



温带亚洲特有维管植物多样性研究现状与未来展望

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摘要 温带亚洲是全球生物多样性研究的热点区域, 共有超过63000种维管植物, 特有种比例高达67%。本文首先综述了温带亚洲特有维管植物多样性的分布特征与研究进展, 该区域四大植物地理单元特征显著: 环北方区研究基础薄弱, 特有种占26%; 东亚区受季风影响, 孑遗植物丰富, 特有种占57%; 伊朗-图兰区为旱生植物演化中心但研究滞后, 特有种占60%; 青藏高原区因隆升促进高海拔植物辐射演化, 特有种占58%。随后, 本文阐述了当前温带亚洲特有植物研究面临的机遇与挑战, 并对未来的研究重点进行了展望。本文对理解北半球温带植物演化与保护具有范式价值, 将助力生物多样性保护、推动未来研究, 并对全球可持续发展与生态安全做出贡献。

关键词 温带亚洲, 维管植物, 特有现象, 生物多样性信息学, 生物地理学

特有现象(endemism), 指生物分类群(科、属、种等)局限于特定地理区域或生境分布的自然现象^[1~3]。分布范围狭窄的特有植物通常比广布种面临更高的灭绝风险^[4~9]。由于其分布的独特性, 特有类群所在生境一旦破坏, 将导致不可替代的生物多样性丧失。因此, 一个区域的特有类群数量或比例, 成为生物多样性保护优先区选择最广泛应用的标准^[6,10~15]。在生物地理学领域, 特有现象及其地理载体——特有性地区(areas of endemism)和特有性中心(centers of endemism)^[3,16,17]的研究具有重要科学价值。作为评估生物独特性核心指标的“生物地理学专属性”(biogeographic specificity)^[18], 其科学内涵自20世纪初便备受关注, 对揭示生物多样性形成机制及制定保护策略至关重

要^[19,20]。通过全球生物多样性热点区域研究^[6,21]、物种分布模式分析^[22,23]以及特有现象量化评估^[24,25]等经典工作, 该指标在生物地理学研究体系中的基础地位得以确立。

亚洲复杂多样的生境和长期稳定的气候, 使其成为银杏(*Ginkgo biloba* L.)和水杉(*Metasequoia glyptostroboides* Hu & W. C. Cheng)等众多孑遗植物的避难所^[26~28], 以及许多古特有和新特有植物的“博物馆”和“摇篮”^[29~32]。全球公认的36个生物多样性热点区域中^[6,33~36], 近三分之一全部或部分位于亚洲大陆。亚洲也是水稻(*Oryza sativa* L.)、茶(*Camellia japonica* L.)、柑橘(*Citrus chinensis* L.)和胡萝卜(*Daucus carota* var. *sativa* Hoffm.)等多种重要作物的起源中心^[37,38]。据统

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计, 亚洲拥有至少119044种维管植物(隶属341科、5521属), 包括6个特有科、1448个特有属, 其中约80% (95796种)为亚洲特有, 堪称“世界植物多样性的天堂”^[39]。然而, 快速的经济增长、城市化、庞大的人口压力以及对自然资源的高度依赖, 导致自然生境丧失和资源过度利用, 成为该地区植物多样性面临的主要威胁^[39]。尽管植物多样性保护已取得进展, 但仍面临巨大挑战^[39-44]。

生物地理区划(biogeographical regionalization, bioregionalization)作为生物地理学的分支学科, 旨在基于特定标准(如特有性和物种分布模式)将全球划分为不同的生物地理单元。早期的划分主要依赖布丰(Buffon)、斯克莱特(Sclater)、华莱士(Wallace)和恩格勒(Engler)等学者的专业知识和直觉^[45], 而现代方法则运用日益复杂的算法。尽管方法和研究对象各异, 其结果往往趋向于共同的全球方案。这些方案可以通过过去和现在的气候、板块构造及生命演化历程来解释。区划研究的重要性日益凸显, 保护具有独特生物群落的区域已成为生物多样性保护的关键方面。因此, 区划研究的目标正转向更实际的应用, 例如通过结合历史、环境和生物地理学的混合方法分析生物地理单元, 以指导区域内脆弱和受威胁栖息地的保护^[46,47]。从这个角度看, 生物多样性热点区域的识别^[6]与生物地理区划具有相似性^[47,48]。简而言之, 特有性度量研究区域内的植物独特性, 而区划则界定这种独特性的空间位置和范围, 二者的结合为空间保护规划提供了科学基础。

温带亚洲(Temperate Asia)作为重要的生物地理单元, 其特有植物多样性研究对区域保护至关重要。本文通过综述涉及温带亚洲四个主要植物地理单元的代表性文献, 并结合亚洲植物多样性数字化计划(Mapping Asia Plants, MAP)倡议下近十多年对温带亚洲植物区系的数字化平台建设与研究成果梳理, 系统回顾该区域特有维管植物多样性的研究进展, 旨在为该区域植物多样性保护提供科学依据, 并推动未来深入地研究。

1 研究范围及其自然地理

温带亚洲的地理范围依据^[49]提出的《世界植物分布记录地理分区方案》(World Geographical Scheme for Recording Plant Distributions, WGSRPD)的界定。其

地理坐标大致为北纬12°~82°, 东经12°~110°, 西起土耳其, 东抵白令海峡, 北自北冰洋, 南达也门。涵盖中国、俄罗斯、日本及蒙古国等45个国家或地区, 总面积约34449538平方公里。该方案由生物多样性信息标准组织(Biodiversity Information Standards, TDWG)发布^[50], 整合了全球主要植物志和名录中的地理单元, 已被世界自然保护联盟(International Union for Conservation of Nature, IUCN)、美国种质资源信息网络(Germplasm Resources Information Network, GRIN)和世界植物在线(Plants of the World Online, POWO)等机构采纳为植物分布信息编制的标准, 并广泛应用于大尺度生物多样性研究^[51-54]。

亚洲作为全球面积最大、人口最多的大陆, 其复杂的地质构造史塑造了独特的地形与气候格局^[55]。东临太平洋、南接印度洋的地理位置, 孕育了三大标志性自然景观: 被誉为“地球第三极”的青藏高原^[56,57]、全球最强季风系统^[58-62]以及广阔的干旱区^[63-67]。这些特征源于约5000万年来(~50 Ma)构造与气候耦合演化^[68]。复杂的地形和气候组合形成了从热带雨林、常绿阔叶林到寒带苔原的独特生态系统梯度^[69]。青藏高原隆升形成了显著的“生态阶梯”, 干旱区的扩张促进了耐旱物种的分化^[63,65], 而季风驱动的水文循环则为亚洲植物多样性“热点区域”提供生境基础^[45]。

亚洲主要地貌受控于两大关键构造事件^[55]: (i) 印度-亚洲碰撞(55~50 Ma)^[70-73], 形成了喜马拉雅造山带, 导致青藏高原阶段性隆升^[57,74,75], 并重塑了区域地形格局^[55,76-78]。(ii) 阿拉伯-亚洲碰撞(35~30 Ma)^[79-81], 驱动了伊朗高原抬升和安纳托利亚地块西移^[82,83]。这两大碰撞体系通过东北向(扎格罗斯至蒙古国西部)的断层带产生协同效应, 共同控制了亚洲的远场变形^[55]。高原隆升深刻影响了区域气候: 青藏高原作为巨大的“热力泵”强化了季风环流^[58,60,68], 而伊朗高原则促进了西风带分异^[84-87]。

亚洲的气候演变受全球温度变化与区域地形抬升双重调控^[68]。晚始新世, 亚热带地区呈现强蒸发-中等降水模式; 渐新世至早中新世, 中纬度半干旱气候定型; 上新世晚期, 北半球冰川作用导致蒸发与降水锐减, 形成新生代最干旱期。长期干旱化趋势与全球变冷导致的蒸发减弱直接相关, 而季风区则呈现阶段性强化特征^[59,61,62,88-94]。自晚中新世以来, 亚洲季风演变可分为三个阶段: (i) 约9~8 Ma, 内陆干旱加剧, 印度

季风和东亚季风开始显现; (ii) 约3.6~2.6 Ma, 东亚夏季风和冬季风继续增强; (iii) 约~2.6 Ma以来, 印度季风和东亚夏季风的变异性增加, 东亚冬季季风继续增强^[58,95]. 构造运动通过地形效应调控季风格局. 特提斯洋关闭(~14 Ma)促成索马里急流形成^[96]. 青藏高原的隆升虽增强了南亚季风, 但也限制了雨带向北扩展, 其边界曾经历了两次显著北移^[97].

2 温带亚洲特有植物多样性空间分布现状

研究表明, 在温带亚洲的45个国家或地区中, 特有属数量最多的为中国(205属)、印度(49属)、阿塞拜疆(28属)、伊朗(26属)和希腊(6属), 其余地区特有属数量少于5或为零. 特有种最丰富为中国(除香港、澳门、台湾以外)(16915种)、土耳其(4313种)、俄罗斯(2700种)、伊朗(2597种)、日本(2544种)、希腊(1435种)和阿富汗(1200种), 其他地区特有种少于1000种或为零(表1).

根据世界维管植物名录和分布^[140,141]的初步统计, 温带亚洲至少拥有63632种维管植物, 涵盖300科4186属. 其中, 特有属的比例高达67%(42487种), 并包含4个特有科, 614个特有属. 按WGSRPD level2(9大地区)统计: 特有种比例最高的地区依次为西亚(50%)、中国(49%)、东亚(37%)和中亚(37%); 其余地区特有种比例均低于30%. 按WGSRPD level3(51个区域)统计: 特有种比例最高的地区包括中国中南部(34%)、土耳其(34%)、伊朗(33%)、日本(29%)、中国东南部(24%)和中国台湾(24%); 其余区域特有种比例均低于20%(详见表2).

3 温带亚洲特有植物分布区域差异

特有植物地理分布格局的形成是物种形成、灭绝和扩散等大尺度演化和生态过程共同作用的结果^[22,142], 同时受到区域地质历史、气候演变、生态与地理隔离以及植物内在生物学特征等多重互作因素的影响^[143~146]. 此类格局通常与特定的植被类型或自然景观紧密关联. 例如, 银杉(*Cathaya argyrophylla* Chun & Kuang)和金钱松(*Pseudolarix amabilis* (J. Nelson) Rehder)等子遗植物主要分布于东亚常绿阔叶林^[147]; 梭梭(*Haloxylon ammodendron* (C. A. Mey.) Bunge ex

Fenzl)和沙拐枣(*Calligonum mongolicum* Turcz.)则集中出现在中亚干旱区^[148]; 高加索冷杉(*Abies nordmanniana* (Steven) Spach)和高加索星首花(*Lomelosia caucasica* (M. Bieb.) Greuter & Burdet)仅见于高加索高地及其周边^[149]; 而红花绿绒蒿(*Meconopsis punicea* Maxim.)和岩生丛菴(*Solms-laubachia calcicola* J. P. Yue, Al-Shehbaz & H. Sun)则特化于青藏高原的高山环境^[150].

特有性一直是植物地理分区最核心的参考标准^[151~153]. 依据早期分区方案, 温带亚洲包含四个特征迥异的植物地理单元: 环北方区(Circumboreal)、东亚区(Eastern Asia)、伊朗-图兰区(Irano-Turanian)和青藏高原区(Qinghai-Xizang Plateau)^[32,151,153~156]. 然而, 关于这些单元的地理范围、边界划分及分区等级, 不同研究之间存在显著差异^[151,153], 并可能随研究的深入而持续调整^[32,157]. 为系统梳理分散于大量不同期刊、主题及标题下的研究成果, 本文将依据上述四个传统植物地理单元进行归纳总结. 同时, 这也契合了温带亚洲特有植物的研究多以这些经典植物地理单元为框架的现状.

依据世界维管植物名录及其分布数据库^[140,141]的粗略统计, 除环北方区外, 其余各植物地理单元级特有性比例均超过50%. 单位面积(每万平方公里, 约相当于100×100公里网格)特有种比例进一步揭示四个植物地理单元在特有性水平上的显著差异: 青藏高原最高(43.4种/万km²), 其次是东亚(33.64种/万km²)和伊朗-图兰区(10.92种/万km²), 环北方最低(2.29种/万km²)(表3). 对四个单元特有区系组成的比较分析显示: 温带亚洲维管植物中, 32%的种(21457种)仅分布于东亚; 20%仅分布于伊朗-图兰地区; 10%仅分布于青藏高原. 这突显了东亚、伊朗-图兰区和青藏高原区系组成的独特性, 同时也表明四个区域区系之间存在密切联系(图1). 鉴于温带亚洲地域辽阔, 且以往大量关于该区域特有植物的研究常基于不同空间尺度进行, 如行政区划^[158,159]、自然地理单元^[160,161]或生物多样性热点区域^[11,162], 为便于归纳总结相关研究进展, 下文将按上述四个植物地理单元概述近年特有植物研究进展.

环北方(Circumboreal): 是世界最大的植物区系单元^[151]. 其温带亚洲部分的地理范围约为北纬40°~82°, 东经28°~177°, 行政区划涵盖俄罗斯、中国和蒙古国等8个国家, 面积约1400万平方公里. 该区域拥有12217种维管植物(隶属162科和1445属), 包括约20个

表 1 温带亚洲45个国家或地区特有维管植物多样性^{a)}

Table 1 Diversity of endemic vascular plants in 45 countries or regions of Temperate Asia^{a)}

编号	温带亚洲涵盖区域	特有属数量	特有种数量	参考文献	说明
1	阿富汗		1200	[98]	
2	亚美尼亚		120	[99]	
3	阿塞拜疆	28	800	[100]	28个特有属和75个亚特有属
4	巴林		0	[101]	
5	不丹		144	[102]	
6	中国(除香港、澳门、台湾以外)	205	16915	[103~105]	严格特有
7	塞浦路斯		108	[106]	
8	埃及		70	[107]	70种特有种, 181种近特有种
9	格鲁吉亚		275	[108]	
10	希腊	6	1435	[109,110]	严格特有
11	中国香港		11	[111]	
12	印度	49		[112]	非严格特有
13	伊朗	26	2597	[11]	包括了近特有
14	伊拉克		174	[113]	严格特有
15	以色列		39	[114]	
16	日本		1836	[115]	
17	约旦		100	[116]	
18	哈萨克斯坦		532	[117]	严格特有
19	科威特	1	1	[118]	
20	吉尔吉斯斯坦		326	[117]	严格特有
21	老挝	2		[119]	
22	黎巴嫩		154	[120]	严格特有
23	中国澳门	0	0	[121]	
24	蒙古		102	[122]	严格特有
25	缅甸		1071	[123]	
26	北塞浦路斯		15	[124]	严格特有
27	尼泊尔		302	[125]	
28	朝鲜		77	[126]	
29	阿曼		77	[127]	严格特有
30	巴基斯坦		306	[128]	严格特有
31	巴勒斯坦		155	[129]	
32	卡塔尔		0	[130]	严格特有
33	俄罗斯		2700	[131]	
34	沙特阿拉伯		147	[132]	严格特有
35	锡亚琴冰川		0	[133]	
36	韩国		193	[126]	
37	叙利亚		243	[134]	
38	中国台湾	4	1041	[135]	严格特有
39	塔吉克斯坦		505	[117]	严格特有
40	土耳其		4313	[136]	
41	土库曼斯坦		175	[117]	严格特有
42	阿拉伯联合酋长国		0	[137]	
43	乌兹别克斯坦		301	[117]	严格特有
44	越南		约1000	[138]	
45	也门		429	[139]	

a) 表中未列出特有属/种数量的空格表明文献未明确报道; “严格特有”指分布范围仅在研究区内的植物, “近/亚特有”指分布范围稍超出研究区域的植物

表 2 温带亚洲9个地区和51个区域(依据WGSRPD)维管植物多样性和特有性

Table 2 Vascular plant diversity and endemism in 9 regions and 51 areas of Temperate Asia (according to WGSRPD)

大陆 (level1)	地区(level2)	科/属/种	特有 (科/属/种)	特有种比例 (%)	区域名称(level3)	科/属/种	特有 (科/属/种)	特有种比例 (%)
温带亚洲	阿拉伯半岛	141/1045/3238	0/5/525	16	海湾国家	80/381/726	0/0/0	0
					科威特	54/219/360	0/0/1	0
					阿曼	109/607/1311	0/1/82	6
					沙特阿拉伯	126/815/2048	0/0/85	4
					也门	135/788/2066	0/0/196	9
	高加索	141/1047/6387	0/11/1494	23	北高加索	131/883/4057	0/1/335	8
					外高加索	140/1015/5564	0/2/681	12
	中国	281/3016/32709	2/162/16174	49	中国中北部	187/1205/5555	0/3/393	7
					中国中南部	259/2372/20186	0/40/6880	34
					中国东南部	258/2070/11537	1/24/2764	24
					海南	223/1278/3607	0/2/443	12
					内蒙古	131/749/2773	0/1/99	4
					辽宁、吉林和黑龙江	140/742/2466	0/0/69	3
					青海	105/561/2200	0/0/163	7
					西藏	199/1282/7100	0/3/970	14
					新疆	109/744/3455	0/1/343	10
	东亚	238/1751/9343	1/44/3477	37	日本	204/1167/4959	1/20/1417	29
					火山列岛	57/129/182	0/0/8	4
					韩国	175/947/3185	0/6/231	7
					琉球群岛	187/794/1805	0/1/142	8
					小笠原群岛	95/237/346	0/1/76	22
					中国台湾	223/1335/4665	0/6/1129	24
	中亚	127/1144/9137	0/45/3397	37	哈萨克斯坦	116/927/5272	0/9/519	10
					塔吉克斯坦	107/830/4311	0/5/552	13
					土库曼斯坦	93/706/2654	0/0/172	6
					乌兹别克斯坦	110/796/3897	0/5/320	8
	蒙古	109/669/2980	0/0/126	4	蒙古国	109/669/2980	0/0/126	4
	俄罗斯远东	139/746/3620	0/3/458	13	阿穆尔	114/503/1431	0/0/16	1
					堪察加半岛	84/362/1130	0/0/36	3
					伯力	122/590/1858	0/0/40	2
					千岛群岛	117/450/1135	0/0/26	2
					马加丹	74/320/1229	0/0/74	6
					滨海边疆区	130/628/2095	0/1/94	4
					库页岛	112/465/1248	0/0/54	4
	西伯利亚	114/774/4662	0/6/692	15	阿尔泰	108/644/2593	0/1/86	3
					布里亚特共和国	101/523/1800	0/0/28	2
					赤塔	103/496/1525	0/0/11	1
					伊尔库茨克	97/524/1711	0/0/37	2
					克拉斯诺亚尔斯克	97/564/2155	0/0/111	5
					图瓦	92/509/1690	0/1/18	1
					西伯利亚西部	101/597/2352	0/1/162	7
					雅库特	88/477/1835	0/0/58	3
	西亚	172/1701/18879	0/80/9477	50	阿富汗	134/994/4505	0/13/865	19
					塞浦路斯	112/607/1620	0/0/114	7
					爱琴海东部群岛	116/639/2079	0/1/65	3
					伊朗	148/1214/8192	0/17/2687	33
					伊拉克	118/818/3093	0/0/156	5
					黎巴嫩-叙利亚	132/953/3860	0/3/304	8
					巴勒斯坦	126/850/2773	0/0/120	4
					西奈半岛	94/524/1239	0/0/23	2
					土耳其	149/1178/9857	0/12/3388	34

表 3 温带亚洲四个植物地理单元维管植物多样性和特有性

Table 3 Diversity and endemism of vascular plants in the four phytogeographical units of Temperate Asia

名称	面积(万km ²)	科/属/种	特有科/属/种	特有种比例(%)	特有种密度(种/万km ²)
环北方	1400	162/1445/12217	0/20/3205	26	2.29
东亚	559	279/2955/32902	3/206/18806	57	33.64
伊朗-图兰	1600	196/2297/29171	0/141/17478	60	10.92
青藏高原	308	259/2734/23010	0/34/13366	58	43.4

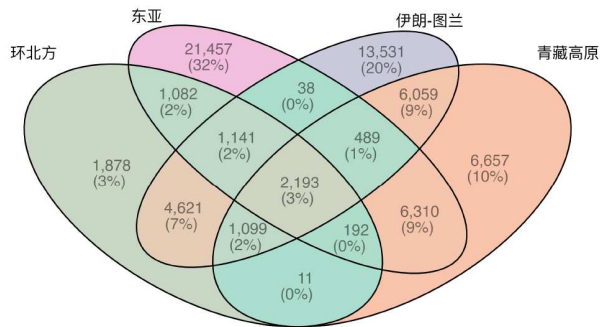


图 1 温带亚洲四个植物地理单元内代表性植物种类的比较

Figure 1 A comparison of representative plant species in the four phytogeographical units of Temperate Asia

特有属, 特有种比例达26%(3205种)。

在MAP倡议推动下, 近年来针对该区域的俄罗斯亚洲部分和蒙古国及其邻近区域开展了大量基础研究^[122,163~189], 导致相关地区的特有植物名录和分布信息持续更新。然而, 基础信息的及时整合与更新仍是当前面临的主要挑战。这尤其需要克服俄文文献获取困难以及不同分类观点差异导致的数据整合障碍^[190~192]。总体而言, 该区域的特有植物研究仍存在显著不足: 地理范围广阔导致野外调查难度大, 研究较为零散, 代表性特有类群的谱系关系与生物地理学历史缺乏深入解析, 空间分布格局的分析与评估不足。因此, 目前对该区域特有植物的组成及其与其他区域的相互关系仍缺乏清晰认识。

东亚(Eastern Asia): 地理范围大致位于北纬13°~54°, 东经98°~157°之间^[153]。在行政区划上, 该区域涵盖中国、日本、朝鲜、韩国、蒙古国和俄罗斯等9个国家, 面积约559万平方公里。区域内维管植物资源丰富, 共有32902种, 隶属于279科、2955属, 其中特有种比例高达57%(18806种), 并包含3个特有科和206个特有属。东亚植物区系以其显著的第三纪孑遗成分^[26,27]和东亚-北美间断分布模式^[193~198]而闻名于世。

作为全球生物多样性热点区域, 东亚特有植物的研究已在多个领域取得重要进展。这得益于扎实的植物区系编研基础^[29,158,199~201]和现代技术的发展, 相关研究已形成多维度的研究体系。生物地理格局: 研究表明中国特有属分布呈现显著的区域分异^[159], 东部以古特有成分为主, 而西部新特有种比例更高^[202]。中国台湾特有植物区系表现出典型的岛屿生物地理特征^[135,203]。日本特有植物的分布则深受地形异质性和历史避难所影响^[115,204~206]。跨区域比较揭示东亚与北美植物区系存在深层演化联系^[207~210], 并与冈瓦纳成分存在关联^[211]。演化机制: 古植物学证据^[28,212]与分子谱系地理学研究^[213,214]共同表明, 印度-欧亚板块碰撞和季风系统的形成是驱动东亚植物演化的关键因子。亚热带常绿阔叶林的主体演化完成于中新世^[147,215~219]。对孑遗植物时空动态的研究^[220,221]显示, 气候变化导致了避难所的迁移。值得注意的是, 基于26978种植物的分析^[30]发现, 中国东西部植物区系存在显著的功能分化: 东部既是木本植物的“博物馆”(保存古老类群)又是“摇篮”(新生类群的演化中心), 而西部则是草本植物的演化中心。方法论整合: 研究范式已从传统分类描述转向多学科融合。空间系统发育分析揭示中国东部保存了更多古老谱系^[30,211]。基于大数据的保护评估^[104,222~226]为东亚特有类群建立了优先保护框架。针对东亚作为植物起源中心的观点, 美国植物学家索恩(Robert Folger Thorne)提出的“活博物馆”假说(living museum)^[227]已获得多维度研究的支持^[28,151,153,212,228,229]。最新研究进一步确认该区系具有多重生物地理起源, 季风演变与造山运动的协同作用塑造了其现代分布格局^[211]。在关于东亚是“博物馆”还是“摇篮”的理论争议中, 区内东西部显著的时空异质性特征为调和理论分歧提供了新视角。当前东亚特有植物研究主要呈现三大趋势: (i) 古生物学证据与分子钟数据的整合日益紧密; (ii) 宏观生态格局与微观遗传分化研究的交叉融合; (iii) 气候变化情景模拟成

为保护生物学研究的新工具. 未来研究需要大力加强跨大陆比较研究并提高古环境重建精度, 以深入解析北温带植物区系的形成机制.

伊朗-图兰(Irano-Turanian): 是欧亚大陆最大的植物区系单元之一, 地理范围横跨北纬29°~60°, 东经30°~150°, 面积约1600万平方公里(占欧亚大陆30%), 涵盖中国、蒙古国等25个国家或地区. 该区域包含喜马拉雅、喀喇昆仑等五大山脉, 并拥有伊朗-安拉托利亚、中亚山地和高加索三大全球生物多样性热点区^[32]. 区域内维管植物极其丰富, 记录有29171种(隶属196科, 2297属), 其中特有种比例高达60%(17478种), 并包含141个特有属. 这些特有植物主要集中分布在三个特征鲜明的热点区域: (i) 伊朗-安拉托利亚, 受山脉分割影响, 形成多个特有中心, 特有植物约2500种^[11,162,230~232]; (ii) 中亚山地(帕米尔-天山), 以半荒漠与草原生境为主, 特有植物约1500种^[233]; (iii) 高加索南部, 保存有希尔卡尼亚亚遗森林(the relic Hyrcanian forest), 特有植物达2791种^[234,235]. 伊朗-图兰地区是多个高多样性属的关键演化中心, 如黄芪属(*Astragalus* L.)、刺头菊属(*Cousinia* Cass.)、矢车菊属(*Centaurea* L.)、荆芥属(*Nepeta* L.)、鼠尾草属(*Salvia* L.)和葱属(*Allium* L.)等^[236~242]. 同时, 它也是地中海等邻近地区旱生植物区系的重要来源地^[238,243,244]. 古生态研究表明, 中亚草原-荒漠生态系统可追溯至始新世, 并经历两次重大转变形成现今格局^[245]. 自19世纪瑞士植物学家德堪多(Augustin Pyramus de Candolle)(1820年)提出“东方地区”(Oriental region)概念以来, 该区域长期吸引植物界的关注. 尽管已有部分类群的系统发育研究(如刺头菊属、矢车菊属), 但整体研究仍存在显著空白: (i) 跨区域关联研究匮乏, 缺乏与青藏高原、地中海等邻近区域的生物地理联系研究; (ii) 保护评估碎片化, 特有植物的保护评估分散, 缺乏基于整体生物地理格局的综合评估; (iii) 区划争议持续, 区域边界, 尤其是东部边界尚未明确. 总体而言, 研究区域面临双重挑战: 一方面基础资料(如植物志)尚不完善, 多停留在“初级”水平^[32,246]; 另一方面, 区域内部的高度异质性增加了整体评估的难度^[32,243]. 虽有研究尝试基于自然地理特征划分东西亚区^[32], 但东南部边界仍存争议, 早期成果^[157]尚未被充分整合. 作为旧世界旱生植物与草原-荒漠生态系统的重要演化中心, 伊朗-图兰地区对理解欧亚植物多样性形成至关重要. 未来研究亟需

在以下方面加强: (i) 跨区域系统发育比较分析; (ii) 整合古植物学与地质学证据; (iii) 推动数字化标本信息共享. 突破这些瓶颈将有助于完整构建欧亚植物演化图景, 并为全球干旱区生态保护提供坚实的科学支撑.

青藏高原(Qinghai-Xizang Plateau): 素有“世界屋脊”和“地球第三极”之称, 是地球系统科学研究的天然实验室^[56,247~250]. 其地理范围横跨北纬20°~40°, 东经60°~110°, 平均海拔超4000米, 面积约308万平方公里, 覆盖中国、印度、巴基斯坦等9个国家^[251~254]. 作为“亚洲水塔”, 青藏高原拥有独特的圈层相互作用系统, 孕育了23010种维管植物(隶属259科2734属), 其中特有种比例高达58%(13366种). 新生代以来, 高原隆升重塑了亚洲气候格局^[57,255,256], 其引发的季风系统形成不仅改变了区域降水模式, 也为生物多样性演化创造了关键条件^[87,97,257~263]. 化石证据表明, 该高原不仅是东亚植物区系的重要起源地, 也与北极-第三纪古植物区系存在密切联系^[87,264,265]. 纵向河谷为冰期物种提供了避难所, 而复杂地形则促进了生态隔离下的物种辐射, 形成了如马先蒿属(*Pedicularis* L.)和杜鹃花属(*Rhododendron* L.)等特有类群的聚集区^[266,267]. 历经半个多世纪的积累, 青藏高原生物多样性研究已从《泛喜马拉雅植物志》编撰发展至青藏高原第二次综合科学考察^[268~270], 物种记录也从9556种^[271]更新至14634种^[269]. 特有物种分布呈现东南-西北梯度递减的特征, 横断山区和东喜马拉雅峡谷是主要的热点区域, 这与高原阶段性隆升及伴随的气候演变密切相关^[266,272]. 研究表明, 隆升过程通过改变季风系统, 驱动了常绿阔叶植被的扩张及其多样性的增加^[87]. 现代研究整合分子系统学与宏观生态学方法, 揭示了生物地理演化的复合机制. 例如, 成员等级模型(Grade of Membership models)证实, 高原存在物种渐变与突变并存的分布格局^[262]. 当前研究亦高度关注气候变暖对高山生境的显著影响, 强调特有植物保护正面临严峻挑战^[273]. 该区域植物区系通过“走出西藏”等扩散模式^[249,265], 与北美、非洲等大陆形成了跨区域关联^[274~278], 展现出复杂的全球生物地理关联. 这些发现不仅印证了早期的东亚植物迁移理论^[228,229], 也凸显了青藏高原在全球生物地理格局中的枢纽地位. 未来研究仍需进一步整合地质、气候与生物等多源数据, 为该区域独特生物多样性的有效保护构建更加系统的

科学框架^[279,280].

4 讨论

在MAP倡议^[281]框架下, 研究者系统梳理了东北亚^[282]、北亚(俄罗斯亚洲部分)^[190,283]、俄罗斯高加索^[284]、中亚^[117,285]、西南亚^[286]、南亚^[287]等地区与国家的植物区系研究. 结果表明, 不同区域和国家在植物多样性编目与分布研究上存在显著差异, 部分地区的研究广度和深度严重不足. 与此同时, 全球植物研究正进入新阶段. 这得益于过去二十多年来生物多样性信息学的快速发展^[288~294], 全球植物保护战略的推动^[295~299], 以及四个开放使用的全球维管植物数据库的发布^[140,141,300,301]. 目前, 全球维管植物多样性较高的地区(物种数和特有种数), 已拥有相对清晰的清单, 取代了过去的经验性估计^[302], 且不同来源的大数据分析得出了相对一致的结论^[54].

这些发展为温带亚洲特有植物研究带来机遇与挑战. 一方面, 全球植物名录整合了当前分类与区系知识, 为全球、区域和国家层面上的系统比较分析提供了重要基础, 是评估植物学知识的关键参考. 例如, 与邱园世界维管植物名录(the World Checklist of Vascular Plants, WCVP)的比较研究^[303]表明, WCVP仅遗漏了约3%的墨西哥维管植物, 其名称与分布信息在国家层面(至少对墨西哥)的质量和全面性相对可靠. 另一方面, 生态学家和演化生物学日益依赖“大数据”方法解决大尺度问题^[304]. 然而, 尽管整合了两个世纪的生物多样性数据, 综合数据库仍面临数据短缺困境^[51,305~307]. 全球植物认知仍在深化(每年约2000个新维管植物种被描述^[308]), 即使国家层面的分布编目也耗时巨大, 导致全球植物特有性的详细比较评估仍显不足^[54,309]. 温带亚洲特有植物研究同样面临“林奈式”(分类学)、“华莱士式”(分布)和“达尔文式”(演化)的数据短缺^[51,305~307]. 基于全球名录的研究评估了国家水平的特有植物受威胁状况^[51]和丰富度分布^[54], 揭示出温带亚洲(除中国外)存在显著的知识空缺. 这些数据对确定植物特有范围、研究区域特有性水平和分布格局至关重要, 但许多问题仍悬而未决. 当然, 数据的覆盖度、不确定性和偏差在分类、地理、时间(系统发育)维度^[310]上与研究目标密切相关, “数据短缺”在生物多样性这类数据密集型研究中可能是普遍且长期存在的

现象.

我们按环北方、东亚、伊朗-图兰和青藏高原四个植物地理单元组织内容, 目的有二: 一是为相对简洁地归纳温带亚洲特有植物研究进展; 二是为未来整合宏观生态与演化方法研究温带亚洲特有植物、解决长期问题奠定基础. 例如伊朗-图兰地区的范围和边界问题^[32,151,157]. Djamali等人^[157]利用生物气候变量分析表明, 该区域与周边的关键差异在于大陆性、冬季温度和降水季节性; 其中大陆性是区分伊朗-图兰、地中海和撒哈拉-辛迪亚地区(Saharo-Sindian)的主要气候因子, 也是其内部区系差异的主因. 然而, 该研究仅关注环境变量空间变异, 未结合种属地理分布, 因此未被^[32]引用. 目前看, 伊朗-图兰的范围确定依赖于相关生态变量^[157], 但未来需要结合系统发育与分布数据进行比较验证^[311]. 在东亚界定范围^[151]基础上, 吴征镒先生提出应调整东北、西北以中国西南边界, 并根据特有性水平将东亚地区提升为东亚界^[153], 并绘制了世界植物区系50区划图. 系统比较该50区方案与塔赫他间(Armen Leonovich Takhtajan)的6界、8亚界、35地区、152省方案^[151], 或能为世界植物区系区划提供新见解.

传统植物区划单元的界定常因缺乏大量属种精确分布信息、量化标准与空间统计检验不足、未整合系统发育信息^[312], 而缺少“数据驱动”模式的验证, 因此常被视为现象描述阶段^[313,314]. 尽管存在“数据不足”“方法局限”“经验性”等问题, 这些经典研究提供了可利用现有植物“大数据”和多种方法检验的科学假设. 近年整合大规模系统发育与分布数据的全球动植物区划研究^[315~317]是有益尝试, 但也可能面临数据、方法乃至概念上的挑战^[318~321].

计算能力的提升推动了重要统计方法的发展(如聚类技术、网络方法和空间一致性分析), 用于确定生物区划图中单元间的边界^[322~325]. 这些方法虽各有助益, 能改变对现有区划的理解, 但也各有局限. 例如, 聚类中不同相似性指数对同一数据集可能产生不同结果^[322,323]. 没有单一方案能涵盖自然群落的所有复杂性. 然而, 现有方案多力图提供全面的区划图, 服务于特定目标(如保护特定生物群落中的物种或谱系组合). 随着对各生物类群分布认知的加深, 区划图的分类学覆盖范围将扩大, 有助于深化对跨大陆生物多样性模式的理解, 并整合空间、时间和系统发育尺度.

5 展望

特有现象研究与生物地理区划是确定保护优先区的关键依据. 作为重点区域的温带亚洲, 覆盖45个国家或地区, 面积约3445万平方公里, 包含环北方、东亚、伊朗-图兰和青藏高原四大植物地理单元, 各具独特的生态特征与演化历史. 该区域拥有维管植物6.3万种, 特有种比例高达67%, 包含4个特有科和614个特有属, 其中中国、土耳其、日本等国特有种最丰富. 四大植物地理单元特征鲜明. 环北方地区(1400万km²): 以俄罗斯及蒙古国为主体, 特有种比例26%. 研究较为零散, 面临数据整合挑战. 东亚地区(559万km²): 特有种比例高达57%, 以第三纪孑遗植物和东亚-北美间断分布为特色, 兼具“博物馆”(保存古老类群)与“摇篮”(产生新类群)功能. 整合古生物学与分子谱系地理学的研究揭示了季风驱动的演化机制. 伊朗-图兰地区(1600万km²): 特有种比例达60%, 涵盖中亚草原-荒漠及高加索山地, 是旱生植物演化中心. 但区划边界争议较大, 基础研究相对滞后. 青藏高原(308万km²): 特有种比例58%. 其隆升过程形成的纵向河谷成为物种避难所, 促进了杜鹃花属等高海拔类群的辐射演化, 并确立了其全球生物地理枢纽地位.

亚洲植物多样性数字计划近年来在推动大范围植物数据整合与共享方面取得了显著成就, 为区域生物多样性研究提供了重要的数据基础与技术支撑. 然而, 尽管该计划促进了多源数据的初步汇集, 针对温带亚洲特有植物的系统性研究仍面临诸多瓶颈. 特有植物作为生物多样性保护中的关键类群, 不仅对生境具有高度依赖性, 还在演化历史与生态系统功能中扮演着不可替代的角色. 在这一背景下, 识别当前研究的核心挑战并明确未来发展方向, 对深化该区域生物地理学研究及提升保护实践的有效性具有重要意义. 当前, 温带亚洲特有植物研究主要面临以下三方面挑战: (i) 生境破碎化持续加剧物种的灭绝风险. 由于特有植物多分布狭窄, 其对生境丧失的响应尤为敏感. 随着温带亚洲地区城市化、农业扩张及基础设施建设的不断推进, 连续生境被分割为孤立斑块, 限制了物种的迁移与基因流, 加剧了局部灭绝的风险. 这一过程在一些生物多样性热点区域(如中国西南山地、中亚山脉等)表现得尤为突出. 因此, 如何从生境层面切入, 量化破碎化对种群存续能力的影响, 已成为保护生物学研究的紧迫议题. (ii) 数据短缺与信息壁垒

严重制约研究的全面性与可比较性. 尽管植物标本与分布记录数量在不断增长, 但数据质量、覆盖范围及可获取性仍存在显著差异. 一方面, 俄文文献及历史标本数据因语言障碍难以被国际研究者充分使用, 形成“数据沉默区”. 另一方面, 植物分类学中存在方法论的分歧, 例如, “林奈式”的经典分类依赖于形态特征的细致描述, 而“华莱士式”研究则更关注物种分布与地理格局, 两者之间的鸿沟使得整合形态、遗传与空间数据变得复杂. 更重要的是, 中亚、北亚及西亚等地区在标本采集、分子数据和生态监测等方面仍存在大量空白, 导致区域间研究难以系统比较, 整体生物地理格局的解析仍处于零散状态. (iii) 区域研究水平不均衡, 中亚、北亚与西亚成为研究薄弱地带. 相比东亚地区, 上述区域因野外调查条件有限、国际合作不足及科研资源投入较少, 其特有植物的分类整理、分布制图和保护评估工作较为滞后. 许多地方特有种甚至尚未被有效记录和描述, 更谈不上进行种群动态分析或受威胁评估. 这一知识断层不仅限制了整个温带亚洲生物多样性格局的综合理解, 也影响了跨区域保护策略的制定. 为应对上述挑战, 未来的研究亟需在以下四个方向展开重点布局: (i) 整合古生物学证据与分子谱系地理学方法, 以揭示温带亚洲乃至北半球洲际间断分布格局的历史成因. 通过融合化石记录、系统发育分析以及物种分布模型, 研究者能够更准确地重建特有植物的起源、扩散与分化过程, 尤其对于理解东亚-北美、欧亚大陆内部等经典生物地理格局的形成机制具有突破性潜力. (ii) 优化生物地理区划方案, 验证重大科学假说. 利用空间系统发育、多样性梯度分析等新兴技术, 可以对传统区划框架(如“东亚界”的范畴与等级)进行定量检验与修正. 这类研究不仅有助于澄清演化生物地理学中的长期争议, 也能为保护优先区的划定提供理论依据. (iii) 构建多源数据融合的平台体系, 实现更为精准的变化情景模拟与风险预警. 特别是在高山生态系统, 特有植物常常集中于脆弱生境, 其对气候变化的响应可能极为敏感. 通过整合物种分布数据、环境变量、遥感影像及基因组信息, 能够开发出更可靠的预测模型, 为适应性保护策略提供支撑. (iv) 加强跨国界、跨学科的国际合作, 共同建立覆盖温带亚洲的生物多样性信息网络与保护联盟. 只有通过数据共享、标准统一和联合野外科考, 才能逐步填补区域研究空白, 打破语言与

行政边界带来的障碍。此外, 应积极引入人工智能和遥感监测等创新方法, 提升数据收集与分析的效率与覆盖范围。

温带亚洲特有植物研究不仅为理解北半球生物演化历史提供了关键线索, 也在全球生物多样性保护中

展现出重要的范式价值。要实现其科学与保护目标, 必须突破传统的分类学障碍与数据共享壁垒, 建立跨区域、多尺度的合作平台, 同时积极推进方法创新与学科融合。这不仅是一项科学任务, 更是对全球可持续发展与生态安全的重要贡献。

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Current status and future prospects of research on endemic vascular plant diversity in Temperate Asia

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Temperate Asia is a global hotspot for biodiversity research, harboring more than 63000 species of vascular plants, with an endemism rate reaching up to 67%. This paper first reviews the distributional patterns and research progress concerning the diversity of endemic vascular plants in Temperate Asia. The region can be divided into four major phytogeographical units, each characterized by distinct ecological and evolutionary features. The research foundation in the Circumboreal Region is relatively weak, with the endemic species accounting for 26%. The Eastern Asiatic region, strongly influenced by the monsoon climate, is rich in relict species and exhibits an endemism rate of 57%. The Irano-Turanian region serves as a center for the evolution of xerophytes, though research there remains limited, with an endemism rate of 60%. Finally, the Qinghai-Xizang Plateau region has undergone extensive uplift, promoted the rapid radiation of alpine plants and resulted in an endemism rate of 58%. We further discuss the current opportunities and challenges in studying endemic plants across Temperate Asia and future research priorities. This article provides a valuable framework for understanding the evolution and conservation of temperate flora in the Northern Hemisphere. It also contributes to biodiversity conservation, guides future research directions, and supports global sustainable development and ecological security.

Temperate Asia, vascular plants, endemism, biodiversity informatics, biogeography

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