究区各样点不同距离植被组成见图2(b)和(c).

3.3 主要类型花粉贡献率

根据研究区主要花粉类型百分含量及其沉降速率, 本文计算获得不同范围植被对花粉组合的贡献(表1). 结果表明, 花粉组合中46%的花粉来自样点周围100 m

表 1 不同距离植被花粉贡献率

Table 1 The proportion of total pollen loading reached within different distances

花粉类型	花粉沉降速率 (m/s)	花粉百分比 (%)	0~0.1 (km)	0~0.5 (km)	0~1 (km)	0~3 (km)	0~5 (km)	0~10 (km)	0~20 (km)	0~40 (km)
Cyperaceae	0.0410	29.75	19.04	23.05	24.44	26.24	26.91	27.67	28.27	28.73
Poaceae	0.0402	5.10	3.23	3.92	4.16	4.47	4.59	4.73	4.83	4.91
Ranunculaceae	0.0165	16.99	5.74	7.67	8.50	9.81	10.39	11.17	11.92	12.62
<i>Aster</i>	0.0208	21.86	8.85	11.60	12.75	14.47	15.22	16.19	17.09	17.91
<i>Taraxacum</i>	0.0287	3.01	1.53	1.95	2.11	2.33	2.43	2.54	2.64	2.72
<i>Artemisia</i>	0.0209	3.48	1.42	1.86	2.04	2.31	2.44	2.59	2.73	2.86
Rosaceae	0.0078	7.84	1.39	1.94	2.20	2.62	2.83	3.12	3.41	3.72
Polygonaceae	0.0274	2.80	1.39	1.77	1.92	2.16	2.22	2.33	2.43	2.51
Gentianaceae	0.0242	2.02	0.91	1.18	1.29	1.45	1.51	1.60	1.67	1.74
其他 ^{a)}	—	7.14	2.65	3.43	3.77	4.28	4.51	4.80	5.08	5.36
总贡献率		100.00	46.16	58.36	63.18	70.15	73.06	76.74	80.08	83.08

a) 其他: 研究区平均花粉含量低于2%的类型之和

范围内植被, 其中莎草科(19.04%)和紫菀属(8.85%)花粉贡献率高, 蒿属(1.42%)和蔷薇科(1.39%)贡献率低; 3 km范围内植被的花粉贡献率达70%以上; 3 km外植被对花粉组合的贡献逐渐降低, 3~40 km范围内植被的贡献率仅增加13%, 即83%的花粉由周围40 km 范围内植被贡献。

4 讨论

4.1 花粉来源范围及其植被指示意义

研究区各样点花粉组合均以莎草科(29.75%)和紫菀属(21.86%)占主导, 其次为毛茛科(16.99%)、禾本科(5.10%)和蔷薇科(7.84%); 样点间花粉类型和含量差异均不显著, 且无明显的群落特征(图2(a))。结合样点植被类型和区域地貌特征, 我们认为研究区表层苔藓花粉沉积主要依靠风力搬运。因此, 根据Prentice等人^[19]提出的花粉沉积散布模型计算了研究区不同范围植被对花粉组合的贡献率。结果显示, 样点周围100 m范围内植被对花粉组合的贡献率仅为46%, 3 km范围内植被对花粉组合的贡献率达70%, 40 km范围内植被对花粉组合的贡献率为83%。参考Prentice等人^[19]、许清海和张生瑞^[36]提出的沉积盆地花粉组合划分方案, 研究区各样点花粉组合可划分为当地花粉(46%, 对应100 m范围内植被)、区域花粉(83%, 对应40 km范围内植被)和区域外花粉(17%, 40 km范围外植被)。此外, 所有样点花粉组合中都出现一定比例的乔木花粉(0.44%~

18.85%)。但研究区现代植被调查显示, 研究区40 km范围内无森林分布; 表明花粉组合中出现的乔木类型主要通过风力作用远距离搬运而来。基于上述结果, 我们认为研究区表层苔藓花粉沉积主要反映当地植被和区域植被组成, 并受区域外植被的影响。因此, 以往不考虑花粉来源和植被贡献率, 将表层花粉组合与样点周围植被(小于20 m×20 m)进行比较, 获得的花粉-植被数量关系可能存在偏差。

为获得研究区主要花粉类型与植被的数量关系, 本文将各样点花粉组合(考虑花粉贡献率)与0~40 km范围内植被组成(将各样点考虑花粉贡献率后的花粉组合分别与不同范围的植被进行比较, 发现花粉组合与区域植被更相近)进行对比, 结果显示: 区域植被中莎草科花粉含量为28.73%, 对应的莎草科植物平均盖度为30.49%, 比值接近于1; 蔷薇科和禾本科花粉含量相对较低(分别为3.72%和4.91%), 但对应的平均植被盖度分别为8.92%和8.45%, 比值仅为0.41和0.58; 而紫菀属花粉含量(17.91%)却明显高于植被盖度(12.47%), 比值达1.57。造成以上各属种花粉-植被关系明显差异的主要原因可能是花粉产量和花粉传播方式的不同: 已有研究显示, 莎草科植物花粉产量和代表性一般相对适中^[51], 但禾本科植物花粉产量普遍较低, 常表现为明显的低代表性^[52-55]。区内蔷薇科植物以金露梅为主, 为虫媒花粉, 且多生长于山地阴坡, 花粉传播易受地形限制, 因而代表性低。前人研究显示, 菊科植物花粉多呈低代表性^[56,57], 但研究区紫菀属植物花粉并不表现为低代

表性;一方面可能与紫菀属植物分布广泛、易于花粉传播有关,另一方面可能与前人研究中未详细区分菊科植物花粉类型有关.我们认为,在考虑花粉组合贡献率和区域植被组成后的花粉-植被数量关系更能真实反映研究区花粉组合与区域植被组成的对应关系,今后解释地层花粉数据时应予以考虑.

4.2 区域外花粉和隐域性植被对花粉组合的影响

青藏高原地区已有地层孢粉记录常将花粉组合中出现的莎草科、蒿属、藜科和乔木花粉等作为重要的植被和气候代用指标.如Li等人^[58]认为青藏高原区自东向西花粉组合从以莎草科为主逐渐演变为以蒿属为主,揭示了高原空间尺度上降水逐渐减少的过程.唐领余和李春海^[13]依据青藏高原区湖泊花粉记录中的蒿属和藜科含量变化,恢复了全新世高原植被的时空分布状况.然而,本研究结果显示,青藏高原东北部灌丛草甸区表层苔藓花粉组合均以莎草科(29.75%)、菊科(22.86%)和毛茛科(16.99%)等为主,蒿属和藜科花粉极少出现(<3%);现代植被调查也表现为以莎草科、菊科和毛茛科等植物为主,蒿属和藜科植物比例极低. Lu等人^[59]对青藏高原高寒草甸现代表土花粉组合分析也获得相近的研究结论:高寒草甸区表土花粉组合以莎草科为主(45%),蒿属和藜科花粉含量低.但该区域55个湖泊表层花粉组合对比显示:湖泊沉积物中蒿属和藜科平均含量分别达18%和5%,明显高于表层苔藓或表土样品^[60]. 苦海表层沉积物中蒿属和藜科含量分别为30%和14%^[61],冬给措纳表层沉积物中蒿属和藜科含量分别为32%和19%^[62],但区域现代植被调查显示,湖区周围现代植被以莎草科和禾本科为主(>60%),蒿属和藜科植物比例极低(<2%)^[39,63]. 对于上述差异产生的原因,可能与不同沉积环境花粉来源范围和传播方式

有关.表土或表层苔藓花粉沉积的来源范围相对小、搬运方式单一;而湖泊表层沉积花粉来源范围则较为广阔(沉积盆地半径大)、且搬运方式多元(风力搬运、河流搬运、地表径流搬运等).因此,与表土或表层苔藓花粉组合相比,湖泊表层沉积花粉组合受区域外花粉或隐域性植被的影响更大.结合研究区现代气候和地形特征,我们认为研究区现代湖泊表层沉积中出现的大量蒿属和藜科花粉除了由区域植被产生外,可能受周边草原植被影响,或者受中纬度西风环流影响,来源于高原西部的荒漠草原或高寒荒漠.此外,蒿属和藜科植物属耐盐碱植物在湖泊周围的河滩湿地也多有生长,其往往与隐域性生境条件密切相关.据此,我们认为青藏高原东北部灌丛草甸区湖泊表层沉积花粉组合出现的蒿属和藜科花粉并不真实代表区域植被组成;依据该区域湖泊沉积花粉组合推测区域植被演替及气候变化时应予以排除.

5 结论

(1) 研究区表层苔藓花粉组合均以莎草科(29.75%)和紫菀属(21.86%)占主导,其次为毛茛科(16.99%)、禾本科(5.1%)和蔷薇科(7.84%);100 m范围内植被为当地植被,对花粉组合的贡献率为46%,40 km范围内植被为区域植被,对花粉组合的贡献率为83%;花粉组合与区域植被相关性更好.

(2) 考虑花粉组合贡献率和区域植被组成影响的花粉-植被数量关系更能真实反映研究区花粉组合与区域植被组成的对应关系.

(3) 青藏高原灌丛草甸区表层苔藓花粉组合与区域湖泊表层花粉组合差异显著;湖泊表层沉积花粉组合受区域外花粉或隐域性植被的影响大,在重建区域植被演替及气候变化时应予以考虑.

参考文献

- 1 Sun H L, Zheng D. Formation, Evolution and Development of the Qinghai-Tibet Plateau (in Chinese). Guangzhou: Science and Technology Press, 1998. 179–213 [孙鸿烈, 郑度. 青藏高原形成演化与发展. 广州: 广东科技出版社, 1998. 179–213]
- 2 Xie G D, Lu C X, Xiao Y, et al. The economic evaluation of grassland ecosystem services in Qinghai-Tibet Plateau (in Chinese). J Mt Sci, 2003, 21: 50–55 [谢高地, 鲁春霞, 肖玉, 等. 青藏高原高寒草地生态系统服务价值评估. 山地学报, 2003, 21: 50–55]
- 3 Sun H L. Working report at the founding conference of China Natural Resources Research Association (in Chinese). J Nat Resour, 2013, 28: 1459–1463 [孙鸿烈. 在中国自然资源研究会成立大会上的工作报告. 自然资源学报, 2013, 28: 1459–1463]
- 4 Yu H Y, Xu J C. Effects of climate change on vegetations on Qinghai-Tibet Plateau: A review (in Chinese). Chin J Ecol, 2009, 28: 747–754 [于海英, 许建初. 气候变化对青藏高原植被影响研究综述. 生态学杂志, 2009, 28: 747–754]
- 5 Fan Q S, Sha Z J, Cao G C, et al. Assessment of ecology and environments on climate changing of Qinghai-Tibetan Plateau (in Chinese). J Salt Lake Res, 2005, 13: 12–18 [樊启顺, 沙占江, 曹广超, 等. 气候变化对青藏高原生态环境的影响评价. 盐湖研究, 2005, 13: 12–18]

- 6 Zhang G L, Zhang Y J, Dong J W, et al. Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011. *J Mt Sci*, 2013, 110: 4309–4314
- 7 Wang C, Shi Y, Zhou W. Dynamic uplift of the Himalaya. *Nature*, 1982, 298: 553–556
- 8 Van Campo E, Gasse F. Pollen- and Diatom-inferred climatic and hydrological changes in Sumxi Co Basin (Western Tibet) since 13000 yr BP. *Quat Res*, 1993, 39: 300–313
- 9 Tang L Y, Shen C M. Progresses in the study of vegetation and climate changes since Pliocene in the Qinghai-Xizang Plateau (in Chinese). *Adv Earth Sci*, 1996, 11: 198–203 [唐领余, 沈才明. 青藏高原上新世以来植被与气候研究进展. *地球科学进展*, 1996, 11: 198–203]
- 10 Liu X Q, Shen J, Wang S M, et al. A 16000-year pollen record of Qinghai Lake and its paleo-climate and paleoenvironment. *Chin Sci Bull*, 2002, 47: 1931–1936
- 11 Herzschuh U. A general cooling trend on the central Tibetan Plateau throughout the Holocene recorded by the Lake Zige tang pollen spectra. *Quat Int*, 2006, 154: 113–121
- 12 Zhu L, Lü X, Wang J, et al. Climate change on the Tibetan Plateau in response to shifting atmospheric circulation since the LGM. *Sci Rep*, 2015, 5: 13318
- 13 Tang L Y, Li C H. Temporal-spatial distribution of the Holocene vegetation in the Tibetan Plateau (in Chinese). *J Glaciol Geocry*, 2001, 23: 367–374 [唐领余, 李春海. 青藏高原全新世植被的时空分布. *冰川冻土*, 2001, 23: 367–374]
- 14 Hou G L, Yang P, Cao G C, et al. Vegetation evolution and human expansion on the Qinghai-Tibet Plateau since the Last Deglaciation. *Quat Int*, 2017, 430: 82–93
- 15 Tian F, Cao X Y, Dallmeyer A, et al. Biome changes and their inferred climatic drivers in northern and eastern continental Asia at selected times since 40 cal ka BP. *Veg Hist Archaeobot*, 2017, 27: 1–15
- 16 Andersen S T. Differential pollen productivity of trees and its significance for the interpretation of a pollen diagram from a forested region. *Symp B Ecol Soc*, 1973, 14: 109–115
- 17 Parsons R W, Prentice I C. Statistical approaches to R-values and the pollen—Vegetation relationship. *Rev Palaeobot Palynol*, 1981, 32: 127–152
- 18 Prentice I C, Parsons R W. Maximum likelihood linear calibration of pollen spectra in terms of forest composition. *Biometrics*, 1983, 39: 1051–1057
- 19 Prentice I C. Pollen representation, source area, and basin size: Toward a unified theory of pollen analysis. *Quat Res (Orlando)*, 1985, 23: 76–86
- 20 Sugita S. Pollen representation of vegetation in Quaternary sediments: Theory and method in patchy vegetation. *J Ecol*, 1994, 82: 881–897
- 21 Xu Q H, Li Y C, Yang X L, et al. Quantitative relationship between pollen and vegetation in northern China (in Chinese). *Sci China Ser D Earth Sci*, 2007, 37: 192–205 [许清海, 李月丛, 阳小兰, 等. 中国北方几种主要花粉类型与植被定量关系. *中国科学D辑: 地球科学*, 2007, 37: 192–205]
- 22 Xu Q H, Li Y C, Zhao D H, et al. Surface pollen assemblages from typical shrub communities in North China (in Chinese). *J Palaeogeogr*, 2006, 8: 157–164 [许清海, 李月丛, 赵登海, 等. 中国北方典型灌丛群落表土花粉组合特征. *古地理学报*, 2006, 8: 157–164]
- 23 Li Y C, Xu Q H, Xiao J L, et al. Pollen indication to source plants in the eastern desert of China (in Chinese). *Chin Sci Bull*, 2005, 50: 1356–1364 [李月丛, 许清海, 肖举乐, 等. 中国荒漠区东部花粉对植被的指示性研究. *科学通报*, 2005, 50: 1356–1364]
- 24 Lü H Y, Wang S Y, Shen C M, et al. Spatial pattern of modern *Abies* and *Picea* pollen in the Qinghai-Xiang Plateau (in Chinese). *Quat Sci*, 2004, 24: 39–49 [吕厚远, 王淑云, 沈才明, 等. 青藏高原现代表土中冷杉和云杉花粉的空间分布. *第四纪研究*, 2004, 24: 39–49]
- 25 Yan S, Kong Z C, Yang Z J, et al. Seeking relationship between vegetation and *Picea* pollen in surface soils of Xinjiang, northwestern China (in Chinese). *Acta Ecol Sin*, 2004, 24: 2017–2023 [阎顺, 孔昭宸, 杨振京, 等. 新疆表土中云杉花粉与植被的关系. *生态学报*, 2004, 24: 2017–2023]
- 26 Chen H, Lü X M, Li S C. A study on topsoil pollens in the east of Qaidam Basin (in Chinese). *Geogr Res*, 2004, 23: 201–210 [陈辉, 吕新苗, 李双成. 柴达木盆地东部表土花粉分析. *地理研究*, 2004, 23: 201–210]
- 27 Yu G, Sun X J, Qin B Q, et al. Vegetation distribution of Middle-Holocene for China based on pollen data (in Chinese). *Sci China Ser D: Earth Sci*, 1998, 199: 73–78 [于革, 孙湘君, 秦伯强, 等. 花粉植被化模拟的中国中全新世植被分布. *中国科学D辑: 地球科学*, 1998, 199: 73–78]
- 28 Shen C, Liu K, Tang L, et al. Quantitative relationships between modern pollen rain and climate in the Tibetan Plateau. *Rev Palaeobot Palynol*, 2006, 140: 61–77
- 29 Herzschuh U, Birks H J B, Mischke S, et al. A modern pollen-climate calibration set based on lake sediments from the Tibetan Plateau and its application to a Late Quaternary pollen record from the Qilian Mountains. *J Biogeogr*, 2010, 37: 752–766
- 30 Lu H, Wu N, Yang X, et al. Spatial pattern of *Abies* and *Picea* surface pollen distribution along the elevation gradient in the Qinghai-Tibetan Plateau and Xinjiang, China. *Boreas*, 2008, 37: 254–262
- 31 Zhang S, Xu Q, Nielsen A B, et al. Pollen assemblages and their environmental implications in the Qaidam Basin, NW China. *Boreas*, 2012, 41: 602–613
- 32 Ma Q, Zhu L, Lu X, et al. Modern pollen assemblages from surface lake sediments and their environmental implications on the southwestern

- Tibetan Plateau. *Boreas*, 2017, 46: 242–253
- 33 Yu G, Tang L, Yang X, et al. Modern pollen samples from alpine vegetation on the Tibetan Plateau. *Glob Ecol Biogeogr*, 2001, 10: 503–519
- 34 Lu X, Chen H, Xu Q. Surface pollen and its relationship to vegetation on the southern slope of the eastern Qilian Mountains. *J Geogr Sci*, 2006, 16: 215–222
- 35 Wei H, Ma H, Zheng Z, et al. Modern pollen assemblages of surface samples and their relationships to vegetation and climate in the northeastern Qinghai-Tibetan Plateau, China. *Rev Palaeobot Palynol*, 2011, 163: 237–246
- 36 Xu Q H, Zhang S R. Advance in pollen source area (in Chinese). *Adv Earth Sci*, 2013, 28: 968–975 [许清海, 张生瑞. 花粉源范围研究进展. 地球科学进展, 2013, 28: 968–975]
- 37 Xu Q, Zhang S, Gaillard M, et al. Studies of modern pollen assemblages for pollen dispersal-deposition-preservation process understanding and for pollen-based reconstructions of past vegetation, climate, and human impact: A review based on case studies in China. *Quat Sci Rev*, 2016, 149: 151–166
- 38 Zhang X S. The Plateau zonality of vegetation in Xizang (in Chinese). *Acta Bot Sin*, 1978, 2: 46–55 [张新时. 西藏植被的高原地带性. 植物学报, 1978, 2: 46–55]
- 39 Wu Z Y, Hou X Y, Zhu Y C, et al. Vegetation of China (in Chinese). Beijing: Science Press, 1980. 1022–1037 [吴征镒, 侯学煜, 朱彦丞, 等. 中国植被. 北京: 科学出版社, 1980. 1022–1037]
- 40 Jiang Z W. Vegetation characteristics, protection and utilization of Henan County, Huangnan (in Chinese). *Qinghai Environ*, 2013, 23: 143–148 [蒋中文. 黄南州河南县植被特点与保护利用意见. 青海环境, 2013, 23: 143–148]
- 41 Li F, Gaillard M J, Sugita S, et al. Relative pollen productivity estimates for major plant taxa of cultural landscapes in central eastern China. *Veget Hist Archaeobot*, 2017, 26: 587–605
- 42 Sun Y H, Zhang S R, Xu Q H, et al. Quantitative indicative significance of pollen assemblages on vegetation coverage in deciduous Quercus forest in the central Loess Plateau, China. *Sci China-Earth Sci*, 2019, 62: 992–1001 [孙沅浩, 张生瑞, 许清海, 等. 黄土高原中部落叶栎林花粉组合对植被盖度的定量指示意义. 中国科学: 地球科学, 2019, 49: 1004–1013]
- 43 Bunting M J, Farrell M, Broström A, et al. Palynological perspectives on vegetation survey: A critical step for model-based reconstruction of Quaternary land cover. *Quat Sci Rev*, 2013, 82: 41–55
- 44 Fægri K, Iversen J. A textbook of pollen analysis. *J Biogeogr*, 1989, IV: 328
- 45 Wang F X. Pollen Flora of China (in Chinese). 2nd ed. Beijing: Science Press, 1995. 11–438 [王伏雄. 中国植物花粉形态. 北京: 科学出版社, 1995. 11–438]
- 46 Wang T, Zhang S R, Xu Q H, et al. Pollen morphology of summer-flowering species of Alpine Meadows in northeastern Tibetan Plateau (in Chinese). *Acta Petrol Sin*, 2018, 57: 524–542 [王涛, 张生瑞, 许清海, 等. 青藏高原东北部高寒灌丛草甸夏季开花植物形态研究. 古生物学报, 2018, 57: 524–542]
- 47 Grimm E C. TILIA 1.7.16 Software. 2011
- 48 Middleton R. Vegetation Survey Manager v 2.0. 2011
- 49 Sugita S. A model of pollen source area for an Entire Lake Surface. *Quat Res (Orlando)*, 1993, 39: 239–244
- 50 Gregory P H. Distribution of airborne pollen and spores and their long distance transport. *Pure Appl Geophys*, 1978, 116: 309–315
- 51 Wei H C, Ma H Z, Zheng Z, et al. Characteristics of pollen assemblages of surface samples from the north-eastern Tibetan Plateau and their implications for vegetation and climate. *Marine Geol Quat Geol*, 2010, 30: 187–192
- 52 Wang F Y, Song C Q, Sun X J. Study on surface pollen in middle inner Mongolia, China. *Acta Bot Sin*, 1996, 38: 902–909
- 53 Cour P, Zheng Z, Duzer D, et al. Vegetational and climatic significance of modern pollen rain in northwestern Tibet. *Rev Palaeobot Palynol*, 1999, 104: 183–204
- 54 He F, Li Y Y, Wu J, et al. A comparison of relative pollen productivity from forest steppe, typical steppe and desert steppe in Inner Mongolia (in Chinese). *Chin Sci Bull*, 2016, 61: 3388–3400 [何飞, 李宜垠, 伍婧, 等. 内蒙古森林草原-典型草原-荒漠草原的相对花粉产量对比. 科学通报, 2016, 61: 3388–3400]
- 55 Zhang P P, Xu Q H, Gaillard M J, et al. Research of main plant species's relative pollen productivities and relevant source area of temperate coniferous and broad-leaved mixed forest in northern China (in Chinese). *Quat Sci*, 2017, 37: 1429–1443 [张攀攀, 许清海, Gaillard M J, 等. 中国北方温带针阔叶混交林主要植物相对花粉产量和相关花粉源范围研究. 第四纪研究, 2017, 37: 1429–1443]
- 56 Wei H C, Zheng Z, Ma H Z, et al. Pollen distribution on patterns of surface soil sample in Qinghai of China and their relationship with vegetation (in Chinese). *Arid Land Geogr*, 2009, 32: 932–940 [魏海成, 郑卓, 马海州, 等. 青海表土花粉分布规律及其与植被的关系. 干旱区地理, 2009, 32: 932–940]
- 57 Zhao Y, Herzschuh U. Modern pollen representation of source vegetation in the Qaidam Basin and surrounding mountains, north-eastern Tibetan Plateau. *Veget Hist Archaeobot*, 2009, 18: 245–260
- 58 Li Q, Lu H Y, Shen C M, et al. Vegetation successions in response to Holocene climate changes in the central Tibetan Plateau. *J Arid Environ*,

- 2016: 136–144
- 59 Lu H Y, Wu N Q, Liu K B, et al. Modern pollen distributions in Qinghai-Tibetan Plateau and the development of transfer functions for reconstructing Holocene environmental changes. *Quat Sci Rev*, 2011, 30: 293–293
- 60 Herzschuh U, Birks H J B. Evaluating the indicator value of Tibetan pollen taxa for modern vegetation and climate. *Rev Palaeobot Palynol*, 2010, 160: 197–208
- 61 Wischniewski J, Mischke S, Wang Y, et al. Reconstructing climate variability on the northeastern Tibetan Plateau since the Last Lateglacial – A multi-proxy, dual-site approach comparing terrestrial and aquatic signals. *Quat Sci Rev*, 2011, 30: 82–97
- 62 Wang Y, Herzschuh U. Reassessment of Holocene vegetation change on the upper Tibetan Plateau using the pollen-based REVEALS model. *Rev Palaeobot Palynol*, 2011, 168: 31–40
- 63 Kürschner H, Herzschuh U, Wagner D. Phytosociological studies in the north-eastern Tibetan Plateau (NW China)—A first contribution to the subalpine scrub and alpine meadow vegetation. *Bot J*, 2005, 126: 273–315

Summary for “青藏高原高寒灌丛草甸花粉组合的植被指示性”

Significance of pollen assemblages for the vegetation composition of alpine shrub meadow in the Qinghai-Tibetan Plateau, China

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The Qinghai-Tibetan Plateau is a fragile, globally significant ecosystem which responds sensitively to global climate change and regional human activity. Modern observations show that the ecological environment of the Qinghai-Tibetan Plateau has changed substantially, with obvious regional differences in vegetation composition, since the 1980s. Studying the history of vegetation succession and changes in the spatial distribution of vegetation on the Qinghai-Tibetan Plateau can provide a scientific basis for accurate assessment and prediction of future changes. For this purpose, we selected Zeku Basin, in the northeastern Qinghai-Tibetan Plateau. The study area is open and flat and it belongs to the alpine and semi-humid climate zone with distinct seasonality. The annual average temperature ranges from $-3-3^{\circ}\text{C}$, and the annual precipitation ranges from 400–700 mm and is concentrated during June–September. The regional vegetation in Zeku Basin includes alpine meadow and alpine shrub, which is mainly composed of herbs and shrubs tolerant of cold and humid conditions. The alpine meadow is dominated by *Kobresia* and *Carex*, accompanied by Compositae, Ranunculaceae, Poaceae and *Potentilla*, which are mainly distributed in basin areas and on the sunlit slopes of the mountains. The alpine shrubs are dominated by *Potentilla fruticosa*, with occasional *Hippophae* and *Spiraea alpina*, mostly distributed on the shaded slopes of the mountains. The extent of the study area was determined according to the degree of vegetation regionalization with reference to Google satellite imagery of Qinghai Province. 31 representative sites were selected within the study area, using the random layout method. At each site surface moss samples were collected and a vegetation inventory conducted. We analyzed the pollen composition of the surface samples and determined the characteristics of the pollen assemblages and the pollen source area in alpine shrub meadow. The principal results are as follows: (1) The pollen assemblages are dominated by Cyperaceae (29.75%), *Aster* (21.86%), Ranunculaceae (16.99%), Rosaceae (7.84%) and Poaceae (5.1%), which mainly originate from the vegetation within 40 km of the sites (the proportion of total pollen loading reached was 83%). There is the minor representation of the pollen of arboreal plants, such as *Betula*, *Pinus* and *Picea*, which was wind-transported over long distances. The vegetation composition varied substantially between different sites within distances of 0–100 m of each site, resulting in a poor relationship with the pollen assemblages. However, the pollen assemblages and the vegetation composition were more similar over the distance of 0–3 km from each site, suggesting that the regionally-homogenized vegetation has a better relationship with the pollen assemblages. (2) We suggest that the surface pollen assemblages from lakes in the Qinghai-Tibetan Plateau may be greatly affected by extra-regional pollen or intrazonal vegetation in the shrub meadow. High percentages of *Artemisia* and Chenopodiaceae in pollen assemblages do not reflect the coverage of these taxa in the corresponding regional vegetation. Therefore, within shrub meadow environments of the Qinghai-Tibetan Plateau, these taxa should be excluded from lake-sediment-based pollen studies of regional vegetation succession and climate change.

Qinghai-Tibetan Plateau, alpine shrub meadow, pollen assemblage, pollen source, regional vegetation

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