

· 研究论文 ·

短穗竹居群遗传结构及气候适应性分析

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摘要 短穗竹(*Brachystachyum densiflorum*)是中国特有种。近年来, 由于气候变化和人类活动加剧, 短穗竹栖息地遭到破坏, 破碎化加剧, 居群数量呈减少趋势。该研究对短穗竹6个居群36个个体开展简化基因组测序(RAD-seq), 获得了16 583个单核苷酸多态性(SNPs)位点, 据此评估短穗竹居群遗传结构, 并整合景观遗传学和物种分布模型, 探讨短穗竹对气候变化的适应机制。结果表明, 短穗竹具有中等水平的遗传多样性($PIC=0.722\ 5$, $H_o=0.087$, $H_e=0.284\ 3$, $\pi=0.317\ 5$), 将不同居群划分为2组, 各居群间存在中度分化($F_{ST}=0.102$)和较高的基因流($Nm=2.442$)。基因型-环境关联分析表明, 短穗竹对气候的局部适应推动2个组的分化, 温差、低温和降水共同驱动遗传变异, 筛选出544个与温差、低温(Bio2、Bio6、Bio11和Bio7)和降水量(Bio19)显著相关的适应性位点。物种分布模型显示, 从末次盛冰期到当前, 短穗竹明显向北迁移, 且其分布面积增加了89.5%。预计在2021–2040年和2041–2060年2个时段适生区波动较小, 2061–2080年适生区范围缩小, 安徽境内高适生区部分衰退和破碎化。研究结果为短穗竹的保护利用提供了理论依据。

关键词 短穗竹, 简化基因组测序, 遗传多样性, 遗传结构, 物种分布模型

张如礼, 李德铎, 张玉霄 (2025). 短穗竹居群遗传结构及气候适应性分析. 植物学报 60, 407–424.

全球气候变化导致生态系统物种多样性和功能多样性下降, 如何应对气候变化直接关系到生态系统的稳定性及其服务功能(Yuan et al., 2023; Jing et al., 2024)。植物如何应对气候变化是其持久生存的基础, 可通过局部适应或迁移到新的合适地点, 亦或通过表型可塑性适应气候变化(Alsos et al., 2012; Keenan, 2015; Poupon et al., 2021; Yang et al., 2022c)。然而, 这些应对策略效果有限, 气候的快速变化打破了基因与环境之间原有的联系, 导致迁徙、局部适应或新突变速率等无法与持续的气候变化保持平衡(Jia et al., 2020; Sang et al., 2022)。遗传多样性决定了物种适应新环境的能力, 也是生物进化的基础, 高杂合性可以抵消有害突变的影响, 增强物种的适应性和抗逆性(Pauls et al., 2013; Exposito-Alonso et al., 2022)。然而, 剧烈的气候变化导致物种遗传多样性大幅降低, 同时降低物种的持久性和进化潜力, 以及改变居群的遗传结构(Guan et al., 2021; Be-

ridze et al., 2023; Liu et al., 2024)。景观遗传学(landscape genetics)为理解物种适应性进化和影响遗传变异的潜在环境因素提供了新见解(Alvarado et al., 2022; Feng and Du, 2022)。景观遗传学研究无需进行大量的胁迫实验, 仅通过遗传变异信息与环境信息或地理信息相结合就能揭示景观特征对遗传变异的影响(Aguirre-Liguori et al., 2021; Haupt and Schmid, 2022)。基因-环境关联(genotype-environment association, GEA)分析和异常位点检验(outlier tests)是了解遗传变异对整个景观适应模式的2种重要方法, 通过上述分析可以确定来自不同环境的物种遗传变异信息中参与环境适应的候选基因和基因组区域(Filipe et al., 2022; Haupt and Schmid, 2022)。利用景观遗传学方法揭示物种在全球环境变化条件下的适应机制, 已在动植物中广泛运用, 如三色黑鹇(*Agelaius tricolor*)、小黄鱼(*Larimichthys polyactis*)、星叶草(*Circaea agrestis*)、茵芋叶茄(*Solanum pimpinellifolium*)

收稿日期: 2024-06-19; 接受日期: 2024-11-15

基金项目: 国家自然科学基金(No.31100148)和云南省高层次人才培养计划青年拔尖人才专项(No.YNWR-QNBJ-2019-148)

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和筒瓣花(*Embothrium coccineum*) (Gibson and Moyle, 2020; Zhang et al., 2020; Barr et al., 2021; Sepúlveda-Espinoza et al., 2022; Wang et al., 2022b)。

竹类遗传多样性研究已取得诸多成果,但多数研究仅采用传统的分子标记,如扩增片段长度多态性(amplified fragment length polymorphism, AFLP)、相关序列扩增多态性(sequence-related amplified polymorphism, SRAP)、表达序列标签-微卫星标记(expressed sequence tags-simple sequence repeat, EST-SSR)、简单重复序列间扩增(inter-simple sequence repeat, ISSR)、简单重复序列(simple sequence repeat, SSR)、随机扩增多态性DNA (random amplified polymorphic DNA, RAPD)和序列标记微卫星(sequence-tagged microsatellite, STMS) (李潞滨等, 2008; Tian et al., 2012; Zhu et al., 2014; Bhandawat et al., 2019; Ely et al., 2019; Silva et al., 2020; Meena et al., 2023a)。随着测序技术的发展,利用高通量测序可在居群水平上对全基因组范围内的变异信息进行筛选并提供大量的变异信息,如单核苷酸多态性(single nucleotide polymorphism, SNP) (Shafer et al., 2015; Wu et al., 2023)。简化基因组测序(reduced-representation genome sequencing, RRGs)技术作为一种高效标记逐渐发展起来(Davey et al., 2011),其中限制性酶切位点测序(restriction site associated DNA sequencing, RAD-seq)作为简化基因组测序,可获得全基因组范围内的大量SNP位点,且所产生的SNP位点在覆盖率、数据质量、稳定性和准确率方面比传统分子标记高,适用于群体遗传学和景观基因组学研究(Morin et al., 2004; Baird et al., 2008; Ouborg et al., 2010; Lin et al., 2021)。RAD-seq技术在评估遗传多样性方面应用广泛,特别是应用于珍稀濒危植物,如荷叶铁线蕨(*Adiantum nelumboides*)、显脉木兰(*Magnolia fistulosa*)、海南风吹楠(*Horsfieldia hainanensis*)和云南蓝果树(*Nyssa yunnanensis*) (张珊珊等, 2019; 蔡超男等, 2021; 孙维悦等, 2022; Yang et al., 2022a)。目前, RAD-seq技术已应用于澜沧梨藤竹(*Melocalamus arrectus*)和云南省极小种群独龙江空竹(*Cephalostachyum manii*)等竹类的遗传多样性评估(赵虎刚等, 2023; 张如礼等, 2024)。

短穗竹(*Brachystachyum densiflorum*)为竹亚科(Bambusoideae)短穗竹属(*Brachystachyum*)植物,是我国特有种,其地下茎为细型,亦称真鞭,每节有3–5个分枝,箨耳发达,箨片开展易落,假花序,花枝极短缩,呈短穗状或头状,主要分布于华东地区(Li et al., 2006)。研究表明,短穗竹可能由苦竹属(*Pleioblastus*)和刚竹属(*Phyllostachys*)杂交形成,其分枝样式与苦竹属相似,箨耳、花序和假小穗与刚竹属类似(Zhang et al., 2012)。近年来,随着经济的快速发展,城市化进程加快,污染物排放量逐年增加(董芳淑等, 2023),短穗竹的栖息地遭到破坏,破碎化加剧,种群数量呈减少趋势。目前,短穗竹已被列入安徽省重点保护野生植物名录(<https://www.ah.gov.cn/public/1681/554202981.html>)。同时,气候变化也加剧了竹类栖息地退化和破碎化的风险,特有或稀有的竹类极易受到栖息地变化的影响(Isik, 2011; Phair et al., 2021; Boban et al., 2022)。遗传多样性是开展珍稀濒危种群保护时需要考虑的重要部分,而上述环境风险使植物种群发生基因漂移和近亲繁殖,从而导致遗传多样性水平降低(Bonin et al., 2007; Salvado et al., 2022)。因此,开展短穗竹遗传多样性研究,评估气候变化对其遗传变异的影响,对于制定短穗竹的保护措施具有重要意义。

本研究针对中国特有种短穗竹,利用RAD-seq技术获得了短穗竹6个居群的SNP数据集,进而评估短穗竹居群遗传结构和遗传多样性水平,同时基于景观遗传学方法,分析气候变化对短穗竹现有遗传结构分布格局的影响和驱动因素,利用物种分布模型(species distribution model, SDM)预测短穗竹当前潜在适生区以及未来气候变化下的分布区变化,以期短穗竹的保护提供理论依据。

1 材料与方法

1.1 植物材料采集

2012年6月在安徽、江苏和浙江采集到短穗竹(*Brachystachyum densiflorum* (Reudle) Keng) 6个居群的36个个体(表1),每个个体间隔1 km以上,以避免采集到来自同一个克隆的植株。每个居群采集3–10个个体,每个个体采集3–5片幼嫩无病虫害的叶片,置于分子采集袋中并迅速用硅胶干燥,用于后续DNA提取。

表1 短穗竹居群采集信息

Table 1 Sampling information of *Brachystachyum densiflorum* populations

Population	Locality	Sample individuals	Longitude	Latitude
AHYX	Yuexi, Anhui	7	116°14'49" E	30°55'27" N
AHHS	Huoshan, Anhui	4	116°26'38" E	31°24'01" N
AHGD	Guangde, Anhui	9	119°14'10" E	30°48'56" N
JSLY	Liyang, Jiangsu	3	119°28'30" E	31°14'39" N
JSYX	Yixing, Jiangsu	10	119°47'54" E	31°16'49" N
ZJXC	Changxing, Zhejiang	3	119°52'31" E	31°07'24" N

1.2 DNA提取、文库构建及测序

采用CTAB法(Doyle and Doyle, 1987)提取短穗竹全基因组DNA, 用1%琼脂糖凝胶电泳检测DNA提取质量, 确保符合后续建库要求。RAD建库采用单酶切法, 全基因组DNA用EcoRI (5'-GAATTC-3')限制性内切酶进行酶切, 在DNA片段的两端添加P1接头, 用超声波将其打断, 然后选择含有P1接头的片段添加P2接头, 并进行PCR扩增。将检测合格的PCR产物送至北京诺禾致源生物信息科技有限公司Illumina Novaseq 6000平台进行双端测序(PE=150 bp)。测序之后用Fastp v0.23.4 (<https://github.com/OpenGene/fastp>)软件过滤掉低质量的reads, 保留795.5 Mb reads, 平均GC含量为42.84%, Q30≥91.58%。使用Stacks v2.62 (<http://catchenlab.life.illinois.edu/stacks/>)软件中的process-radtag模块将Clean reads截短至140 bp。

1.3 SNP筛选和过滤

以毛竹(*Phyllostachys edulis*)基因组(Zhao et al., 2018)为参考基因组。首先, 使用BWA v0.7.17软件(<https://github.com/lh3/bwa>)的mem模块将reads比对到参考基因组, 平均对比率为98.89%, 用SAMtools v1.6软件(<https://github.com/samtools/samtools>)的view和sort模块转化格式并进行排序和去除重复。然后, 利用Stacks软件的gstacks模块合并比对成功的reads并构建位点, populations模块用于输出SNP。最后, 利用VCFtools v0.1.16软件(<https://vcftools.github.io/documentation.html>)过滤SNP, 仅保留平均深度≥5的SNP (-minDP=5), 剔除次数等位基因频率低于0.05的SNP (-maf=0.05)。

1.4 遗传多样性和居群遗传结构分析

利用Stacks软件populations模块计算遗传多样性指

标, 包括多态性信息含量(PIC)、观测杂合度(H_o)、期望杂合度(H_e)、核苷酸多样性(π)和近交系数(F_{is})。使用NeEstimator v2.0软件(<https://help.rc.ufl.edu/doc/NeEstimator>)评估6个居群的当前有效群体大小。基于最大似然法(maximum likelihood, ML)利用IQ-TREE v2.2.0.3软件(<http://www.iqtree.org/>)构建系统发育树, 靴带值(bootstrap)重复1 000次并进行ASC校正, 以减小长枝影响。建树最适模型为GTR+F+I+G, 该模型基于贝叶斯信息准则(Bayesian Information Criterion, BIC), 利用IQ-TREE软件自带的ModelFinder模块筛选得出。随后用R v4.3.1语言LEA包(<https://www.r-project.org/>)进行遗传结构分析, 假定分群数K值为2–15, 且每个K值重复运行10次, 交叉检验错误率(cross-validation error, CV error)最小时即为最优分群。使用adegenet包进行主成分分析(principal component analysis, PCA)和主成分判别分析(discriminant analysis of principal components, DAPC)。遗传分化指数(F_{ST})反映居群间的遗传差异, 使用hierfstat包评估居群间的遗传分化指数。利用BayesAss v3.0.4软件(<https://rannala.org>)评估当前短穗竹群体间的基因流动率。

1.5 遗传变异与气候关联分析

从WorldClim v.2.1数据库(Fick and Hijmans, 2017; <https://www.worldclim.org/data/worldclim21.html>)下载1970–2000年19个生物气候因子数据, 空间分辨率为30" (1 km × 1 km)。使用raster包根据每个短穗竹采样地点的经纬度提取气候数据(附表1), 然后用皮尔逊(Pearson)相关系数进行相关性检验(附表2), 保留相关系数小于0.75 ($r < |0.75|$)的气候因子。最终保留8个气候因子, 分别为平均气温日较差(Bio2)、最冷月份最低温度(Bio6)、气温年较差(Bio7)、最湿季度

平均温度(Bio8)、最冷季度平均温度(Bio11)、降水量季节性变化(Bio15)、最湿季度降水量(Bio17)和最冷季度降水量(Bio19)。用基因-环境关联分析确定遗传结构与地理或气候变量之间的关联性。使用vegan包进行冗余分析(redundancy analysis, RDA)。为了确定影响遗传变异的关键气候因子,需进行冗余分析和梯度森林(gradient forest, GF)分析,其中梯度森林分析用gradientForest包完成。为了识别与遗传局部适应和气候密切相关的SNP位点,使用3种方法筛选异常SNP (outlier SNP)。一是使用BayeScan v2.1软件(<https://github.com/mfoll/BayeScan>)进行筛选,该软件采用贝叶斯法搜索处于自然选择下的高分化SNP,将错误发现率(false discovery rate, FDR)低于0.01的SNP视为异常SNP,这些SNP可能与局部适应有关(Jia et al., 2020)。另2种方法均基于基因-环境关联分析进行筛选,分别用vegan包和lfmm包完成。首先进行冗余分析,从前3个约束轴中筛选出异常SNP;然后设置标准差为3作为分界(two-tailed p -value=0.002 7)(DeSaix et al., 2022);最后用lfmm包中潜在因素混合模型(latent factor mixed modeling, LFMM)筛选出异常SNP,潜在因子数量为遗传结构分析中交叉检验错误率(CV error)最小时的 K 值(Yang et al., 2022b),使用 q -value包在错误发现率(FDR)为0.01的条件下识别异常SNP (Jia et al., 2020)。

1.6 潜在地理分布预测

物种分布模型广泛用于预测当前和未来气候变化背景下物种的潜在分布(Yang et al., 2022b)。为明确过去和当前气候条件下短穗竹的潜在分布区以及预测未来全球气候变化下其空间分布趋势,我们根据短穗竹已知位置进行物种分布建模。通过野外调查和检索全球生物多样性信息组织(<https://www.gbif.org/>)、中国国家标本资源平台(<http://www.nsii.org.cn/2017/home.php>)、中国数字植物标本馆(<https://www.cvh.ac.cn/>)和相关文献,共获得175个短穗竹分布地点(附表3)。为消除采样偏差的影响,使用spThin包删除距离小于10 km的分布地点,最终保留103个分布地点。末次盛冰期(Last Glacial Maximum)、全新世中期(Mid Holocene)、当前和未来的19个生物气候因子均从WorldClim数据库中下载,空间分辨率为2.5' (2.5 km × 2.5 km)。未来时段(2021–2040年、2041–2060年以

及2061–2080年)选择BCC-CSM2-MR模型下2种共享社会经济路径(shared socioeconomic pathways, SSPs),分别为SSP 1–2.6和SSP 5–8.5 (He et al., 2022)。基于筛选的8个气候因子,使用ENMeval包筛选要素类型与正则化乘数,要素类型为LQ,正则化乘数为1 (附表4)。随后,使用MaxEnt v3.4.4软件(<https://biodiversityinformatics.amnh.org>)预测短穗竹在不同气候情景下的潜在分布格局,设置25%的分布点为测试集,75%的分布点为训练集,设置5 000作为最大迭代次数,重复训练10次。最后,将MaxEnt预测结果导入ArcGIS v10.8.1软件(<https://www.esri.com>)中,根据自然间断点分级法将分布区域分为非适生区、低适生区、中适生区和高适生区。

2 结果与分析

2.1 SNP位点统计和遗传多样性评估

研究显示,经VCFtools软件过滤后保留了16 583个高质量SNPs (附图1),其中9 196个SNPs发生了转换,转换率为55.5%,7 387个SNPs发生了颠换,颠换率为44.5%,转换与颠换的比值为1.24。基于16 583个SNPs评估6个短穗竹居群的遗传多样性(表2),表明短穗竹居群具有中等水平遗传多样性($PIC=0.722$ 5, $H_o=0.087$, $H_e=0.284$ 3, $\pi=0.317$ 5),各居群遗传多样性水平差异不大,安徽广德(AHGD)和江苏宜兴(JSYX)两居群的遗传多样性较高,而浙江长兴(ZJCX)居群的遗传多样性最低。各居群近交系数(Fis)均为正值,平均为0.566 5,居群存在杂合子缺失且以近交或自交为主。6个居群当前有效群体大小分析显示,江苏溧阳(JSLY)居群无法获得 Ne 值,可能其 Ne 值为无限大,也可能由于个体数量较少导致,其余5个居群的当前有效群体大小在3.8 (3.6, 4.0)– 9.4 (8.4, 10.4)之间。当前有效群体大小均值(5.6)极低,可能在过去经历了瓶颈效应,导致短穗竹分布区发生严重的居群收缩。

2.2 居群遗传结构

通过系统发育和遗传结构分析、主成分分析(PCA)和主成分判别分析(DAPC)明确了短穗竹现有居群遗传结构分布格局。系统发育树包括2个主要分支(图1A),

表2 6个居群遗传多样性指标

Table 2 Genetic diversity indices of six populations

Population	<i>PIC</i>	<i>Ho</i>	<i>He</i>	π	<i>Fis</i>	<i>Ne</i> (95% CI)
AHYX	0.8102	0.0880	0.3051	0.3295	0.6466	5.4 (5.2, 5.7)
AHHS	0.6412	0.0863	0.2712	0.3099	0.4899	9.4 (8.4, 10.4)
AHGD	0.8802	0.0885	0.3148	0.3339	0.7123	3.8 (3.6, 4.0)
JSLY	0.5502	0.0841	0.2492	0.2990	0.4098	Inf (inf, inf)
JSYX	0.9069	0.0884	0.3183	0.3358	0.7385	4.0 (3.9, 4.2)
ZJCX	0.5462	0.0865	0.2474	0.2969	0.4017	4.8 (4.5, 5.1)
Mean	0.7225	0.0870	0.2843	0.3175	0.5665	5.6 (5.1, 5.9)

AHYX、AHHS、AHGD、JSLY、JSYX和ZJCX同表1。*PIC*: 多态性信息含量; *Ho*: 观测杂合度; *He*: 期望杂合度; π : 核苷酸多样性; *Fis*: 近交系数; *Ne*: 当前有效群体大小; Inf: 无限大

AHYX, AHHS, AHGD, JSLY, JSYX, and ZJCX are the same as shown in Table 1. *PIC*: Polymorphism information content; *Ho*: Observed heterozygosity; *He*: Expected heterozygosity; π : Nucleotide diversity; *Fis*: Inbreeding coefficient; *Ne*: Contemporary effective population size; Inf: Infinity

安徽霍山(AHHS)和安徽岳西(AHYX)两居群地理位置相对较近, 最先分离, 表明两居群之间亲缘关系较近。安徽广德(AHGD)、江苏溧阳(JSLY)、江苏宜兴(JSYX)和浙江长兴(ZJCX) 4个居群聚为一支, 它们可能拥有共同的祖先, 但个体间存在交叉混合。

遗传结构分析表明, 遗传聚类值 $K=2$ 时交叉检验错误率(CV error)最低(图2), 说明遗传物质来源于2个祖先并表现出稳定的遗传结构(图1A)。随着 K 值(3–4)的增加, 有不同的遗传信息加入, 并在安徽广德(AHGD)、江苏溧阳(JSLY)、江苏宜兴(JSYX)和浙江长兴(ZJCX) 4个居群中表现最明显, 安徽霍山(AHHS)和安徽岳西(AHYX)两居群遗传结构较稳定(图1A)。主成分分析(PCA)显示, 前2个轴分别解释3.3%和3.2%的遗传变异, 安徽霍山(AHHS)和安徽岳西(AHYX) 2个居群与其余4个居群分别形成独立的聚类且二者之间存在明显的遗传分化(图1B)。利用上述3种分析方法所得结果一致, 主成分判别分析(DAPC)进一步验证了短穗竹当前遗传结构的稳定性, 并确定短穗竹2个组的划分(图1C)。

短穗竹居群存在中度遗传分化($F_{ST}=0.102$, $0.05 < F_{ST} < 0.15$), 遗传分化值(F_{ST})介于0.048–0.151之间(表3)。江苏溧阳(JSLY)和浙江长兴(ZJCX)两居群虽然地理位置相近, 但居群间的遗传分化值($F_{ST}=0.151$)是所有群体中最大的。分子方差分析(AMOVA)显示(附表5), 遗传变异主要发生在居群内($Va=79.71\%$), 居群间变异很小($Va=0.45\%$)。尽管各居群存在中度的遗传分化($F_{ST}=0.102$), 但是基因流水平很高($Nm=2.442$, $Nm > 1$), 说明居群间存在一定的遗传交换, 从而抵消

了基因漂变造成的强烈遗传分化(表3)。但是, 短穗竹各居群间近期(1–3代)基因流动率较低(附表5), 其范围在0.020 7–0.037 4之间, 平均值为0.029 4。

2.3 遗传变异与气候关联分析

为明确气候与地理是否影响短穗竹现有遗传结构分布格局, 对地理、气候以及两者混合的影响进行分析。独立的气候因素占总解释量的35.48%, 独立的地理因素占22.22%, 气候和地理混合因素占42.30%, 说明气候因素更能解释短穗竹的遗传变异(附表6)。分别对地理和气候(图3C)、地理(图3E)、气候(图3A)进行冗余分析对比, 显示8个气候因子将6个居群划分为2个类群(图3A), 与遗传结构分析结果一致(图1), 气候因素比地理因素更能解释遗传变异(附表6; 图3), 局部适应在推动2个类群的形成和分化过程中发挥重要作用。

基于冗余分析和梯度森林分析, 将8个气候因子与短穗竹的遗传信息联系起来, 进一步确定影响其居群间遗传变异的因子(图3A, B)。冗余分析表明, RDA1和RDA2轴分别解释14.00%和12.88%的遗传变异(图3A)。RDA1轴中Bio6和Bio2的载荷最高(图3A), RDA2轴主要受到Bio11和Bio7的影响(附表6), 表明遗传变异与温差和低温之间密切相关。利用ordistep函数逐步排除法筛选可解释遗传变异的独立因子(附表6), 表明Bio19也是显著的预测因子($P < 0.05$, $R_{adj}^2=0.004 4$), 这有助于解释遗传结构的差异。梯度森林分析表明, Bio2是最重要的预测因子, 其次是Bio6(图3B)。Bio2在8.2–9.0°C时发生变化,

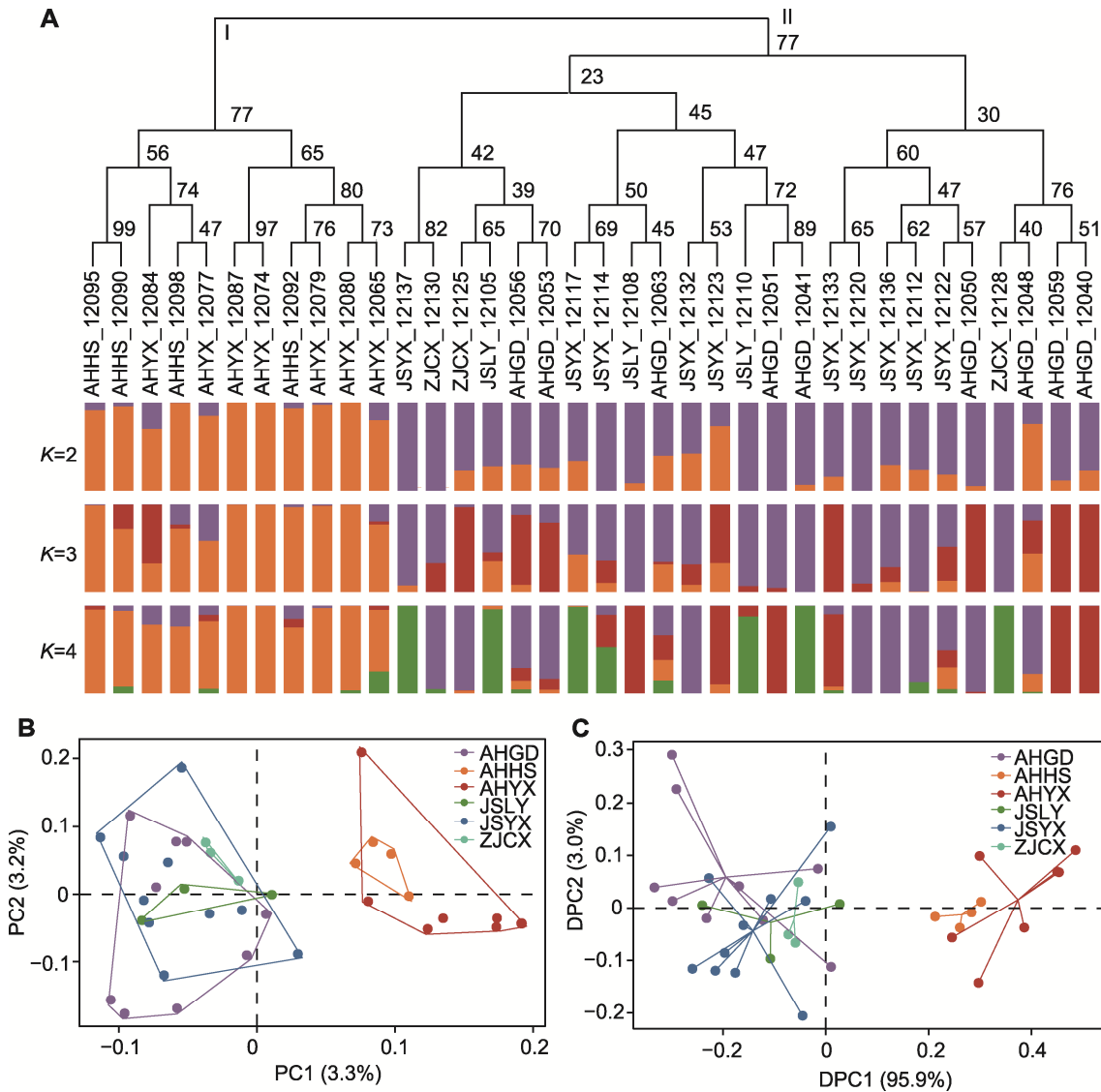


图1 短穗竹居群遗传结构分析

(A) 系统进化树和K=2, 3, 4时每个个体的遗传成分, 分支上方的数字表示靴带值; (B) 主成分分析(PCA); (C) 主成分判别分析(DAPC)。AHYX、AHHS、AHGD、JSLY、JSYX和ZJCX同表1。

Figure 1 Population genetic structure analysis of *Brachystachyum densiflorum*

(A) Phylogenetic tree and individual genetic components at K=2, 3, 4, the numbers above the branch are the bootstrap values; (B) Principal component analysis (PCA); (C) Discriminant analysis of principal components (DAPC). AHYX, AHHS, AHGD, JSLY, JSYX, and ZJCX are the same as shown in Table 1.

在8.9°C时突然变化(图3D); Bio6在-2.1-- -0.7°C时发生变化, -2.1-- -1.4°C变化较为平缓, -1.2-- -0.7°C变化幅度较大(图3F)。此外, 排在前5位的气候因子中还有最冷季度降水量(Bio19), 说明降水和低温影响短穗竹的遗传变异。

综合冗余分析和梯度森林分析, 表明遗传变异与5个气候因子(Bio2、Bio6、Bio19、Bio11和Bio7)之

间存在显著关联, 共同驱动短穗竹的遗传变异。本研究筛选出短穗竹居群适应性位点(异常SNPs) 617个, 去除重复后剩余544个。利用BayeScan软件基于贝叶斯概率法检测出98个潜在的候选位点(图4A)。通过冗余分析识别出170个异常SNPs (图4B), 其中57个适应Bio19, 37个适应Bio2, 26个适应Bio6, 26个适应Bio7, 24个适应Bio11。基于潜在因素混合模型(LFMM)

筛选出349个异常SNPs (图4C), 其中217个与Bio19相关, 99个与Bio7相关, 23个与Bio11相关, 6个与Bio2相关, 4个与Bio6相关。冗余分析和偏冗余分析(pRDA)进一步验证了适应性位点与5个气候因子之间的关联性(附表7), 结果显示适应性位点与温差、低温(Bio2、Bio6、Bio11和Bio7)和最冷季度降水量呈(Bio19)极显著相关($R_{adj}^2=0.034$, $P<0.01$)。

2.4 潜在地理分布预测

MaxEnt模型能够准确预测短穗竹不同时期的适生区域(AUC值>0.9), 其ROC曲线下方面积AUC值为0.976, 平均标准偏差为0.006(附图2)。基于综合贡献率、置换重要值(附表8)和刀切法检验(附图3), 结果表明短穗竹的分布和生长主要受Bio6、Bio11、Bio17和Bio19四个因子的影响。

通过MaxEnt模型预测短穗竹在末次盛冰期、全新世中期、当前和未来的潜在分布区, 发现从末次盛冰期(图5C)、全新世中期(图5B)到当前(图5A)短穗竹栖息地随着时间的推移发生了巨大变化, 适生区波动

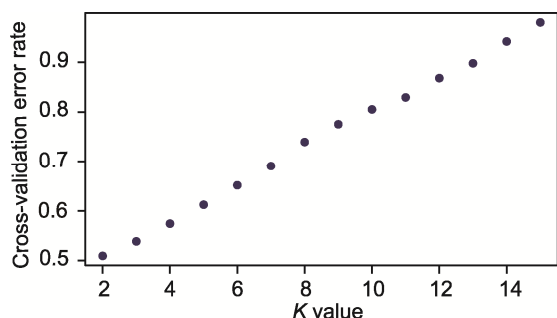


图2 K值对应的交叉检验错误率

Figure 2 The cross-validation error rate of K value

表3 6个居群间遗传分化值(F_{ST} , 左下三角)和基因流(Nm , 右上三角)

Table 3 Genetic differentiation (F_{ST} , lower left triangle) and gene flow (Nm , upper right triangle) among six populations

Population	AHGD	AHYX	AHHS	JSLY	JSYX	ZJCX
AHGD	0.000	3.596	2.497	2.065	4.958	2.108
AHYX	0.065	0.000	2.382	1.869	3.848	1.887
AHHS	0.091	0.095	0.000	1.523	2.591	1.562
JSLY	0.108	0.118	0.141	0.000	2.154	1.406
JSYX	0.048	0.061	0.088	0.104	0.000	2.177
ZJCX	0.106	0.117	0.138	0.151	0.103	0.000

AHYX、AHHS、AHGD、JSLY、JSYX和ZJCX同表1。

AHYX, AHHS, AHGD, JSLY, JSYX, and ZJCX are the same as shown in Table 1.

明显, 其分布范围不断扩大, 由 $1.06 \times 10^5 \text{ km}^2$ 增大到 $1.02 \times 10^6 \text{ km}^2$, 分布面积增加了89.5%且明显向北迁移(附表9; 图5A–C), 说明短穗竹在末次盛冰期和全新世中期不同气候条件下通过迁移持续进行适应性生长并延续至今。当前气候条件下, 短穗竹实际分布点被适生区覆盖, 且集中分布于高适生区内(图5A); 适生区分布范围在 108°E – 120°E 、 23°N – 34°N 之间, 其中高适生区面积为 $1.9 \times 10^5 \text{ km}^2$ (附表9), 主要位于浙江、安徽中部至南部和江苏南部, 江西和湖南交界处也有分布(图5A)。未来气候条件下, 在2021–2040年(图5D, G)和2041–2060年(图5E, H) 2个时段, 相比当前适生区面积和分布区波动将较小。在SSP 1–2.6路径下高适生区有向北迁移的趋势(图5D, E), 在2021–2040年高适生区面积将略有增加, 但在2041–2060年将减小。预计2061–2080年(图5F, I), 高适生区范围将缩小, 特别是在SSP 5–8.5路径下, 短穗竹在湖南的适生区将明显收缩, 在安徽高适生区将出现部分衰退和破碎化(图5I)。

3 讨论

3.1 短穗竹遗传多样性

遗传多样性水平反映了物种短期生态适应和长期进化所需遗传资源的可用性(Meena et al., 2019)。竹类的遗传多样性表现在广泛的变异(Perez-Alquicira et al., 2021)。本研究中, 短穗竹具有中等水平的遗传多样性($PIC=0.7225$, $H_o=0.087$, $H_e=0.2843$, $\pi=0.3175$), 遗传多样性水平高于RAD测序的2种热带木本竹类澜沧梨藤竹($H_o=0.160$, $H_e=0.162$, $\pi=0.174$)和独龙江空竹($H_o=0.217$, $H_e=0.252$, $\pi=0.257$) (赵虎刚

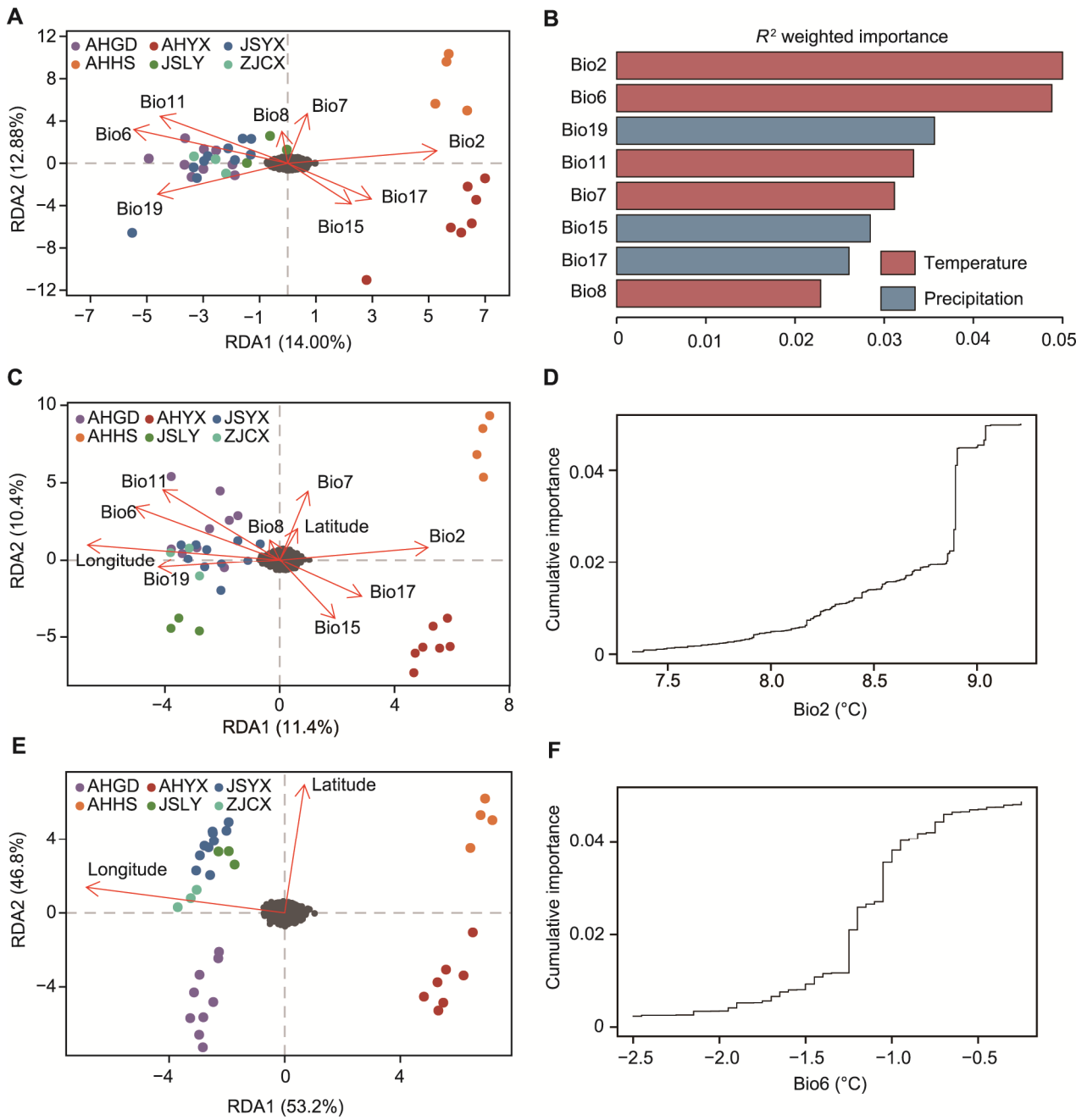


图3 冗余分析(RDA)和梯度森林(GF)分析

(A), (C), (E) 气候和地理与遗传结构之间的关联分析; (B) 梯度森林分析; (D), (F) Bio2和Bio6响应曲线。Bio2: 平均气温日较差; Bio6: 最冷月份最低温度; Bio7: 气温年较差; Bio8: 最湿季度平均温度; Bio11: 最冷季度平均温度; Bio15: 降水量季节性变化; Bio17: 最湿季度降水量; Bio19: 最冷季度降水量。AHYX、AHHS、AHGD、JSLY、JSYX和ZJCX同表1。

Figure 3 Redundancy analysis (RDA) and gradient forest (GF) analysis

(A), (C), (E) Association analysis between climate, geography and genetic structure; (B) Gradient forest analysis; (D), (F) Bio2 and Bio6 response curves. Bio2: Average daily temperature range; Bio6: The lowest temperature in the coldest month; Bio7: Annual temperature range; Bio8: The average temperature of the wettest quarter; Bio11: The average temperature of the coldest quarter; Bio15: Seasonal variation of precipitation; Bio17: The wettest season precipitation; Bio19: The coldest season precipitation. AHYX, AHHS, AHGD, JSLY, JSYX, and ZJCX are the same as shown in Table 1.

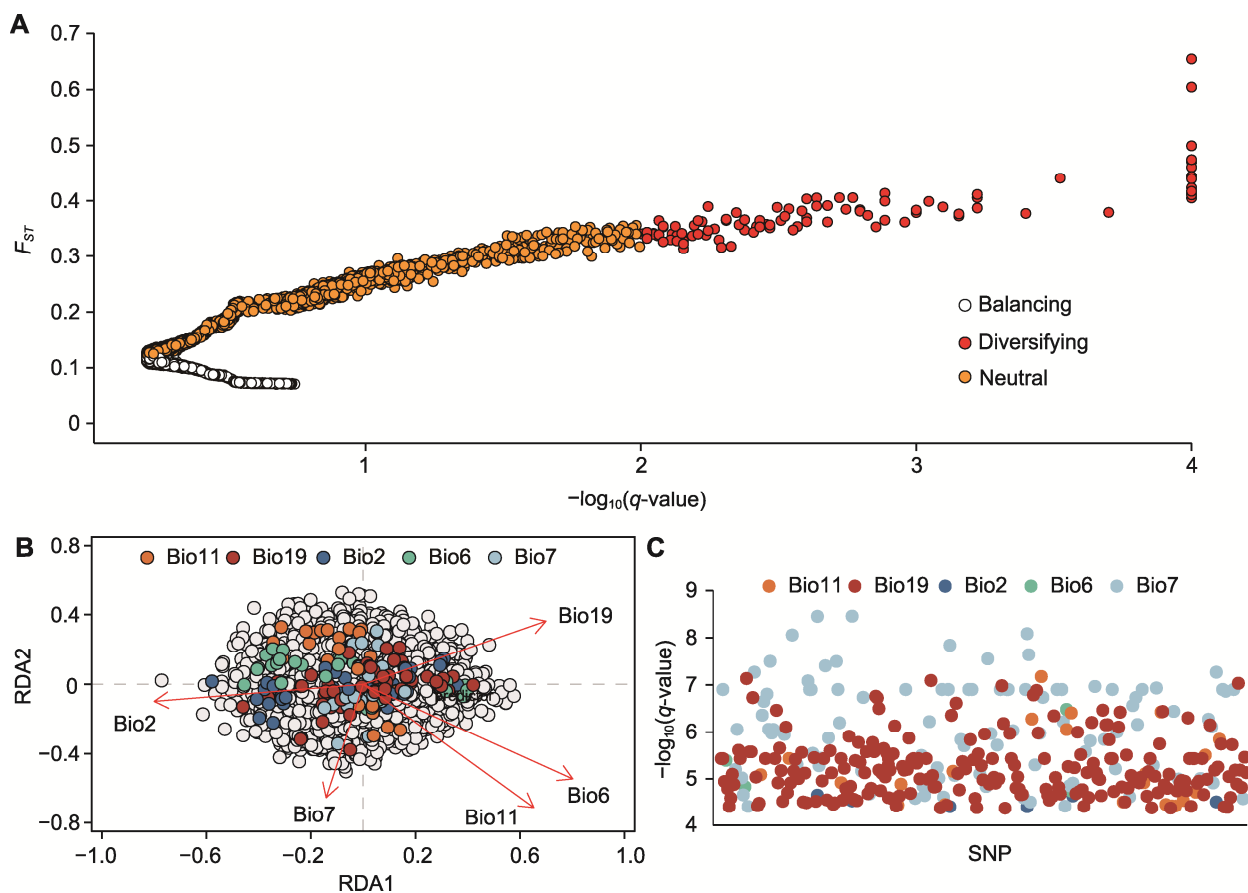


图4 利用3种方法筛选的异常单核苷酸多态性(SNP)位点

(A) BayeScan软件筛选; (B) 冗余分析(RDA)筛选; (C) 潜在因素混合模型(LFMM)筛选。 F_{ST} : 遗传分化指数。Bio2、Bio6、Bio7、Bio11和Bio19同图3。

Figure 4 Screening of outlier single nucleotide polymorphism (SNP) sites by three methods

(A) Screening by BayeScan software; (B) Screening by redundancy analysis (RDA); (C) Screening by latent factor mixed modeling (LFMM). F_{ST} : Fixation index of subdivision. Bio2, Bio6, Bio7, Bio11, and Bio19 are the same as shown in Figure 3.

等, 2023; 张如礼等, 2024)。多种因素决定了物种的遗传多样性, 多倍体是使竹类保持高水平遗传多样性的因素之一, 原因是每个基因座的等位基因数量较多(Perez-Alquicira et al., 2021)。目前, 已在基因组水平证实木本竹类是不均匀的多倍体, 短穗竹隶属青篱竹族(Arundinarieae), 是四倍体温带木本竹类($2n=46-48$)的一员(Guo et al., 2019; Clark, 2023)。地理分布范围广或多年生的物种保持较高的遗传多样性, 短穗竹在江苏、浙江、安徽、福建、湖北和江西均有分布(附表3)。木本竹类也是禾本科乃至单子叶植物中寿命最长的物种, 其寿命长达15–150年, 广泛而连续的分布和较长的寿命使得短穗竹具有丰富的遗传多样性(Meena et al., 2019; Oumer et al., 2020; Poupon et

al., 2021; Clark, 2023)。此外, 克隆植物居群可能具有多个多源基因型, 并保持较高的遗传多样性。竹类繁殖多以克隆为主且进化速率较慢, 基因组变异较小, 现有居群可能保留了其祖先的高遗传多样性, 尽管最近的气候变化和人为压力导致居群数量减少, 但居群仍表现出较高的遗传多样性(Yang et al., 2012; Das et al., 2017; Jiang et al., 2017; Li et al., 2020; Clark, 2023)。取样不足或取样范围较小也会影响对遗传多样性的评估。本研究中短穗竹个体主要采集于当前的分布中心区域(表1), 且每个居群个体较少(3–10个)。地理代表性取样不够全面可能会影响等位基因的获取, 导致评价结果无法反映出居群整体的遗传多样性水平(Wang et al., 2017; 张如礼等, 2024)。

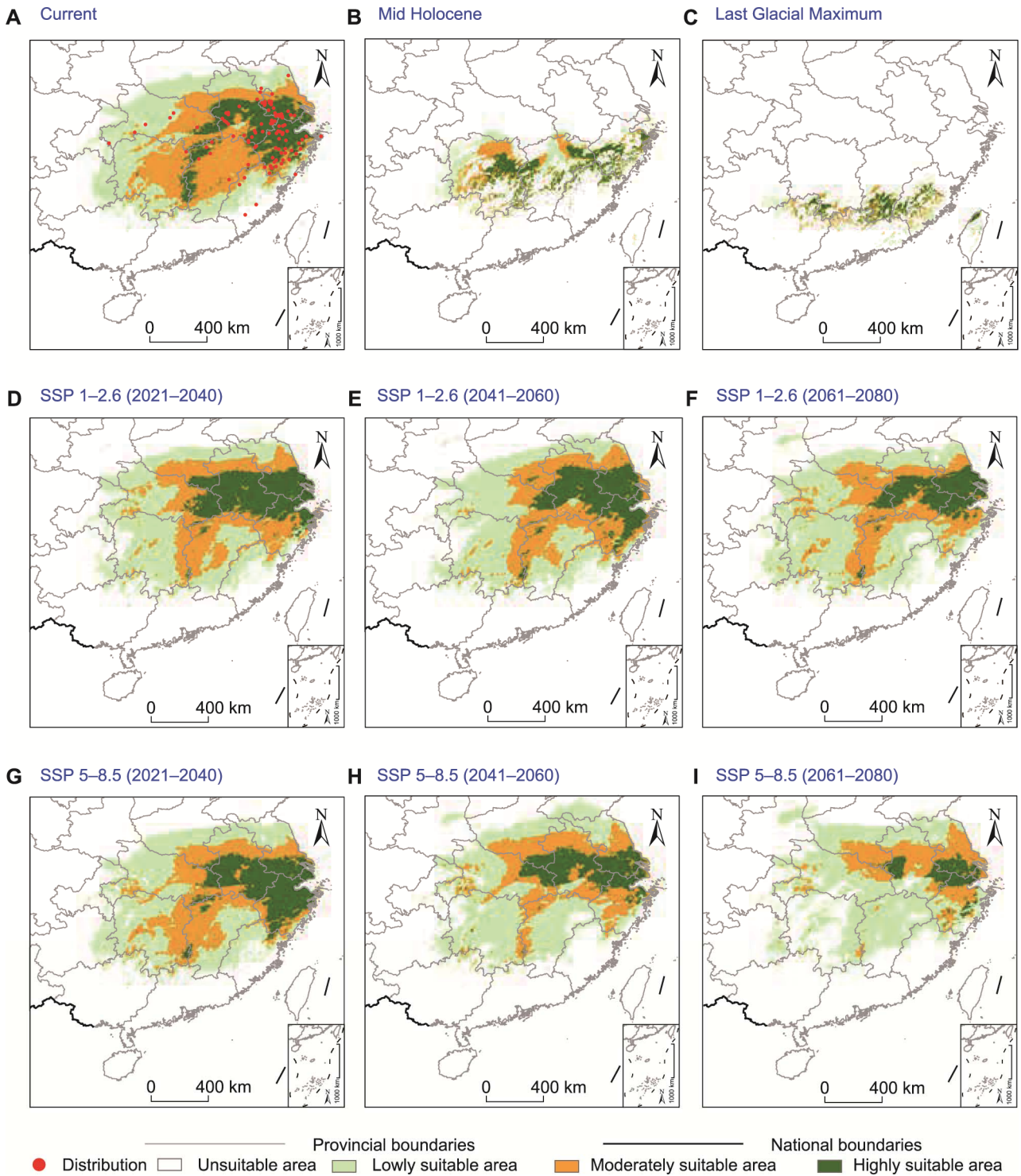


图5 不同时期短穗竹适宜性生境分布

(A) 当前(1970–2000年)气候条件下; (B) 全新世中期气候条件下; (C) 末次盛冰期气候条件下; (D), (G) 2021–2040年间气候; (E), (H) 2041–2060年间气候; (F), (I) 2061–2080年间气候

Figure 5 Distribution of suitable habitats for *Brachystachyum densiflorum* in different periods (A) Current (1970–2000) climate scenarios; (B) Mid Holocene climate scenarios; (C) Last Glacial Maximum climate scenarios; (D), (G) 2021–2040 climate scenarios; (E), (H) 2041–2060 climate scenarios; (F), (I) 2061–2080 climate scenarios

3.2 居群遗传结构和遗传分化

本研究中, 通过遗传结构分析将6个居群划分为2组, 安徽霍山(AHHS)和安徽岳西(AHYX) 2个居群与其余4个居群之间有很强的遗传结构分化(图1)。基因流受限是居群遗传结构形成的主要原因, 而地理距离较远阻碍了2个组之间的连通性, 如安徽霍山(AHHS)和安徽岳西(AHYX) 2个居群与其余4个居群地理距离较远(274.4–346.42 km), 阻碍了2个组之间的基因交流(Hardy et al., 2006; Perez-Alquicira et al., 2021; Wang et al., 2022a)。此外, 居群的历史事件、自然选择和人为压力也会促进居群遗传结构的形成(Cheng et al., 2020)。研究还发现地理分布区域邻近的居群遗传背景具有较高的相似性, 大多数竹类居群可通过无性繁殖建立并扩展到附近区域, 共享相同的基因库, 因此居群间的亲缘关系较近, 同源性较高(Meena et al., 2019; Oumer et al., 2020; Silva et al., 2020)。本研究中短穗竹取样个体并未完全覆盖分布区域内的所有居群(附表3), 除当前的分布中心(表1)区域外, 尚缺乏对福建、江西、湖北、江苏北部及浙江南部等地的取样(图5A), 可能会造成对居群遗传结构评价的偏差, 从而无法准确判断居群间的遗传关系。因此, 增加地理代表性分布区域内居群取样并确保每个居群有足够的个体数量, 从而增加遗传信息数量, 提高物种居群遗传结构预测的准确性(Perez-Alquicira et al., 2021)。

短穗竹居群较大的遗传变异比例局限在居群内(79.71%), 但依然存在中度遗传分化($F_{ST}=0.102$), 在一些竹类中也存在中度遗传分化, 如须弥箬竹(*Himalayacalamus falconeri*) ($F_{ST}=0.121$)、瓜多竹($F_{ST}=0.098$)和*Kuruna debilis* ($F_{ST}=0.113$) (Attigala et al., 2017; Perez-Alquicira et al., 2021; Meena et al., 2023b)。居群间的遗传分化与基因流动呈负相关, 尽管短穗竹居群之间基因流水平很高($Nm=2.442$), 但地理分布较近的江苏溧阳(JSLY)与浙江长兴(ZJXC)的居群存在较大分化($F_{ST}=0.151>0.15$)。即使地理位置接近的居群, 由于开花时间不同步、开花不频繁及花的数量少等原因造成花粉传播率低, 可能会阻碍基因流动, 促进居群间的分化(Nilkanta et al., 2017; Perez-Alquicira et al., 2021)。人为压力增大及全球气候变化等原因导致栖息地退化和破碎化可能加剧江苏溧阳(JSLY)和浙江长兴(ZJXC)两居群的遗传漂

变, 从而导致基因交流减弱(近期基因流动率为0.029 4), 因而表现出更强的遗传分化(Nilkanta et al., 2017; Meena et al., 2019)。

3.3 遗传变异与气候关联分析

气候和地理是影响居群遗传变异的重要驱动力。冗余分析表明, 与地理因素(22.22%)相比, 气候因素对遗传变异的解释率(35.48%)更高, 在推动居群分化的过程中气候因素比地理因素更重要。虽然地理隔离可能会引起最初的分化, 但气候因素的分化选择会进一步提高居群的遗传分化(Wang et al., 2017; Bolte et al., 2022)。气候推动短穗竹居群分化为2个组(图2A)。局部适应被认为是导致分化的重要原因, 许多物种存在对气候变化条件下的局部适应(Harrison et al., 2017; Wang et al., 2022b)。

冗余分析和梯度森林分析表明, 短穗竹适应性遗传变异很大程度上与Bio2、Bio6、Bio7、Bio11和Bio19这5个气候因子紧密关联, 温差和低温是影响短穗竹遗传变异的关键因子, 此外也与最冷季度降水量(Bio19)有关。温度是许多物种存在适应性变化的驱动因素, 其通过影响光合作用、呼吸作用和蒸腾作用影响植物的生长(Jia et al., 2020; Butler et al., 2022)。温度和降水是影响植物生长发育、生存和繁殖的重要因素, 但还需综合考虑其它相关因素, 如土壤特性和光照辐射, 这可能会改变对适应性遗传变异的认识和理解(Perez-Alquicira et al., 2021; Filipe et al., 2022)。本研究基于16 583个SNPs筛选适应性位点(异常SNP), 但由于大多数SNP是中性的, 仅发现98个高分化的SNP位点(图4A)。Wang等(2017)认为利用简化基因组测序技术在基因组水平上筛选适应性位点有一定的局限性, 可能无法发现与适应性有关的低频等位基因。通过冗余分析和潜在因素混合模型筛选, 发现与降水量(Bio19)有关的异常SNP比各温度因子多(图4B, C)。气候因子可能不是某些假定的适应性SNP变异的主要驱动因素, 相关SNP可能具有多效性并受到其它生物或非生物因素的选择(Filipe et al., 2022)。

3.4 潜在地理分布预测

第四纪气候在冰期和间冰期之间振荡对当今物种的分布格局产生重要影响。许多植物无法适应寒冷干燥的气候而被迫向南迁移避难, 众多物种被隔离在不同

的避难所(胡菀等, 2020; Polic et al., 2022)。在末次冰期许多植物并未完全迁移到24°N以南区域, 在末次盛冰期大降温背景下短穗竹的分布范围在23°–27°N之间, 说明该分布区(图5C)可能是短穗竹在冰期的避难所(胡菀等, 2020)。全新世中期气候开始变暖, 一些物种向北迁移并且分布面积增大(胡菀等, 2020; He et al., 2022)。短穗竹在全新世中期明显向北扩张且分布范围扩大59.12% (图5B; 附表9)。全新世中期到当前短穗竹同样向北迁移和扩张(图5A, B), 此期间温度降低可能是影响短穗竹扩张的原因, 已证实全新世中期(约6 000年前)到当前发生了5次冷事件, 分别发生在5.9、4.2、2.8、1.4和0.4 kyr (Wang et al., 2013)。在进行短穗竹分布预测时也发现最冷月份最低温度(Bio6)、最冷季度平均温度(Bio11)和最冷季度降水量(Bio19)影响短穗竹的分布和生长。未来气候条件下, 物种的承受能力将受降水和温度等因素的影响, 物种的分布范围可能会缩小或转移(Yebeyen et al., 2022)。2021–2040年和2041–2060年2个时段, 在SSP 1–2.6路径下短穗竹高适生区有向北迁移的趋势。此外, 预测江西和湖南交界处的高适生区面积将减小甚至消失, 以及在2061–2080年间SSP 5–8.5路径下高适生区会出现部分衰退和破碎化, 短穗竹可能将受到全球变暖的严重威胁。

作者贡献声明

张如礼: 撰写论文, 完成数据分析和图表绘制; 李德铎: 构思主题和设计论文框架, 修改并完善论文; 张玉霄: 样品采集, 构思主题和设计论文框架, 修改并完善论文, 定稿。

参考文献

- Aguirre-Liguori JA, Ramírez-Barahona S, Gaut BS (2021). The evolutionary genomics of species' responses to climate change. *Nat Ecol Evol* **5**, 1350–1360.
- Alsos IG, Ehrich D, Thuiller W, Eidesen PB, Tribsch A, Schönswetter P, Lagaye C, Taberlet P, Brochmann C (2012). Genetic consequences of climate change for northern plants. *Proc Roy Soc B* **279**, 2042–2051.
- Alvarado AH, Bossu CM, Harrigan RJ, Bay RA, Nelson ARP, Smith TB, Ruegg KC (2022). Genotype-environment associations across spatial scales reveal the importance of putative adaptive genetic variation in divergen-

- ce. *Evol Appl* **15**, 1390–1407.
- Attigala L, Gallaher T, Nason J, Clark LG (2017). Genetic diversity and population structure of the threatened temperate woody bamboo *Kuruna debilis* (Poaceae: Bambusoideae: Arundinarieae) from Sri Lanka based on microsatellite analysis. *J Natl Sci Found Sri Lanka* **45**, 53–65.
- Baird NA, Etter PD, Atwood TS, Currey MC, Shiver AL, Lewis ZA, Selker EU, Cresko WA, Johnson EA (2008). Rapid SNP discovery and genetic mapping using sequenced RAD markers. *PLoS One* **3**, e3376.
- Barr K, Beichman AC, Kalhori P, Rajbhandary J, Bay RA, Ruegg K, Smith TB (2021). Persistent panmixia despite extreme habitat loss and population decline in the threatened tricolored blackbird (*Agelaius tricolor*). *Evol Appl* **14**, 674–684.
- Beridze B, Sękiewicz K, Walas Ł, Thomas PA, Danelia I, Fazaliyev V, Kvartskhava G, Sós J, Dering M (2023). Biodiversity protection against anthropogenic climate change: conservation prioritization of *Castanea sativa* in the South Caucasus based on genetic and ecological metrics. *Ecol Evol* **13**, e10068.
- Bhandawat A, Sharma V, Singh P, Seth R, Nag A, Kaur J, Sharma RK (2019). Discovery and utilization of EST-SSR marker resource for genetic diversity and population structure analyses of a subtropical bamboo, *Dendrocalamus hamiltonii*. *Biochem Genet* **57**, 652–672.
- Boban S, Maurya S, Jha Z (2022). DNA fingerprinting: an overview on genetic diversity studies in the botanical taxa of Indian Bamboo. *Genet Resour Crop Evol* **69**, 469–498.
- Bolte CE, Faske TM, Friedline CJ, Eckert AJ (2022). Divergence amid recurring gene flow: complex demographic histories for two North American pine species (*Pinus pungens* and *P. rigida*) fit growing expectations among forest trees. *Tree Genet Genomes* **18**, 35.
- Bonin A, Nicole F, Pompanon F, Miaud C, Taberlet P (2007). Population adaptive index: a new method to help measure intraspecific genetic diversity and prioritize populations for conservation. *Conserv Biol* **21**, 697–708.
- Butler JB, Harrison PA, Vaillancourt RE, Steane DA, Tibbitts JFG, Potts BM (2022). Climate adaptation, drought susceptibility, and genomic-informed predictions of future climate refugia for the Australian forest tree *Eucalyptus globulus*. *Forests* **13**, 575.
- Cai CN, Hou QX, Ci XQ, Xiao JH, Zhang CY, Li J (2021). Genetic diversity of *Horsfieldia hainanensis*: an endangered species with extremely small populations. *J Trop Subtrop Bot* **29**, 547–555. (in Chinese)

- 蔡超男, 侯勤曦, 慈秀芹, 肖建华, 张灿瑜, 李捷 (2021). 极小种群野生植物海南风吹楠的遗传多样性研究. *热带亚热带植物学报* **29**, 547–555.
- Cheng J, Kao HX, Dong SB (2020). Population genetic structure and gene flow of rare and endangered *Tetraena mongolica* Maxim. revealed by reduced representation sequencing. *BMC Plant Biol* **20**, 391.
- Clark LG (2023). Integrating genomic and morphological data into bamboo taxonomic and evolutionary studies. *Plant Divers* **45**, 123–124.
- Das S, Singh YP, Negi YK, Shrivastav PC (2017). Genetic variability in different growth forms of *Dendrocalamus strictus*: deogun revisited. *N Z J For Sci* **47**, 235.
- Davey JW, Hohenlohe PA, Etter PD, Boone JQ, Catchen JM, Blaxter ML (2011). Genome-wide genetic marker discovery and genotyping using next-generation sequencing. *Nat Rev Genet* **12**, 499–510.
- DeSaix MG, George TL, Seglund AE, Spellman GM, Zavaleta ES, Rugg KC (2022). Forecasting climate change response in an alpine specialist songbird reveals the importance of considering novel climate. *Divers Distrib* **28**, 2239–2254.
- Dong FS, Lian LS, Sun BW, Chen Z, Zhu YB (2023). Spatial-temporal variation of visibility and its influencing factors in East China. *Meteor Sci Technol* **51**, 510–519. (in Chinese)
- 董芳淑, 廉丽姝, 孙博雯, 程祺, 朱艳冰 (2023). 华东地区能见度时空变化特征及影响因子分析. *气象科技* **51**, 510–519.
- Doyle JJ, Doyle JL (1987). A rapid DNA isolation procedure for small quantities of fresh leaf tissue. *Phytochem Bull* **19**, 11–15.
- Ely F, Rada F, Fermin G, Clark LG (2019). Ecophysiology and genetic diversity in species of the bamboo *Chusquea* in the high Andes, Venezuela. *Plant Ecol Divers* **12**, 555–572.
- Exposito-Alonso M, Booker TR, Czech L, Gillespie L, Hateley S, Kyriazis CC, Lang PLM, Leventhal L, Nogues-Bravo D, Pagowski V, Ruffley M, Spence JP, Toro Arana SE, Weiß CL, Zess E (2022). Genetic diversity loss in the Anthropocene. *Science* **3**, 1431–1435.
- Feng L, Du FK (2022). Landscape genomics in tree conservation under a changing environment. *Front Plant Sci* **13**, 822217.
- Fick SE, Hijmans RJ (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int J Climatol* **37**, 4302–4315.
- Filipe JC, Rymer PD, Byrne M, Hardy G, Mazanec R, Ahrens CW (2022). Signatures of natural selection in a foundation tree along Mediterranean climatic gradients. *Mol Ecol* **31**, 1735–1752.
- Gibson MJS, Moyle LC (2020). Regional differences in the abiotic environment contribute to genomic divergence within a wild tomato species. *Mol Ecol* **29**, 2204–2217.
- Guan BC, Gao JJ, Chen W, Gong X, Ge G (2021). The effects of climate change on landscape connectivity and genetic clusters in a small subtropical and warm-temperate tree. *Front Plant Sci* **12**, 671336.
- Guo ZH, Ma PF, Yang GQ, Hu JY, Liu YL, Xia EH, Zhong MC, Zhao L, Sun GL, Xu YX, Zhao YJ, Zhang YC, Zhang YX, Zhang XM, Zhou MY, Guo Y, Guo C, Liu JX, Ye XY, Chen YM, Yang Y, Han B, Lin CS, Lu Y, Li DZ (2019). Genome sequences provide insights into the reticulate origin and unique traits of woody bamboos. *Mol Plant* **12**, 1353–1365.
- Hardy OJ, Maggia L, Bandou E, Breyne P, Caron H, Chevallier MH, Doligez A, Dutech C, Kremer A, Latouche-Hallé C, Troispoux V, Veron V, Degen B (2006). Fine-scale genetic structure and gene dispersal inferences in 10 neotropical tree species. *Mol Ecol* **15**, 559–571.
- Harrison KA, Amish SJ, Pavlova A, Narum SR, Telonis-Scott M, Rourke ML, Lyon J, Tonkin Z, Gilligan DM, Ingram BA, Lintermans M, Gan HM, Austin CM, Luikart G, Sunnucks P (2017). Signatures of polygenic adaptation associated with climate across the range of a threatened fish species with high genetic connectivity. *Mol Ecol* **26**, 6253–6269.
- Haupt M, Schmid K (2022). Using landscape genomics to infer genomic regions involved in environmental adaptation of soybean genebank accessions. *bioRxiv* doi: 10.1101/2022.02.18.480989.
- He HL, Zheng XF, Wang YQ, Wang WQ, Li MB, Wang SG, Wang J, Wang CM, Zhan H (2022). Effects of climate change and environmental factors on bamboo (*Ferrocalamus strictus*), a PSESP unique to China. *Forests* **13**, 2108.
- Hu W, Zhang ZY, Chen LD, Peng YS, Wang X (2020). Changes in potential geographical distribution of *Tsoongiodendron odorum* since the Last Glacial Maximum. *Chin J Plant Ecol* **44**, 44–55. (in Chinese)
- 胡蕊, 张志勇, 陈陆丹, 彭焱松, 汪旭 (2020). 末次盛冰期以来观光木的潜在地理分布变迁. *植物生态学报* **44**, 44–55.
- İşik K (2011). Rare and endemic species: why are they

- prone to extinction? *Turk J Bot* **35**, 411–417.
- Jia KH, Zhao W, Maier PA, Hu XG, Jin YQ, Zhou SS, Jiao SQ, El-Kassaby YA, Wang TL, Wang XR, Mao JF** (2020). Landscape genomics predicts climate change-related genetic offset for the widespread *Platykladus orientalis* (Cupressaceae). *Evol Appl* **13**, 665–676.
- Jiang WX, Bai TD, Dai HM, Wei Q, Zhang WJ, Ding YL** (2017). Microsatellite markers revealed moderate genetic diversity and population differentiation of moso bamboo (*Phyllostachys edulis*)—a primarily asexual reproduction species in China. *Tree Genet Genomes* **13**, 130.
- Jing HY, Xiong XS, Jiang F, Pu XC, Ma WH, Li DJ, Liu ZL, Wang ZH** (2024). Climate change filtered out resource-acquisitive plants in a temperate grassland in Inner Mongolia, China. *Sci China Life Sci* **67**, 403–413.
- Keenan RJ** (2015). Climate change impacts and adaptation in forest management: a review. *Ann For Sci* **72**, 145–167.
- Li DZ, Wang ZP, Zhu ZD, Xia NH, Jia LZ, Guo ZH, Yang GY, Stapleton CMA** (2006). Bambuseae (poaceae). In: Wu ZY, Raven PH, Hong DY, eds. *Flora of China*, Vol. 22. Beijing: Science Press. pp. 7–180.
- Li LB, Guo XJ, Peng ZH, Liu GS, Yuan HS, Zhu BC, Yang K** (2008). Effect of the quantity of AFLP primer combinations on accurately identifying bamboo genetic relationships. *Chin Bull Bot* **25**, 449–454. (in Chinese)
- 李瀚滨, 郭晓军, 彭镇华, 刘贯水, 袁洪水, 朱宝成, 杨凯** (2008). AFLP引物组合数量对准确研究竹子系统关系的影响. *植物学通报* **25**, 449–454.
- Li ST, Ramakrishnan M, Vinod KK, Kalendar R, Yrjälä K, Zhou MB** (2020). Development and deployment of high-throughput retrotransposon-based markers reveal genetic diversity and population structure of Asian bamboo. *Forests* **11**, 31.
- Lin N, Landis JB, Sun YX, Huang XH, Zhang X, Liu Q, Zhang HJ, Sun H, Wang HC, Deng T** (2021). Demographic history and local adaptation of *Myriopholis dioica* (Asteraceae) provide insight on plant evolution in northern China flora. *Ecol Evol* **11**, 8000–8013.
- Liu YH, Wang HC, Yang J, Dao ZL, Sun WB** (2024). Conservation genetics and potential geographic distribution modeling of *Corybas taliensis*, a small ‘sky Island’ orchid species in China. *BMC Plant Biol* **24**, 11.
- Meena RK, Bhandari MS, Barhwal S, Ginwal HS** (2019). Genetic diversity and structure of *Dendrocalamus hamiltonii* natural metapopulation: a commercially important bamboo species of northeast Himalayas. *3 Biotech* **9**, 60.
- Meena RK, Negi N, Shankhwar R, Bhandari MS, Kant R, Pandey S, Kumar N, Sharma R, Ginwal HS** (2023a). Ecological niche modelling and population genetic analysis of Indian temperate bamboo *Drepanostachyum falcatum* in the western Himalayas. *J Plant Res* **136**, 483–499.
- Meena RK, Negi N, Shankhwar R, Bhandari MS, Sharma R** (2023b). Population genetic analysis illustrated a high gene diversity and genetic heterogeneity in *Himalayacalamus falconeri*: a socio-economically important Indian temperate woody bamboo taxon. *J Plant Biochem Biotechnol* **32**, 438–450.
- Morin PA, Luikart G, Wayne RK, The SNP Workshop Group** (2004). SNPs in ecology, evolution and conservation. *Trends Ecol Evol* **19**, 208–216.
- Nilkanta H, Amom T, Tikendra L, Rahaman H, Nongdam P** (2017). ISSR marker based population genetic study of *Melocanna baccifera* (Roxb.) Kurz: a commercially important bamboo of Manipur, North-East India. *Scientifica* **2017**, 3757238.
- Ouborg NJ, Pertoldi C, Loeschcke V, Bijlsma R, Hedrick PW** (2010). Conservation genetics in transition to conservation genomics. *Trends Genet* **26**, 177–187.
- Oumer OA, Dagne K, Feyissa T, Tesfaye K, Durai J, Hyder MZ** (2020). Genetic diversity, population structure, and gene flow analysis of lowland bamboo [*Oxytenanthera abyssinica* (A. Rich.) Munro] in Ethiopia. *Ecol Evol* **10**, 11217–11236.
- Pauls SU, Nowak C, Bálint M, Pfenninger M** (2013). The impact of global climate change on genetic diversity within populations and species. *Mol Ecol* **22**, 925–946.
- Perez-Alquicira J, Aguilera-Lopez S, Rico Y, Ruiz-Sanchez E** (2021). A population genetics study of three native Mexican woody bamboo species of *Guadua* (Poaceae: Bambusoideae: Bambuseae: Guaduiniae) using nuclear microsatellite markers. *Bot Sci* **99**, 542–559.
- Phair NL, Nielsen ES, Von der Heyden S** (2021). Applying genomic data to seagrass conservation. *Biodivers Conserv* **30**, 2079–2096.
- Polic D, Yıldırım Y, Lee KM, Franzén M, Mutanen M, Vila R, Forsman A** (2022). Linking large-scale genetic structure of three Argynnini butterfly species to geography and environment. *Mol Ecol* **31**, 4381–4401.
- Poupon V, Chakraborty D, Stejskal J, Konrad H, Schueler S, Lstibůrek M** (2021). Accelerating adaptation of forest trees to climate change using individual tree response functions. *Front Plant Sci* **12**, 758221.
- Salvado P, Aymerich Boixader P, Parera J, Vila Bonfill A, Martin M, Quélenec C, Lewin JM, Delorme-Hinoux V,**

- Bertrand JAM** (2022). Little hope for the polyploid endemic Pyrenean Larkspur (*Delphinium montanum*): evidences from population genomics and ecological niche modeling. *Ecol Evol* **12**, e8711.
- Sang YP, Long ZQ, Dan XM, Feng JJ, Shi TT, Jia CF, Zhang XX, Lai Q, Yang GL, Zhang HY, Xu XT, Liu HH, Jiang YZ, Ingvarsson PK, Liu JQ, Mao KS, Wang J** (2022). Genomic insights into local adaptation and future climate-induced vulnerability of a keystone forest tree in East Asia. *Nat Commun* **13**, 6541.
- Sepúlveda-Espinoza F, Bertin-Benavides A, Hasbún R, Toro-Núñez Ó, Varas-Myrik A, Alarcón D, Guillemin ML** (2022). The impact of pleistocene glaciations and environmental gradients on the genetic structure of *Embothrium coccineum*. *Ecol Evol* **12**, e9474.
- Shafer ABA, Wolf JBW, Alves PC, Bergström L, Bruford MW, Brännström I, Colling G, Dalén L, De Meester L, Ekblom R, Fawcett KD, Fior S, Hajibabaei M, Hill JA, Hoesel AR, Höglund J, Jensen EL, Krause J, Kristensen TN, Krützen M, McKay JK, Norman AJ, Ogden R, Österling EM, Ouborg NJ, Piccolo J, Popović D, Primmer CR, Reed FA, Roumet M, Salmona J, Schenkar T, Schwartz MK, Segelbacher G, Senn H, Thaulow J, Valtonen M, Veale A, Vergeer P, Vijay N, Vilà C, Weissensteiner M, Wennerström L, Wheat CW, Ziełiński P** (2015). Genomics and the challenging translation into conservation practice. *Trends Ecol Evol* **30**, 78–87.
- Silva SMM, Martins K, Costa FHS, de Campos T, Scherwinski-Pereira JE** (2020). Genetic structure and diversity of native *Guadua* species (Poaceae: Bambusoideae) in natural populations of the Brazilian Amazon rainforest. *An Acad Bras Ciênc* **92**, e20190083.
- Sun WY, Shu JP, Gu YF, Morigengaowa, Du XJ, Liu BD, Yan YH** (2022). Conservation genomics analysis revealed the endangered mechanism of *Adiantum nelumboides*. *Biodiv Sci* **30**, 21508. (in Chinese)
- 孙维悦, 舒江平, 顾钰峰, 莫日根高娃, 杜夏瑾, 刘保东, 严岳鸿 (2022). 基于保护基因组学揭示荷叶铁线蕨的濒危机制. *生物多样性* **30**, 21508.
- Tian B, Yang HQ, Wong KM, Liu AZ, Ruan ZY** (2012). ISSR analysis shows low genetic diversity versus high genetic differentiation for giant bamboo, *Dendrocalamus giganteus* (Poaceae: Bambusoideae), in China populations. *Genet Resour Crop Evol* **59**, 901–908.
- Wang GP, Lai H, Bi S, Guo DL, Zhao XP, Chen XL, Liu S, Liu XG, Su YQ, Yi HD, Li GF** (2022a). ddRAD-Seq reveals evolutionary insights into population differentiation and the cryptic phylogeography of *Hyporhamphus intermedius* in Mainland China. *Ecol Evol* **12**, e9053.
- Wang J, Feng C, Jiao TL, Von Wettberg EB, Kang M** (2017). Genomic signature of adaptive divergence despite strong nonadaptive forces on edaphic islands: a case study of *Primulina juliae*. *Genome Biol Evol* **9**, 3495–3508.
- Wang L, Liu SF, Yang Y, Meng ZN, Zhuang ZM** (2022b). Linked selection, differential introgression and recombination rate variation promote heterogeneous divergence in a pair of yellow croakers. *Mol Ecol* **31**, 5729–5744.
- Wang SW, Ge QS, Wang F, Wen XY, Huang JB** (2013). Abrupt climate changes of Holocene. *Chin Geogr Sci* **23**, 1–12.
- Wu RF, Qi JW, Li WB, Wang L, Shen Y, Liu JW, Teng Y, Roos C, Li M** (2023). Landscape genomics analysis provides insights into future climate change-driven risk in rhesus macaque. *Sci Total Environ* **899**, 165746.
- Yang FM, Cai L, Dao ZL, Sun WB** (2022a). Genomic data reveals population genetic and demographic history of *Magnolia fistulosa* (Magnoliaceae), a plant species with extremely small populations in Yunnan Province, China. *Front Plant Sci* **13**, 811312.
- Yang FY, Crossley MS, Schrader L, Dubovskiy IM, Wei SJ, Zhang RZ** (2022b). Polygenic adaptation contributes to the invasive success of the Colorado potato beetle. *Mol Ecol* **31**, 5568–5580.
- Yang H, Li JL, Milne RI, Tao WJ, Wang Y, Miao JB, Wang WT, Ju T, Tso S, Luo J, Mao KS** (2022c). Genomic insights into the genotype-environment mismatch and conservation units of a Qinghai-Tibet Plateau endemic cypress under climate change. *Evol Appl* **15**, 919–933.
- Yang HQ, An MY, Gu ZJ, Tian B** (2012). Genetic diversity and differentiation of *Dendrocalamus membranaceus* (Poaceae: Bambusoideae), a declining bamboo species in Yunnan, China, as based on inter-simple sequence repeat (ISSR) analysis. *Int J Mol Sci* **13**, 4446–4457.
- Yebeyen D, Nemomissa S, Hailu BT, Zewdie W, Sileshi GW, Rodríguez RL, Woldie TM** (2022). Modeling and mapping habitat suitability of highland bamboo under climate change in Ethiopia. *Forests* **13**, 859–875.
- Yuan S, Shi Y, Zhou BF, Liang YY, Chen XY, An QQ, Fan YR, Shen Z, Ingvarsson PK, Wang BS** (2023). Genomic vulnerability to climate change in *Quercus acutissima*, a dominant tree species in East Asian deciduous forests. *Mol*

Ecol **32**, 1639–1655.

Zhang RL, Liu WY, Zhang YX, Tu DD, Zhu LY, Zhang WJ, Hui CM (2024). Genetic diversity analysis of *Melocalamus arrectus* based on reduced-representation genome sequencing. *Mol Plant Breed* **22**, 8076–8087. (in Chinese)

张如礼, 刘蔚漪, 张玉霄, 涂丹丹, 朱礼月, 张文君, 辉朝茂 (2024). 基于简化基因组测序的澜沧梨藤竹遗传多样性分析. *分子植物育种* **22**, 8076–8087.

Zhang SS, Kang HM, Yang WZ (2019). Population genetic analysis of *Nyssa yunnanensis* by reduced-representation sequencing technique. *Bull Bot Res* **39**, 899–907. (in Chinese)

张珊珊, 康洪梅, 杨文忠 (2019). 基于简化基因组技术的云南蓝果树群体遗传分析. *植物研究* **39**, 899–907.

Zhang X, Sun YX, Landis JB, Zhang JW, Yang LS, Lin N, Zhang HJ, Guo R, Li LJ, Zhang YH, Deng T, Sun H, Wang HC (2020). Genomic insights into adaptation to heterogeneous environments for the ancient relictual *Circaea agrestis* (Circaceasteraceae, Ranunculales). *New Phytol* **228**, 285–301.

Zhang YX, Zeng CX, Li DZ (2012). Complex evolution in Arundinarieae (Poaceae: Bambusoideae): incongruence between plastid and nuclear GBSSI gene phylogenies. *Mol Phylogenet Evol* **63**, 777–797.

Zhao HG, Zhang RL, Xiong Y, Ma CL, Zhang YX (2023). Genetic diversity of *Cephalostachyum mannii*: an endangered species with extremely small populations. *Chin Wild Plant Resour* **42**, 112–120. (in Chinese)

赵虎刚, 张如礼, 熊云, 马长乐, 张玉霄 (2023). 极小种群野生植物独龙江空竹遗传多样性研究. *中国野生植物资源* **42**, 112–120.

Zhao HS, Gao ZM, Wang L, Wang JL, Wang SB, Fei BH, Chen CH, Shi CC, Liu XC, Zhang HL, Lou YF, Chen LF, Sun HY, Zhou XQ, Wang SN, Zhang C, Xu H, Li LC, Yang YH, Wei YL, Yang W, Gao Q, Yang HM, Zhao SC, Jiang ZH (2018). Chromosome-level reference genome and alternative splicing atlas of moso bamboo (*Phyllostachys edulis*). *GigaScience* **7**, giy115.

Zhu S, Liu T, Tang Q, Fu L, Tang S (2014). Evaluation of bamboo genetic diversity using morphological and SRAP analyses. *Genetika* **50**, 306–313.

Population Genetic Structure and Climate Adaptation Analysis of *Brachystachyum densiflorum*

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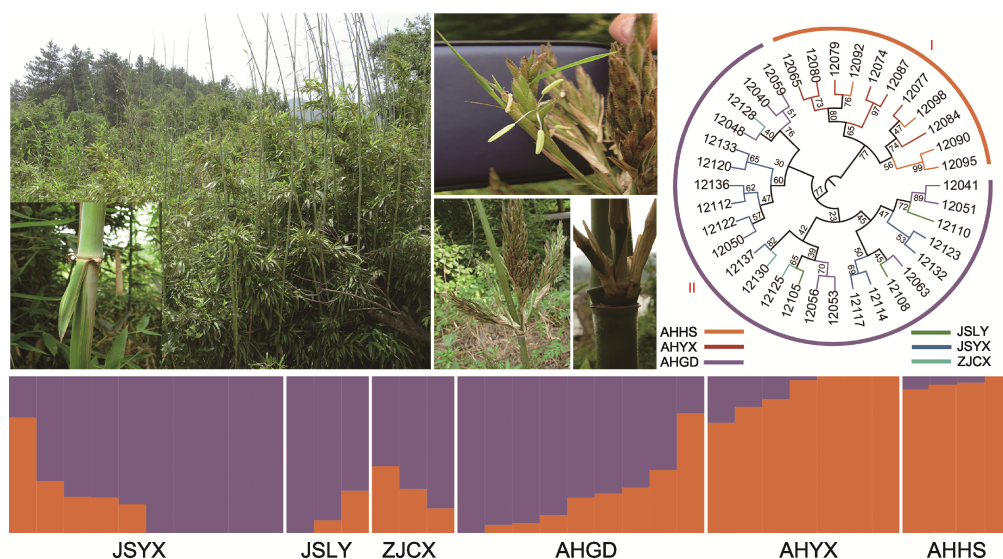
INTRODUCTION: Genetic diversity is considered as a crucial aspect in assessment and conservation of rare and endangered species. *Brachystachyum densiflorum* is a species endemic to eastern China. In recent years, with rapid economic development, accelerated urbanization, and escalating pollutant emissions, the habitat of *B. densiflorum* has been continuously degraded, habitat fragmentation has intensified, and its populations have shown a tendency to decline.

RATIONALE: Genetic diversity endows species with abundant genetic resources and plays a pivotal role in shaping their capacity to adapt to new environments. To elucidate the genetic diversity of *B. densiflorum* and evaluate the influence of climate change on its genetic variation, reduced-representation genome sequencing technology was employed to obtain single nucleotide polymorphisms (SNPs), and subsequently population genetics and landscape genetics together with species distribution modelling were analyzed.

RESULTS: *B. densiflorum* had a moderate level of genetic diversity. Six populations were divided into two groups, and there was moderate differentiation ($F_{ST}=0.102$) and high gene flow ($Nm=2.442$) between them. Genotype-environment association analysis indicated that the two groups were diverged attributable to local adaptation to the climate. Temperature differences and low-temperature regimes interacting together with precipitation gave rise to genetic variation of this species. In total, 544 adaptive loci were identified, which displayed significant correlations with temperature difference, low-temperature factors (Bio2, Bio6, Bio11, and Bio7), and precipitation factors (Bio19). *B. densiflorum* migrated evidently

northward from the Last Glacial Maximum to the current, with its distribution area increased by 89.5%. However, during the period from 2061 to 2080, the extent of the suitable area for this species will be contracted, and there will be partial degradation and fragmentation occurring in highly suitable areas within Anhui Province.

CONCLUSION: *B. densiflorum* showed a moderate level of genetic diversity and a moderate degree of genetic differentiation. Local adaptation drove the formation of the current genetic pattern of *B. densiflorum*, and temperature differences, low-temperature, and precipitation led to genetic variation. *B. densiflorum* has evidently migrated northward from the Last Glacial Maximum to the current with increase of distribution area. However, niche modelling indicated that during the period from 2061 to 2080, the suitable habitat area of *B. densiflorum* would be contracted, with partial degradation and fragmentation occurring in highly suitable areas within Anhui Province. These results provide the basis for conservation and utilization of *B. densiflorum*.



Population genetic structure analysis of *Brachystachyum densiflorum*

Key words *Brachystachyum densiflorum*, reduced-representation genome sequencing, genetic diversity, genetic structure, species distribution model

Zhang RL, Li DZ, Zhang YX (2025). Population genetic structure and climate adaptation analysis of *Brachystachyum densiflorum*. *Chin Bull Bot* 60, 407–424.

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附表1 从短穗竹采样地点经纬度提取的气候数据

Appendix table 1 Climate data extracted from latitude and longitude of the sampled sites of *Brachystachyum densiflorum*

附表2 19个气候因子相关性分析

Appendix table 2 Correlation analysis of 19 climate factors

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Appendix table 9 The potential distribution area of *Brachystachyum densiflorum* under different periods

附图1 SNP转换与颠换统计

Appendix figure 1 Transition and transversion statistics of SNP

附图2 MaxEnt模型中的ROC预测

Appendix figure 2 Prediction of the ROC in the MaxEnt model

附图3 气候变量对短穗竹潜在分布模型的Jackknife检验得分

Appendix figure 3 Jackknife test scores of climate variables on potential distribution model of *Brachystachyum densiflorum*

<https://www.chinbullbotany.com/fileup/1674-3466/PDF/24-094-1.pdf>



扫一扫看附表和附图

附表1 从短穗竹采样地点经纬度提取的气候数据

Appendix table 1 Climate data extracted from latitude and longitude of the sampled sites of *Brachystachyum densiflorum*

Sample	Population	Longitude (°E)	Latitude (°N)	Bio1	Bio10	Bio11	Bio12	Bio13	Bio14	Bio15	Bio16	Bio17	Bio18	Bio19	Bio2	Bio3	Bio4	Bio5	Bio6	Bio7	Bio8	Bio9
12040	AHGD	119.4011	30.9003	15.80833340	26.53333282	4.533333302	1220	198	32	50.96058273	498	127	495	143	8.266666412	25.67287636	894.3124390	31.60000038	-0.600000024	32.200000076	24.21666718	6.633333206
12041	AHGD	119.3391	30.8479	15.59166622	26.18333244	4.483333111	1244	200	33	49.88211823	504	130	494	146	8.416666985	26.13871574	881.3982544	31.299999924	-0.899999976	32.200000076	23.85000038	6.533333302
12048	AHGD	119.2622	30.6995	15.72083282	26.23333359	4.633333206	1275	207	34	49.42464447	517	132	494	150	8.258333206	25.80729294	877.1168213	31.399999962	-0.600000024	32.000000000	23.95000076	6.683333397
12050	AHGD	119.2428	30.7687	15.79583359	26.36666679	4.666666508	1255	205	33	50.05082321	512	129	492	145	8.225000381	25.70312500	881.0852051	31.500000000	-0.500000000	32.000000000	24.04999924	6.733333111
12051	AHGD	119.1466	30.7519	15.72916698	26.33333206	4.533333302	1267	205	33	49.21348190	514	132	490	147	8.475000381	26.31987572	884.8817139	31.500000000	-0.699999988	32.200000076	24.01666641	6.599999905
12053	AHGD	119.1686	30.7116	15.74583340	26.31666565	4.583333015	1274	206	34	49.15116501	516	132	491	149	8.341666222	25.98649979	881.7839966	31.500000000	-0.600000024	32.099999847	24.00000000	6.650000095
12056	AHGD	119.1708	30.7891	15.76249981	26.33333397	4.583333492	1257	205	33	49.46453094	511	130	489	146	7.991666794	25.13102722	883.0245361	31.399999962	-0.400000006	31.799999924	24.03333282	6.683333397
12059	AHGD	119.2115	30.9448	15.87500000	26.60000038	4.599999905	1208	195	32	49.30416489	489	128	477	141	8.250000000	25.54179573	894.4818115	31.700000076	-0.600000024	32.299999924	24.28333282	6.699999809
12063	AHGD	119.2585	30.9278	15.80416679	26.51666641	4.533333302	1211	195	32	49.45672989	490	128	479	142	8.191666603	25.43995857	893.8259277	31.500000000	-0.699999988	32.200000076	24.18333435	6.633333206
12065	AHYX	116.3525	30.8475	14.89166641	25.46666718	3.883333206	1530	267	31	56.14744568	659	134	659	134	8.716666222	27.41090202	878.0190430	30.500000000	-1.299999952	31.799999924	25.46666718	3.883333206
12074	AHYX	116.2825	30.8813	14.52083302	25.01666641	3.566666603	1517	261	31	55.83609009	651	133	651	133	8.658332825	27.31335449	870.8576050	30.000000000	-1.700000048	31.700000076	25.01666641	3.566666603
12077	AHYX	116.2406	30.9171	13.93750000	24.35000038	3.083333254	1523	260	31	55.91870499	656	134	656	134	8.608333588	27.41507339	863.6000977	29.200000076	-2.200000048	31.40000153	24.35000038	3.083333254
12079	AHYX	116.1017	31.0654	13.25416660	23.58333397	2.400000095	1504	245	31	55.90260696	655	133	655	133	8.324999809	26.68269157	858.9117432	28.399999962	-2.799999952	31.199999886	23.58333397	2.400000095
12080	AHYX	116.3548	30.8516	14.89166641	25.43333435	3.900000095	1521	265	31	56.01321030	653	133	653	133	8.733333588	27.46331215	875.7745972	30.500000000	-1.299999952	31.799999924	25.43333435	3.900000095
12084	AHYX	116.2196	30.9519	13.96666622	24.36666679	3.100000143	1513	256	31	55.75383377	652	133	652	133	8.650000572	27.46031761	862.7264404	29.299999924	-2.200000048	31.500000000	24.36666679	3.100000143
12087	AHYX	116.1774	30.9559	14.07083321	24.50000000	3.183333397	1503	253	31	55.83724213	649	133	649	133	8.641666412	27.43386269	864.3980103	29.399999962	-2.099999905	31.500000000	24.50000000	3.183333397
12090	AHHS	116.4765	31.4377	15.73750019	26.48333359	4.483333111	1276	184	28	49.98061752	529	121	529	121	9.058333397	27.61686897	892.8735962	31.700000076	-1.100000024	32.799999924	26.48333359	4.483333111
12092	AHHS	116.4821	31.427	15.72916698	26.48333359	4.483333111	1281	183	28	49.90797043	530	121	530	121	9.074999809	27.66768265	893.4699097	31.700000076	-1.100000024	32.799999924	26.48333359	4.483333111
12095	AHHS	116.3424	31.4118	15.90000057	26.68333435	4.549999714	1329	203	32	50.23246765	557	133	557	133	9.349999428	28.16265106	896.9975586	32.000000000	-1.200000048	33.200000076	26.68333435	4.549999714
12098	AHHS	116.4751	31.3257	14.99166679	25.58333397	4.000000000	1366	205	28	52.06966400	576	122	576	122	8.466667175	26.70872688	875.1696777	30.60000038	-1.100000024	31.700000076	25.58333397	4.000000000
12105	JSLY	119.499	31.2177	15.46249962	26.14999962	4.300000191	1152	185	31	50.88801575	476	124	476	134	8.008333206	25.10449219	886.6923218	31.100000038	-0.800000012	31.899999962	26.14999962	6.450000286
12108	JSLY	119.4373	31.2462	15.58749962	26.31666565	4.349999905	1141	182	31	49.96936417	466	123	466	132	8.158333778	25.41536903	891.9109497	31.299999924	-0.800000012	32.099999847	26.31666565	6.483333588
12110	JSLY	119.4892	31.269	15.26666641	25.93333244	4.083333492	1150	184	31	50.81145477	476	123	476	133	7.949999809	25.00000000	887.0772705	30.799999924	-1.000000000	31.799999924	25.93333244	6.233333111
12112	JSYX	119.8005	31.2747	15.85000038	26.66666794	4.583333492	1106	181	33	53.72935104	476	122	476	138	7.866666794	24.58333397	897.7218628	31.60000038	-0.400000006	32.000000000	26.66666794	6.799999714
12114	JSYX	119.7113	31.2797	15.66250038	26.38333321	4.466666698	1102	179	31	52.78942490	468	119	468	133	7.841666698	24.58202744	890.4368896	31.299999924	-0.600000024	31.899999962	26.38333321	6.683333397
12117	JSYX	119.7123	31.3141	15.49166679	26.18333244	4.333333492	1101	179	31	52.95930099	469	118	469	131	7.633333206	24.15611839	887.5677490	31.000000000	-0.600000024	31.60000038	26.18333244	6.533333302
12120	JSYX	119.8445	31.2546	15.91666698	26.70000076	4.650000095	1143	185	37	53.50419998	498	128	498	152	7.699999809	24.13792992	897.2086182	31.60000038	-0.300000012	31.899999962	26.70000076	11.750000000
12122	JSYX	119.8745	31.3205	15.86250019	26.66666603	4.616666794	1079	175	34	53.04386902	463	120	463	139	7.558333397	23.84332275	896.9218140	31.299999924	-0.400000006	31.699999886	26.66666603	11.733333590
12123	JSYX	119.8708	31.2178	15.78750038	26.46666718	4.599999905	1101	181	33	54.19209671	476	119	476	140	7.324999809	23.32802391	889.6171875	31.200000076	-0.200000003	31.40000153	26.46666718	11.716666220
12132	JSYX	119.8704	31.1876	15.69999981	26.33333397	4.566666603	1096	181	32	54.63258743	473	117	473	137	7.333333492	23.42918015	885.6020508	31.10000038	-0.200000003	31.30000114	26.33333210	11.633333210
12133	JSYX	119.7359	31.3788	15.78750038	26.61666679	4.516666889	1076	173	34	50.88619614	450	124	450	135	7.691666126	24.18762970	898.8050537	31.399999962	-0.400000006	31.799999924	26.61666679	6.699999809
12136	JSYX	119.7789	31.2532	15.65833282	26.43333244	4.449999809	1103	181	32	53.85558701	474	119	474	134	7.883333206	24.71264458	893.7379150	31.299999924	-0.600000024	31.899999962	26.43333244	6.666666508
12137	JSYX	119.7844	31.324	15.64166641	26.39999962	4.416666508	1094	177	32	53.30795670	470	119	470	134	7.633333206	24.07991600	894.1268921	31.200000076	-0.500000000	31.700000076	26.39999962	6.650000095
12125	ZJCX	119.8801	31.1483	15.25833321	25.85000038	4.199999809	1118	186	31	56.16527176	488	117	488	134	7.433333397	23.82478714	880.3894653	30.60000038	-0.600000024	31.200000076	25.85000038	11.199999810
12128	ZJCX	119.8797	31.1215	15.69166660	26.39999962	4.549999714	1111	186	31	56.08693314	484	116	484	135	7.633333206	24.23280334	888.6297607	31.200000076	-0.300000012	31.500000000	26.39999962	11.5500000190
12130	ZJCX	119.8661	31.1004	15.66666698	26.41666603	4.483333111	1117	188	31	56.16132736	486	117	486	135	7.799999714	24.52830124	891.4960327	31.299999924	-0.500000000	31.799999924	26.41666603	11.500000000

附表2 19个气候因子相关性分析

Appendix table 2 Correlation analysis of 19 climate factors

	Bio1	Bio10	Bio11	Bio12	Bio13	Bio14	Bio15	Bio16	Bio17	Bio18	Bio19	Bio2	Bio3	Bio4	Bio5	Bio6	Bio7	Bio8
Bio10	0.9957																	
Bio11	0.9949	0.984																
Bio12	-0.773	-0.793	-0.756															
Bio13	-0.793	-0.815	-0.767	0.9549														
Bio14	0.3449	0.3225	0.3503	-0.313	-0.175													
Bio15	-0.592	-0.565	-0.572	0.2872	0.4496	-0.156												
Bio16	-0.835	-0.846	-0.819	0.9787	0.9613	-0.318	0.4688											
Bio17	-0.47	-0.508	-0.464	0.8012	0.7839	0.2035	-0.099	0.7142										
Bio18	-0.851	-0.853	-0.84	0.9549	0.9399	-0.359	0.5309	0.9933	0.6516									
Bio19	0.324	0.2703	0.3488	-0.18	-0.057	0.8824	-0.286	-0.243	0.3373	-0.319								
Bio2	-0.328	-0.336	-0.342	0.7562	0.58	-0.427	-0.199	0.6638	0.6618	0.6383	-0.294							
Bio3	-0.505	-0.516	-0.51	0.8687	0.7201	-0.456	-0.047	0.7959	0.7146	0.7725	-0.317	0.9779						
Bio4	0.8931	0.9293	0.8502	-0.8	-0.825	0.2532	-0.445	-0.817	-0.563	-0.793	0.0951	-0.334	-0.512					
Bio5	0.9838	0.9803	0.9728	-0.68	-0.735	0.2765	-0.657	-0.761	-0.379	-0.78	0.2745	-0.163	-0.354	0.8841				
Bio6	0.9247	0.9167	0.9387	-0.855	-0.794	0.4251	-0.37	-0.872	-0.599	-0.882	0.3863	-0.627	-0.75	0.7957	0.8494			
Bio7	0.5112	0.5162	0.4705	-0.042	-0.234	-0.094	-0.698	-0.168	0.1535	-0.191	-0.042	0.5976	0.4172	0.5103	0.65	0.151		
Bio8	0.3913	0.4555	0.3626	-0.551	-0.549	-0.116	0.2097	-0.436	-0.717	-0.348	-0.458	-0.339	-0.41	0.6126	0.358	0.4111	0.0786	
Bio9	0.6035	0.602	0.6206	-0.77	-0.651	0.462	0.0687	-0.702	-0.641	-0.687	0.3826	-0.788	-0.838	0.5379	0.4766	0.7761	-0.225	0.4273

附表3 短穗竹分布位置筛选

Appendix table 3 Screening of the distribution of *Brachystachyum densiflorum*

No.	Species	Longitude (°E)	Latitude (°N)	Locality
1	<i>Brachystachyum densiflorum</i>	116.10171	31.06538	Riverside, Baojia, Yuexi County, Anqing City, Anhui Province
2	<i>Brachystachyum densiflorum</i>	116.17741	30.95594	Heping Village, Yuexi County, Anqing City, Anhui Province
3	<i>Brachystachyum densiflorum</i>	116.21958	30.95190	Banzhu Village, Laibang Town, Yuexi County, Anqing City, Anhui Province
4	<i>Brachystachyum densiflorum</i>	116.24063	30.91715	Qingtian, Yuexi County, Anqing City, Anhui Province
5	<i>Brachystachyum densiflorum</i>	116.24713	30.93667	Shichong, Laibang Village, Yuexi County, Anqing City, Anhui Province
6	<i>Brachystachyum densiflorum</i>	116.27466	30.89595	Zhuwu, Lianyun Township, Yuexi County, Anqing City, Anhui Province
7	<i>Brachystachyum densiflorum</i>	116.28255	30.88129	Changsheng Village, Lianyun Township, Yuexi County, Anqing City, Anhui Province
8	<i>Brachystachyum densiflorum</i>	116.34244	31.41181	Yuerjie Town, Huoshan County, Liuan City, Anhui Province
9	<i>Brachystachyum densiflorum</i>	116.35252	30.84748	Dabieshan Martyrs Cemetery, Tiantang Township, Yuexi County, Anqing City, Anhui Province
10	<i>Brachystachyum densiflorum</i>	116.35475	30.85156	Road from Baojia to Hongshan, Yuexi County, Anqing City, Anhui Province
11	<i>Brachystachyum densiflorum</i>	116.37830	30.85594	Zhongxing Alley, Tiantang Town, Yuexi County, Anqing City, Anhui Province
12	<i>Brachystachyum densiflorum</i>	116.45329	31.39237	Yuerjie Town, Huoshan County, Liuan City, Anhui Province
13	<i>Brachystachyum densiflorum</i>	116.47506	31.32572	Siguchong, Yuerjie Town, Huoshan County, Liuan City, Anhui Province
14	<i>Brachystachyum densiflorum</i>	116.47649	31.43766	Huashizui Village, Danjiangmiao Town, Huoshan County, Liuan City, Anhui Province
15	<i>Brachystachyum densiflorum</i>	116.47832	31.40469	Baifuan Village, Yuerjie Town, Huoshan County, Liuan City, Anhui Province
16	<i>Brachystachyum densiflorum</i>	116.48207	31.42703	Shanwanghe, Yuerjie Town, Huoshan County, Liuan City, Anhui Province
17	<i>Brachystachyum densiflorum</i>	116.48679	31.32955	Road from Yuerjie to Siguchong, Huoshan County, Liuan City, Anhui Province
18	<i>Brachystachyum densiflorum</i>	117.96098	29.90626	Qiaotou, Yuting Town, Yi County, Huangshan City, Anhui Province
19	<i>Brachystachyum densiflorum</i>	119.14662	30.75194	Jinyang Village, Yangtan Township, Guangde, Xuancheng City, Anhui Province
20	<i>Brachystachyum densiflorum</i>	119.16861	30.71156	Yuewan Village, Yangtan Township, Guangde, Xuancheng City, Anhui Province
21	<i>Brachystachyum densiflorum</i>	119.17076	30.78908	Dushu Village, Yangtan Township, Guangde, Xuancheng City, Anhui Province
22	<i>Brachystachyum densiflorum</i>	119.17367	30.72585	Sanhe Village, Yangtan Township, Guangde, Xuancheng City, Anhui Province
23	<i>Brachystachyum densiflorum</i>	119.18028	30.71557	Dushu Middle School, Yangtan Township, Guangde, Xuancheng City, Anhui Province
24	<i>Brachystachyum densiflorum</i>	119.21149	30.94481	Su Village, Shijie Town, Guangde, Xuancheng City, Anhui Province
25	<i>Brachystachyum densiflorum</i>	119.22326	30.94826	Xiangsheng Village, Shijie Town, Guangde, Xuancheng City, Anhui Province
26	<i>Brachystachyum densiflorum</i>	119.23578	30.74192	Daliu Village, Sihe Township, Guangde, Xuancheng City, Anhui Province
27	<i>Brachystachyum densiflorum</i>	119.24278	30.76866	Qiancheng Village, Baidian Town, Guangde, Xuancheng City, Anhui Province
28	<i>Brachystachyum densiflorum</i>	119.24753	30.74460	Yujiaba, Baidian Town, Guangde, Xuancheng City, Anhui Province
29	<i>Brachystachyum densiflorum</i>	119.25444	30.77231	Government of Baidian Town, Guangde, Xuancheng City, Anhui Province
30	<i>Brachystachyum densiflorum</i>	119.25850	30.92781	Dongxing Village, Shijie Town, Guangde, Xuancheng City, Anhui Province
31	<i>Brachystachyum densiflorum</i>	119.26223	30.69946	Fuling Village, Sihe Township, Guangde, Xuancheng City, Anhui Province
32	<i>Brachystachyum densiflorum</i>	119.30130	30.98318	Zhenruan Village, Shijie Town, Guangde, Xuancheng City, Anhui Province
33	<i>Brachystachyum densiflorum</i>	119.31221	30.92314	Huagu Village, Shijie Town, Guangde, Xuancheng City, Anhui Province
34	<i>Brachystachyum densiflorum</i>	119.33911	30.84794	Shixianglou Village, Baidian Town, Guangde, Xuancheng City, Anhui Province
35	<i>Brachystachyum densiflorum</i>	119.40111	30.90033	Tuanshan, Taozhou Town, Guangde, Xuancheng City, Anhui Province
36	<i>Brachystachyum densiflorum</i>	119.41913	31.41460	Dashishan, Liyang, Changzhou City, Jiangsu Province
37	<i>Brachystachyum densiflorum</i>	119.43728	31.24621	Nanzhu Village, Daibu Town, Liyang, Changzhou City, Jiangsu Province
38	<i>Brachystachyum densiflorum</i>	119.48919	31.26904	Longtan Forestry Farm, Liyang, Changzhou City, Jiangsu Province
39	<i>Brachystachyum densiflorum</i>	119.49151	31.42210	Qingfengshan, Liyang, Changzhou City, Jiangsu Province
40	<i>Brachystachyum densiflorum</i>	119.49875	31.31596	Dainan Village, Daibu Town, Liyang, Changzhou City, Jiangsu Province
41	<i>Brachystachyum densiflorum</i>	119.49904	31.21772	Heluogang, Hengjian Town, Liyang, Changzhou City, Jiangsu Province
42	<i>Brachystachyum densiflorum</i>	119.71134	31.27971	Furong Village, Zhangzhu Town, Yixing, Wuxi City, Jiangsu Province
43	<i>Brachystachyum densiflorum</i>	119.71225	31.31412	Guijing Village, Yixing, Wuxi City, Jiangsu Province
44	<i>Brachystachyum densiflorum</i>	119.73589	31.37883	Jianbei Village, Hufu Town, Yixing, Wuxi City, Jiangsu Province

附表 3 (续)

Appendix table 3 (continued)

No.	Species	Longitude (°)	Latitude (°)	Locality
45	<i>Brachystachyum densiflorum</i>	119.77894	31.25317	Zhanggongdong, Hufu Town, Yixing, Wuxi City, Jiangsu Province
46	<i>Brachystachyum densiflorum</i>	119.78443	31.32403	Meiyuan Village, Yixing, Wuxi City, Jiangsu Province
47	<i>Brachystachyum densiflorum</i>	119.80051	31.27473	Jiangli Village, Dingshu Town, Yixing, Wuxi City, Jiangsu Province
48	<i>Brachystachyum densiflorum</i>	119.80345	31.33395	Longbeishan Forest Park, Yixing, Wuxi City, Jiangsu Province
49	<i>Brachystachyum densiflorum</i>	119.83161	31.34296	Miaogan, Hufu Town, Yixing, Wuxi City, Jiangsu Province
50	<i>Brachystachyum densiflorum</i>	119.84448	31.25460	Nanzhong Village, Yicheng, Yixing, Wuxi City, Jiangsu Province
51	<i>Brachystachyum densiflorum</i>	119.86611	31.10038	Liuwu, Shuikou Township, Changxing County, Huzhou City, Zhejiang Province
52	<i>Brachystachyum densiflorum</i>	119.87045	31.18765	Shangba Village, Dingshu Town, Yixing, Wuxi City, Jiangsu Province
53	<i>Brachystachyum densiflorum</i>	119.87077	31.21778	Fudong Village, Yixing, Wuxi City, Jiangsu Province
54	<i>Brachystachyum densiflorum</i>	119.87449	31.32049	Linjia Village, Dingshu Town, Yixing, Wuxi City, Jiangsu Province
55	<i>Brachystachyum densiflorum</i>	119.87722	31.10442	Chenqiling Village, Shuikou Township, Changxing County, Huzhou City, Zhejiang Province
56	<i>Brachystachyum densiflorum</i>	119.87970	31.12146	Longshan Village, Jiapu Town, Changxing County, Huzhou City, Zhejiang Province
57	<i>Brachystachyum densiflorum</i>	119.88013	31.14832	Beichuan Village, Jiapu Town, Changxing County, Huzhou City, Zhejiang Province
58	<i>Brachystachyum densiflorum</i>	119.94039	31.14168	Xiangshan Village, Jiapu Town, Changxing County, Huzhou City, Zhejiang Province
59*	<i>Brachystachyum densiflorum</i>	117.53830	25.00886	Huaan County, Zhangzhou City, Fujian Province
60*	<i>Brachystachyum densiflorum</i>	114.51374	30.51200	Hubei Academy of Forestry, Wuhan City, Hubei Province
61*	<i>Brachystachyum densiflorum</i>	114.57207	28.55193	Xihe, Huanggang Town, Yifeng County, Yichun City, Jiangxi Province
62*	<i>Brachystachyum densiflorum</i>	114.62854	28.51962	Lijiaping, Huanggang Town, Yifeng County, Yichun City, Jiangxi Province
63*	<i>Brachystachyum densiflorum</i>	115.10744	29.26235	Zhaili, Shimenlou Town, Wuning County, Jiujiang City, Jiangxi Province
64*	<i>Brachystachyum densiflorum</i>	115.45340	29.58835	Qingshan Forestry Farm, Ruichang, Jiujiang City, Jiangxi Province
65*	<i>Brachystachyum densiflorum</i>	118.76637	28.00567	Xitoushan, Baoxi Township, Longquan, Zhejiang Province
66*	<i>Brachystachyum densiflorum</i>	118.86145	32.05974	Sun Yat-sen Mausoleum, Nanjing City, Jiangsu Province
67*	<i>Brachystachyum densiflorum</i>	119.06219	32.15528	Baohuashan, Zhenjiang, Nanjing City, Jiangsu Province
68*	<i>Brachystachyum densiflorum</i>	119.44917	31.25010	Huanggangling, Daibu Town, Liyang, Changzhou City, Jiangsu Province
69*	<i>Brachystachyum densiflorum</i>	119.67473	31.30946	Shanjuan Village, Yixing, Wuxi City, Jiangsu Province
70*	<i>Brachystachyum densiflorum</i>	119.81859	28.21943	Liandufengyuan, Lishui City, Zhejiang Province
71*	<i>Brachystachyum densiflorum</i>	119.87486	30.08784	Xinlian Village, Fuyang District, Hangzhou City, Zhejiang Province
72*	<i>Brachystachyum densiflorum</i>	120.10722	30.24302	Feilaifeng, Xihu District, Hangzhou City, Zhejiang Province
73*	<i>Brachystachyum densiflorum</i>	120.11749	30.26585	Lingfeng Hill, Xihu District, Hangzhou City, Zhejiang Province
74*	<i>Brachystachyum densiflorum</i>	120.12464	30.25978	Hangzhou Botanical Garden, Xihu District, Hangzhou City, Zhejiang Province
75*	<i>Brachystachyum densiflorum</i>	120.15064	30.26722	Baoshi Hill, Xihu District, Hangzhou City, Zhejiang Province
76*	<i>Brachystachyum densiflorum</i>	120.23341	31.52977	Huishan, Binhu District, Wuxi City, Jiangsu Province
77*	<i>Brachystachyum densiflorum</i>	120.29155	31.53464	Huishan, Binhu District, Wuxi City, Jiangsu Province
78*	<i>Brachystachyum densiflorum</i>	122.39001	29.98963	Putuo Hill, Putuo District, Zhoushan City, Zhejiang Province
79*	<i>Brachystachyum densiflorum</i>	110.60000	30.20000	Wufeng Tujia Autonomous County, Hubei Province
80*	<i>Brachystachyum densiflorum</i>	111.27000	30.70000	Xiling District, Yichang City, Hubei Province
81*	<i>Brachystachyum densiflorum</i>	115.35000	28.87000	Jingan County, Jiangxi Province
82*	<i>Brachystachyum densiflorum</i>	116.52573	27.21845	Nanfeng County, Jiangxi Province
83*	<i>Brachystachyum densiflorum</i>	118.13000	30.30000	Huangshan City, Anhui Province
84*	<i>Brachystachyum densiflorum</i>	118.79000	32.05000	Nanjing City, Jiangsu Province
85*	<i>Brachystachyum densiflorum</i>	119.05000	27.62000	Qingyuan County, Zhejiang Province
86*	<i>Brachystachyum densiflorum</i>	119.13000	28.08000	Longquan, Zhejiang Province
87*	<i>Brachystachyum densiflorum</i>	119.17000	31.95000	Jurong, Jiangsu Province
88*	<i>Brachystachyum densiflorum</i>	119.27000	28.60000	Suichang County, Zhejiang Province

附表 3 (续)

Appendix table 3 (continued)

No.	Species	Longitude (°)	Latitude (°)	Locality
89*	<i>Brachystachyum densiflorum</i>	119.67000	29.80000	Tonglu County, Zhejiang Province
90*	<i>Brachystachyum densiflorum</i>	119.68000	30.63000	Anji County, Zhejiang Province
91*	<i>Brachystachyum densiflorum</i>	119.82000	31.35000	Yixing, Jiangsu Province
92*	<i>Brachystachyum densiflorum</i>	119.82000	31.37000	Yixing, Jiangsu Province
93*	<i>Brachystachyum densiflorum</i>	119.91000	28.45000	Lishui City, Zhejiang Province
94*	<i>Brachystachyum densiflorum</i>	120.05258	29.16551	Zhejiang Province
95*	<i>Brachystachyum densiflorum</i>	120.17000	30.27000	Hangzhou City, Zhejiang Province
96*	<i>Brachystachyum densiflorum</i>	120.17297	30.27398	Hangzhou City, Zhejiang Province
97*	<i>Brachystachyum densiflorum</i>	120.25000	33.78000	Sheyang County, Jiangsu Province
98*	<i>Brachystachyum densiflorum</i>	122.30000	29.95000	Putuo District, Zhoushan City, Zhejiang Province
99#	<i>Brachystachyum densiflorum</i>	119.66723	30.59700	Anji Bamboo Expo Park, Anji, Huzhou City, Zhejiang Province
100#	<i>Brachystachyum densiflorum</i>	119.60398	30.27218	Taihu Yuan Town, Lin'an District, Hangzhou City, Zhejiang Province
101#	<i>Brachystachyum densiflorum</i>	118.29374	32.28648	Langya Hill, Langya District, Chuzhou City, Anhui Province
102#	<i>Brachystachyum densiflorum</i>	118.64335	30.25012	Jiaotou Village, Qiaotou Township, Jixi County, Xuancheng City, Anhui Province
103#	<i>Brachystachyum densiflorum</i>	121.12587	29.74195	Lizhou, Simingshan Town, Yuyao, Ningbo City, Zhejiang Province
104#	<i>Brachystachyum densiflorum</i>	119.77319	28.18750	Dashanfeng, Dagangtou Town, Liandu District, Lishui City, Zhejiang Province
105#	<i>Brachystachyum densiflorum</i>	119.06508	32.06474	Tangshan, Jiangning District, Nanjing City, Jiangsu Province
106#	<i>Brachystachyum densiflorum</i>	117.49942	27.34647	Shaowu, Nanping City, Fujian Province
107#	<i>Brachystachyum densiflorum</i>	117.18260	26.90566	Taining County, Sanming City, Fujian Province
108#	<i>Brachystachyum densiflorum</i>	118.23866	25.65596	Daiyunshan, Chishui Town, Dehua County, Quanzhou City, Fujian Province
109#	<i>Brachystachyum densiflorum</i>	119.50663	30.13691	Baima Village, Wanshi Town, Fuyang District, Hangzhou City, Zhejiang Province
110#	<i>Brachystachyum densiflorum</i>	119.91473	30.17875	Kengxi Village, Yinhu Street, Fuyang District, Hangzhou City, Zhejiang Province
111#	<i>Brachystachyum densiflorum</i>	116.80000	29.96667	Dahaoshan, Pengze County, Jiujiang City, Jiangxi Province
112#	<i>Brachystachyum densiflorum</i>	118.60218	32.05628	Laoshan, Pukou District, Nanjing City, Jiangsu Province
113#	<i>Brachystachyum densiflorum</i>	117.46667	30.00417	Guniujiang, Dayan Township, Shitai County, Chizhou City, Anhui Province
114#	<i>Brachystachyum densiflorum</i>	119.40480	30.91390	Hengshan National Forestry Park, Guangde, Xuancheng City, Anhui Province
115#	<i>Brachystachyum densiflorum</i>	120.14228	30.22178	Siyanjing, Xihu District, Hangzhou City, Zhejiang Province
116#	<i>Brachystachyum densiflorum</i>	117.16972	31.83472	Shushan National Forestry Park, Shushan District, Hefei City, Anhui Province
117#	<i>Brachystachyum densiflorum</i>	112.81638	31.10892	Dakou Forestry Farm, Zhongxiang, Jingmen City, Hubei Province
118#	<i>Brachystachyum densiflorum</i>	113.03257	31.41574	Qijia Village, Lvlin Town, Jingshan County, Hubei Province
119#	<i>Brachystachyum densiflorum</i>	108.98680	29.51180	Pingbaying National Forestry Park, Xianfeng County, Shi'en, Hubei Province
120#	<i>Brachystachyum densiflorum</i>	120.02457	30.66433	Shangqiang Village, Dixi Town, Wuxing District, Huzhou City, Zhejiang Province
121#	<i>Brachystachyum densiflorum</i>	118.18333	30.16667	Mount Huang, Huangshan City, Anhui Province
122#	<i>Brachystachyum densiflorum</i>	119.46660	29.21404	Zhizhe Temple, Jinhuashan, Lanxi, Jinhua City, Zhejiang Province
123#	<i>Brachystachyum densiflorum</i>	118.78550	32.11542	Mufu Hill, Gulou District, Nanjing City, Jiangsu Province
124#	<i>Brachystachyum densiflorum</i>	118.85989	32.07610	Zijin Hill, Xuanwu District, Nanjing City, Jiangsu Province
125#	<i>Brachystachyum densiflorum</i>	119.33254	31.72664	Shijiashan, Jintan District, Changzhou City, Jiangsu Province
126#	<i>Brachystachyum densiflorum</i>	119.48220	31.21807	Huijia Village, Liyang, Changzhou City, Jiangsu Province
127#	<i>Brachystachyum densiflorum</i>	119.50082	31.27310	Longtan Forestry Farm, Liyang, Changzhou City, Jiangsu Province
128#	<i>Brachystachyum densiflorum</i>	119.70464	31.22265	Longchi Hill, Yixing, Wuxi City, Jiangsu Province
129#	<i>Brachystachyum densiflorum</i>	119.74066	31.24854	Xiaoheigou, Yixing, Wuxi City, Jiangsu Province
130#	<i>Brachystachyum densiflorum</i>	117.73333	29.68333	Tongkuang District, Dexing, Shangrao City, Jiangxi Province
131#	<i>Brachystachyum densiflorum</i>	117.73333	28.16667	Yongpingkuangqu, Hekou Town, Qianshan County, Shangrao City, Jiangxi Province
132#	<i>Brachystachyum densiflorum</i>	119.19615	32.12957	Kongqing Hill, Baorong, Zhenjiang City, Jiangsu Province

附表 3 (续)

Appendix table 3 (continued)

No.	Species	Longitude (°)	Latitude (°)	Locality
133#	<i>Brachystachyum densiflorum</i>	119.25470	34.65050	Jiulong Bridge, Huaguoshan, Haizhou District, Lianyungang City, Jiangsu Province
134#	<i>Brachystachyum densiflorum</i>	117.75000	29.56667	Liugujian, Hecheng Township, Xiuning County, Huangshan City, Anhui Province
135#	<i>Brachystachyum densiflorum</i>	113.82741	28.97467	Mubu Hill, Nanjiang Town, Yueyang City, Hunan Province
136#	<i>Brachystachyum densiflorum</i>	118.56057	30.72310	Caicun Town, Jing County, Xuancheng City, Anhui Province
137#	<i>Brachystachyum densiflorum</i>	119.90775	30.60552	Mogan Hill, Deqing County, Huzhou City, Zhejiang Province
138#	<i>Brachystachyum densiflorum</i>	118.88207	32.10619	Jubao Hill, Xuanwu District, Nanjing City, Jiangsu Province
139#	<i>Brachystachyum densiflorum</i>	119.82257	28.89824	Niutou Hill, Wuyi County, Jinhua City, Zhejiang Province
140#	<i>Brachystachyum densiflorum</i>	118.16161	29.26142	Gutian Hill, Suzhuang Town, Kaihua County, Quzhou City, Zhejiang Province
141#	<i>Brachystachyum densiflorum</i>	119.06949	27.62543	Qingyuan County, Lishui City, Zhejiang Province
142#	<i>Brachystachyum densiflorum</i>	120.39901	31.28823	Qionglong Hill, Guangfu Town, Wuzhong District, Suzhou City, Jiangsu Province
143#	<i>Brachystachyum densiflorum</i>	118.14761	30.27865	Shilishan, Huangshan District, Huangshan City, Anhui Province
144#	<i>Brachystachyum densiflorum</i>	119.23333	31.98333	Xiashu Forest ecological Positioning Station, Jurong County, Jiangsu Province
145#	<i>Brachystachyum densiflorum</i>	119.48854	28.45506	Songyang County, Lishui City, Zhejiang Province
146#	<i>Brachystachyum densiflorum</i>	119.67712	31.30390	Zhuling Village, Zhangzhu Town, Yixing, Wuxi City, Jiangsu Province
147#	<i>Brachystachyum densiflorum</i>	120.63851	31.26826	Dongshan, Wuzhong District, Suzhou City, Jiangsu Province
148#	<i>Brachystachyum densiflorum</i>	119.49725	30.20635	Tianmu Mountains, Lin'an District, Hangzhou City, Zhejiang Province
149#	<i>Brachystachyum densiflorum</i>	116.47512	30.72245	Tianshu Mountain, Qianshan, Anqing City, Anhui Province
150#	<i>Brachystachyum densiflorum</i>	118.49223	32.73797	Tieshan Temple, Yangying Township, Xuyi County, Huaian City, Jiangsu Province
151#	<i>Brachystachyum densiflorum</i>	120.58863	31.24408	Shangfang Hill, Huqiu District, Suzhou City, Jiangsu Province
152#	<i>Brachystachyum densiflorum</i>	119.01667	31.60000	Wuxiang Temple Forestry Park, Lishui District, Nanjing City, Jiangsu Province
153#	<i>Brachystachyum densiflorum</i>	118.55000	32.96667	Tieshan Temple, Yangying Township, Xuyi County, Huaian City, Jiangsu Province
154#	<i>Brachystachyum densiflorum</i>	120.05455	28.89420	Yongkang, Jinhua City, Zhejiang Province
155#	<i>Brachystachyum densiflorum</i>	119.23806	32.60944	Youizshan National Forestry Park, Gaochun District, Nanjing City, Jiangsu Province
156#	<i>Brachystachyum densiflorum</i>	121.38107	29.94727	Dayin, Yuyao, Ningbo City, Zhejiang Province
157#	<i>Brachystachyum densiflorum</i>	118.78592	32.00887	Yuhuatai Martyrs Memorial Park, Yuhuatai District, Nanjing City, Jiangsu Province
158#	<i>Brachystachyum densiflorum</i>	120.70000	27.55000	Yucangshan Scenic Spot, Qiaodun Town, Cangnan County, Wenzhou City, Zhejiang Province
159#	<i>Brachystachyum densiflorum</i>	119.47285	28.05177	Yunhe Terraced Fields National Wetland Park, Yunhe County, Lishui City, Zhejiang Province
160#	<i>Brachystachyum densiflorum</i>	119.65254	29.13424	North Hill, Chisong Town, Jindong District, Jinhua City, Zhejiang Province
161#	<i>Brachystachyum densiflorum</i>	119.21612	27.93928	Fengyang Mountain, Longquan, Lishui City, Zhejiang Province
162#	<i>Brachystachyum densiflorum</i>	118.23333	29.33333	Gutian Mountain, Suzhuang Town, Kaihua County, Quzhou City, Zhejiang Province
163#	<i>Brachystachyum densiflorum</i>	120.30691	28.47262	Dayang Hill, Jinyun County, Lishui City, Zhejiang Province
164#	<i>Brachystachyum densiflorum</i>	119.73152	30.23981	Longtang Hill, Lin'an District, Hangzhou City, Zhejiang Province
165#	<i>Brachystachyum densiflorum</i>	120.45651	29.06010	Panan County, Jinhua City, Zhejiang Province
166#	<i>Brachystachyum densiflorum</i>	119.36667	28.33333	Ruoliaoxian Nature Reserve, Fengping Township, Songyang County, Lishui City, Zhejiang Province
167#	<i>Brachystachyum densiflorum</i>	121.01355	29.14951	Tiantai County, Taizhou City, Zhejiang Province
168#	<i>Brachystachyum densiflorum</i>	120.10293	29.69687	Wuxie Scenic Area, Wuxie Town, Zhuji, Shaoxing City, Zhejiang Province
169#	<i>Brachystachyum densiflorum</i>	120.75422	28.84754	Yong'an River, Xianju County, Zhejiang Province
170#	<i>Brachystachyum densiflorum</i>	120.91057	29.50554	Xinchang County, Shaoxing City, Zhejiang Province
171#	<i>Brachystachyum densiflorum</i>	119.04304	30.13598	Qingliang Hill, Lin'an District, Hangzhou City, Zhejiang Province
172#	<i>Brachystachyum densiflorum</i>	118.60965	32.10147	Maozi Hill, Pukou District, Nanjing City, Jiangsu Province
173#	<i>Brachystachyum densiflorum</i>	118.75020	31.90500	Niushou Hill, Jiangning District, Nanjing City, Jiangsu Province
174#	<i>Brachystachyum densiflorum</i>	118.97637	32.16387	Qixia Hill, Qixia District, Nanjing City, Jiangsu Province

Note: Information of localities 1-58 was from field investigation; *information of locality 59 was from National Specimen Information Infrastructure (NSII), information of localities 60-78 was from Chinese Virtual Herbarium (CVH), and information for localities 79-98 was from Global Biodiversity Information Facility (GBIF); # information of localities 99-174 was from literature that can be downloaded from China National Knowledge Infrastructure (CNKI) and references corresponding to these localities were listed as follows:

Locality No.	Reference title
99#	Study on chemical composition of culm and stem of 28 species of bamboo
100#	Relationship between nutrients of sheath blades and taste quality of bamboo shoots across 22 bamboo species from 6 genera
101#	Bamboo species and distribution in the east Anhui Province
102#	Bamboo species and distribution in Jixi County of Anhui Province
103#	Bamboo species and distribution in Jixi County of Anhui Province
104#	Current Situation and Countermeasure of Flower Industry in Zhejiang
105#	Eco-geographical distribution, biological characters of <i>Brachystachyum Kenq</i> and its conservation
106#	Economic Bamboo Resources in Fujian Province
107#	A Study on the Flora of Bambusoideae and Its Development in Fujian Province
108#	Mechanism of drought resistance and the bamboo shoots law of special bamboo in Fujian Province
109#	Current Status of Bamboo Diversity and Strategies for Its Conservation and Utilization in Fuyang
110#	Current Status of Bamboo Diversity and Strategies for Its Conservation and Utilization in Fuyang
111#	Investigation of rare and endangered plants in Dahao Mountain Jiangxi
112#	Comparing the Effectiveness of Birdwatching to Line Transect for Biodiversity Surveys: A Case Study of Laoshan, Nanjing
113#	Investigation and evaluation of wild ornamental plant resources in Guniujiang
114#	The Current preservation Status and Construction Countermeasures of the National Forest Tree Germplasm Resource Bank in Guangde County
115#	Report on the species of Poaceae in Hangzhou
116#	Investigation and Research on the Resources of Hefei Shushan Forest Park
117#	Study on the flora of vascular plant and wild plant resources of South Dahong Mountain
118#	Study on the flora of vascular plant and wild plant resources of South Dahong Mountain
119#	Study on the Flora of Seed Plants in Hubei Pingbaoying National Forest Park
120#	An old-growth community dominated by <i>Cinnamomum camphora</i> in Dabi Town of Huzhou City, China
121#	Vegetation of Mubunt Huang
122#	Landscape design of Sage Temple Scenic Spot in Jinhua Mountain based on health tourism
123#	Diversity, distribution, and conservation of rare and endangered plant species in Jiangsu Province
124#	Diversity, distribution, and conservation of rare and endangered plant species in Jiangsu Province
125#	Diversity, distribution, and conservation of rare and endangered plant species in Jiangsu Province
126#	Diversity, distribution, and conservation of rare and endangered plant species in Jiangsu Province
127#	Diversity, distribution, and conservation of rare and endangered plant species in Jiangsu Province
128#	Diversity, distribution, and conservation of rare and endangered plant species in Jiangsu Province
129#	Diversity, distribution, and conservation of rare and endangered plant species in Jiangsu Province
130#	The vegetation of Dexing Copper Mine Field in Jiangxi and their influences on environment
131#	Analysis of Vegetation Characteristics and Succession Patterns in Yongping Mining Area, Jiangxi Province
132#	Studies on community types and species diversity of secondary broad-leaved forests in Kongqing Mountain
133#	An investigation on Bamboo Species in Yuntai Mountain Scenery District of Lianyungang, Jiangsu Province
134#	The sustainable utilization and evaluation of plant resources in Liujuan Nature Reserve
135#	The Floristic Phytogeography of Spermatophyte Flora in Luoxiao Range
136#	Effects of simulated nitrogen deposition on vegetation diversity and nutrient characteristics of <i>Phyllanthus heterocyclos</i> cv. <i>pubescens</i> underforest vegetation
137#	Flora of Woody Plant in Mogao Mountain of Zhejiang Province
138#	Study on the niche of dominant population in Jubao Shan Forest Park in Nanjing
139#	The floristic analysis of seed plant in Mt. Niutou National Forest
140#	Status and analysis of rare and endangered plant resources in Gutianshan of Qianjiangyuan National Park, East China
141#	Resources and classification of wild timber tree species in Qingyuan County
142#	Research on the evaluation of aromatic plant resources and the construction of health care landscape in Qionglongshan Forest Park
143#	Study of vegetation on Mt. Shili in Anhui Province
144#	Studies on structure and dynamics characteristics of <i>Quercus variabilis</i> population
145#	Analysis and development suggestions of forest biodiversity protection in Songyang County
146#	A study of the conservation planning for the rare and risk plant species in Jiangsu, Zhejiang and Anhui Provinces
147#	Investigation on wild plants resources and analysis of landscape utilization value in East Mountain of Tai Lake
148#	Research on the planning and design of Tianmushan rare Botanical Garden
149#	Investigation and research on vegetation and seed plant diversity of Tianzhu Mountain
150#	An investigation of vascular plants resources in Tieshan National Forest Park
151#	Application of microhabitat construction method in the design of birds exhibition area of city zoo—a case study on the reconstruction design of bird exhibition area of Shuangfangshan Zoo in Suzhou
152#	Community characteristics of <i>Quercus acutissima</i> forest in Wuxiang Temple Forest Park
153#	Studies on flora of Tieshan Temple Nature Protection Area, Xuji and plant resources
154#	Woody Plant Resources in Yongkang
155#	Community Characteristics of <i>Cunninghamia lanceolata</i> Plantation at Mt. Youzi National Forest Park
156#	Exploitation and utilization of bamboo resources in Yuyao of Zhejiang
157#	A study on spatial structure and scenic beauty estimation of plant landscape in Yuhustai Martyrs Memorial Park
158#	Research on the optimization of forest plant landscape in Yucangshan Scenic Area
159#	Analysis of landscape forest resources in Yunhe Terrace National Wetland Park
160#	The plant resources of the Bei Mountain in Zhejiang Province and their development and utilization
161#	A floristic statistics and analysis of seed plants of Fengyangshan Nature Reserve in Zhejiang Province
162#	Spermatophyta flora of Gutianshan Nature Reserve in Zhejiang
163#	Resources of rare and precious plants of Lishui Ecological Demonstrative Area in Zhejiang Province
164#	A study on the floristic character of Mt. Longtangshan, Zhejiang Province
165#	Analysis on characteristics of Pan'an seed plants flora in Zhejiang Province
166#	The rare and endangered plants of Ruolaoxian Nature Reserve and their basic characteristics
167#	Floristic analysis on seed plants of Tiantai County in Zhejiang Province
168#	Typical Plant Community Evaluation of Wuxie Scenic Spot in Zhejiang
169#	Current situation and management strategy of bamboo resources in Yong'an River Basin in Xianju County of Zhejiang Province
170#	Wild ornamental plant resources in Xinchang, Zhejiang
171#	Multi-dimensional diversity pattern and assembly mechanism of endangered plant communities in Zhejiang Qinglangfeng Reserve
172#	The natural distribution and characteristics of the rare and endangered plants in Jiangsu, China
173#	The natural distribution and characteristics of the rare and endangered plants in Jiangsu, China
174#	The natural distribution and characteristics of the rare and endangered plants in Jiangsu, China

附表4 要素类型与正则化乘数

Appendix table 4 The feature combinations and the regularization multipliers

FC	RM	Delta.AICc	AICc	tune.args	auc.train	cbi.train	auc.diff.avg	auc.diff.sd	auc.val.avg	auc.val.sd	cbi.val.avg	cbi.val.sd	or.10p.avg	or.10p.sd	or.mtp.avg	or.mtp.sd	w.AIC	ncoef
LQ	1	0	2137.5076	fc.LQ_rm.1	0.9187896	0.92	0.218988481	0.154620213	0.70460665	0.1644653	0.5815	0.0294901	0.0984615	0.0492948	0.0096154	0.0192308	0.9999308	9
LQ	2	19.1592173	2156.6668	fc.LQ_rm.2	0.9111361	0.906	0.216189803	0.14990684	0.702437465	0.1601654	0.53325	0.2049038	0.0884615	0.0474934	0.0096154	0.0192308	6.91E-05	8
LQH	3	32.0816429	2169.5892	fc.LQH_rm.3	0.9125995	0.924	0.208504495	0.134887324	0.710005106	0.1464621	0.54575	0.1143864	0.0784615	0.0536774	0.01	0.02	1.08E-07	12
LQH	4	39.77289319	2177.2805	fc.LQH_rm.4	0.9092688	0.91	0.21180646	0.141179297	0.702071582	0.1546927	0.46175	0.1969896	0.0784615	0.0536774	0	0	2.31E-09	11
LQ	5	40.65321414	2178.1608	fc.LQH_rm.5	0.9075124	0.905	0.215303461	0.146157523	0.696569649	0.1590545	0.56	0.2208212	0.0684615	0.065627	0	0	1.49E-09	10
LQ	3	47.41359264	2184.9212	fc.LQ_rm.3	0.9040866	0.898	0.211728731	0.139905497	0.701620996	0.1506335	0.526	0.1508111	0.0884615	0.0474934	0.0096154	0.0192308	5.06E-11	9
LQH	2	50.73454913	2188.2421	fc.LQH_rm.2	0.9194995	0.937	0.209129381	0.13652723	0.714575126	0.145314	0.44375	0.2844203	0.0984615	0.0369231	0.01	0.02	9.62E-12	19
LQ	4	54.44056456	2191.9481	fc.LQ_rm.4	0.8998361	0.893	0.210382558	0.141385969	0.698996217	0.1516278	0.4815	0.2242209	0.0884615	0.0474934	0.0096154	0.0192308	1.51E-12	7
LQ	5	58.97688877	2196.4845	fc.LQ_rm.5	0.8984589	0.889	0.213443637	0.146772463	0.694393113	0.1566887	0.55175	0.1223966	0.0784615	0.0536774	0.0096154	0.0192308	1.56E-13	7
H	3	69.11969461	2206.6273	fc.H_rm.3	0.918951	0.951	0.132238551	0.079656293	0.788403328	0.0693501	0.50775	0.2736937	0.0692308	0.0501516	0	0	9.79E-16	23
H	5	81.38206582	2218.8896	fc.H_rm.5	0.9125609	0.968	0.130741864	0.08608497	0.797121376	0.0940214	0.4595	0.3273708	0.0582308	0.0395138	0	0	2.13E-18	13
H	2	92.54191547	2230.0495	fc.H_rm.2	0.9212649	0.959	0.141335454	0.076465782	0.782638986	0.067267	0.57775	0.2748362	0.0692308	0.0501516	0.01	0.02	8.03E-21	33
H	4	96.81341865	2234.321	fc.H_rm.4	0.9156926	0.935	0.123591319	0.091112338	0.794147277	0.0787682	0.5115	0.3040566	0.0592308	0.0395138	0	0	9.49E-22	24
H	1	130.971882	2268.4795	fc.H_rm.1	0.9272134	0.977	0.140795385	0.057232408	0.789858503	0.0515729	0.65525	0.3137912	0.0884615	0.0662492	0.02	0.023094	3.63E-29	33
LQH	1	139.0239976	2276.5316	fc.LQH_rm.1	0.9295688	0.98	0.159020345	0.039733088	0.772427024	0.0420703	0.54775	0.232216	0.1184615	0.0301999	0.0292308	0.0369658	6.48E-31	44
L	5	1018.296362	3155.8039	fc.L_rm.5	0.8824678	0.956	0.224554945	0.147011115	0.669459782	0.1520988	0.3945	0.2455884	0.1069231	0.1377732	0.02	0.04	7.58E-222	5
L	4	1085.873541	3223.3811	fc.L_rm.4	0.8832797	0.951	0.227924746	0.146359755	0.667164176	0.1516969	0.39475	0.3110995	0.1069231	0.1377732	0.02	0.04	1.61E-236	6
L	3	1181.006197	3318.5138	fc.L_rm.3	0.8868361	0.956	0.235853509	0.152365044	0.662257068	0.155921	0.38925	0.2872402	0.1169231	0.1285697	0.02	0.04	3.53E-257	6
L	2	1267.184625	3404.6922	fc.L_rm.2	0.8890748	0.964	0.245327879	0.164231437	0.65543191	0.1655004	0.415	0.2557251	0.1169231	0.1285697	0.02	0.04	6.83E-276	7
L	1	1332.485951	3469.9935	fc.L_rm.1	0.8900856	0.965	0.254307125	0.177284074	0.648107427	0.1772798	0.359	0.27506	0.1269231	0.1219791	0.02	0.04	4.51E-290	7

附表5 分子方差分析

Appendix table 5 Analysis of molecular variance (AMOVA)

	Df	Sum Sq	Mean Sq	Sigma	Rate (%)
Between population	5	35446.78	7089.3566	17.22669	0.45
Between samples within population	30	206754.72	6891.8240	3064.57018	79.71
Within samples	36	27456.61	762.6836	762.6836	19.84
Total	71	269658.11	3798.0016	3844.48046	100.00

Current levels of gene flow in *Brachystachyum densiflorum*

	Source of migration					
	AHGD	AHYX	AHHS	JSLY	JSYX	ZJXC
Recipient of migration	AHGD	AHYX	AHHS	JSLY	JSYX	ZJXC
AHGD	0.8889	0.0221	0.0222	0.0222	0.0222	0.0223
AHYX	0.0256	0.8721	0.0255	0.0258	0.0255	0.0255
AHHS	0.0337	0.0337	0.8330	0.0331	0.0330	0.0335
JSLY	0.0369	0.0370	0.0370	0.8149	0.0371	0.0370
JSYX	0.0208	0.0212	0.0210	0.0207	0.8951	0.0213
ZJXC	0.0370	0.0367	0.0371	0.0374	0.0368	0.8149

附表6 地理和气候、气候、地理3组数据对短穗竹遗传结构影响对比

Appendix table 6 Comparison of the effects on the genetic structure of *Brachystachyum densiflorum* of three data sets: climate and geography, climate, geography

Factor	Df	R ²	R _{adj} ²
Climate	8	0.23332	0.00616
Geography	2	0.06196	0.00511
Climate + Geography	10	0.29137	0.00792
Climate Geography	8		0.00281
Geography Climate	2		0.00176

Individual climate: (0.00281/0.00792)*100=35.48%

Individual geography: (0.00176/0.00792)*100=22.22%

Climate & Geography: ((0.00792-0.00281-0.00176)/0.00792)*100=42.30%

Loadings of climate factors in RDA1 and RDA2 axes

Factor	RDA1	RDA2
Bio6	0.77989635	0.4557206
Bio2	0.75512569	0.1686344
Bio19	0.65903421	0.4171224
Bio11	0.6462801	0.6344097
Bio17	0.42329286	0.4828083
Bio15	0.32196423	0.5488604
Bio7	0.0990923	0.6700309
Bio8	0.02995758	0.4290794

Stepwise screening of independent factors using the *ordistep* function

Factor	Df	AIC	F	Pr (>F)	R_{adj}^2
Bio6	1	333.04	1.1008	0.005	0.0029
Bio19	1	333.91	1.0506	0.045	0.0044

附表7 适应性位点冗余分析和偏冗余分析

Appendix table 7 Redundancy analysis and partial redundancy analysis of adaptive loci

	BayeScan SNPs 98	RDA SNPs 170	LFMM SNPs 349	All outlier SNPs 544
Combined fractions				
F-temperature	0.044***	0.048***	0.005 ^{ns}	0.025***
F-precipitation	0.019***	0.020***	0.005***	0.012***
Individual fractions				
F-temperature precipitation	0.037***	0.040***	0.006 ^{ns}	0.022***
F-precipitation temperature	0.011***	0.013***	0.006**	0.009***
Total explained	0.056***	0.060***	0.013**	0.034***
Total confounded	0.008	0.007	0.001	0.003
Total unexplained	0.944	0.940	0.987	0.966
Total	1.000	1.000	1.000	1.000

数据为调整后的 R^2 值。 * $P < 0.01$; *** $P < 0.001$; ns 表示不显著

The data are the adjusted R^2 value. * $P < 0.01$; *** $P < 0.001$; ns indicates insignificance

附表8 8个气候因子及其重要性参数

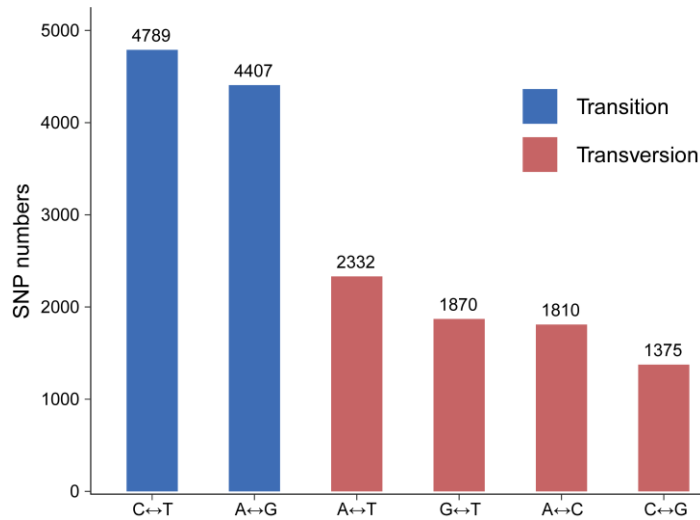
Appendix table 8 Eight climate factors and their importance parameters

Factor	Contribution rate (%)	Important values (%)
Bio6	55.7	62
Bio15	25.2	2.9
Bio11	6.9	13.5
Bio19	6.6	18.5
Bio8	3.1	1.5
Bio17	1.8	0.6
Bio2	0.6	0.9
Bio7	0.1	0.1

附表9 不同时期短穗竹的潜在分布面积

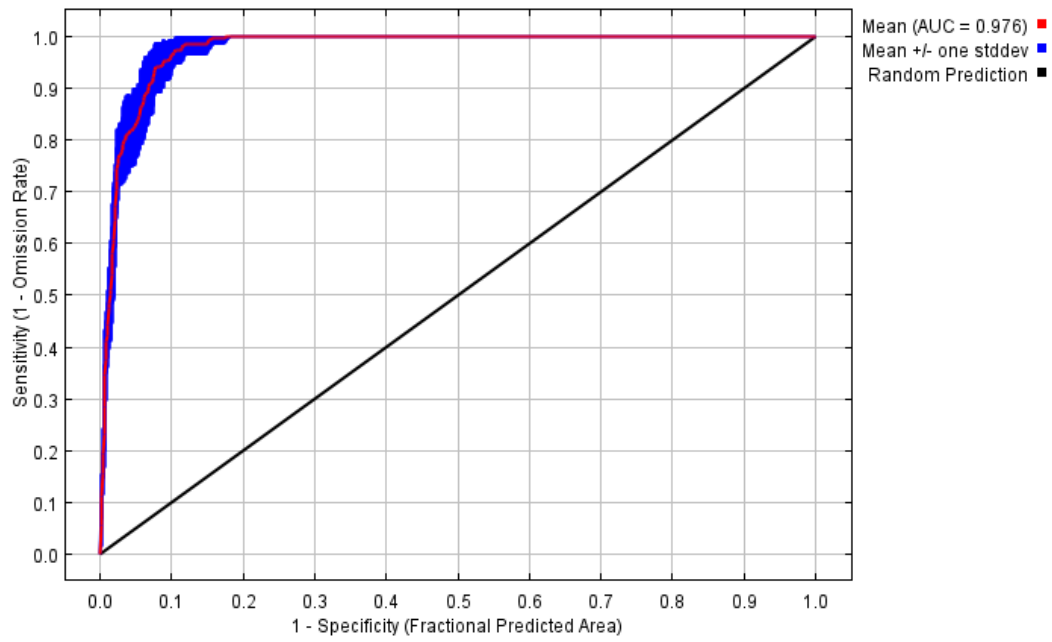
Appendix table 9 The potential distribution area of *Brachystachyum densiflorum* under different periods

Area ($\times 10^4$ km ²)	Last Glacial Maximum	Mid Holocene	Current	2021-2040		2041-2060		2061-2080	
				SSP 1-2.6	SSP 5-8.5	SSP 1-2.6	SSP 5-8.5	SSP 1-2.6	SSP 5-8.5
Unsuitable areas	949.38	934.01	858.47	857.50	854.82	857.77	842.80	856.11	897.80
Low suitable areas	4.15	10.60	44.37	50.45	52.43	51.63	71.15	59.41	38.23
Medium suitable areas	3.33	8.34	37.83	31.38	32.79	31.64	30.47	30.64	18.49
High suitable areas	3.15	7.04	19.33	20.67	19.95	18.95	15.58	13.84	5.48
Suitable area	10.62	25.99	101.53	102.50	105.18	102.23	117.20	103.89	62.20

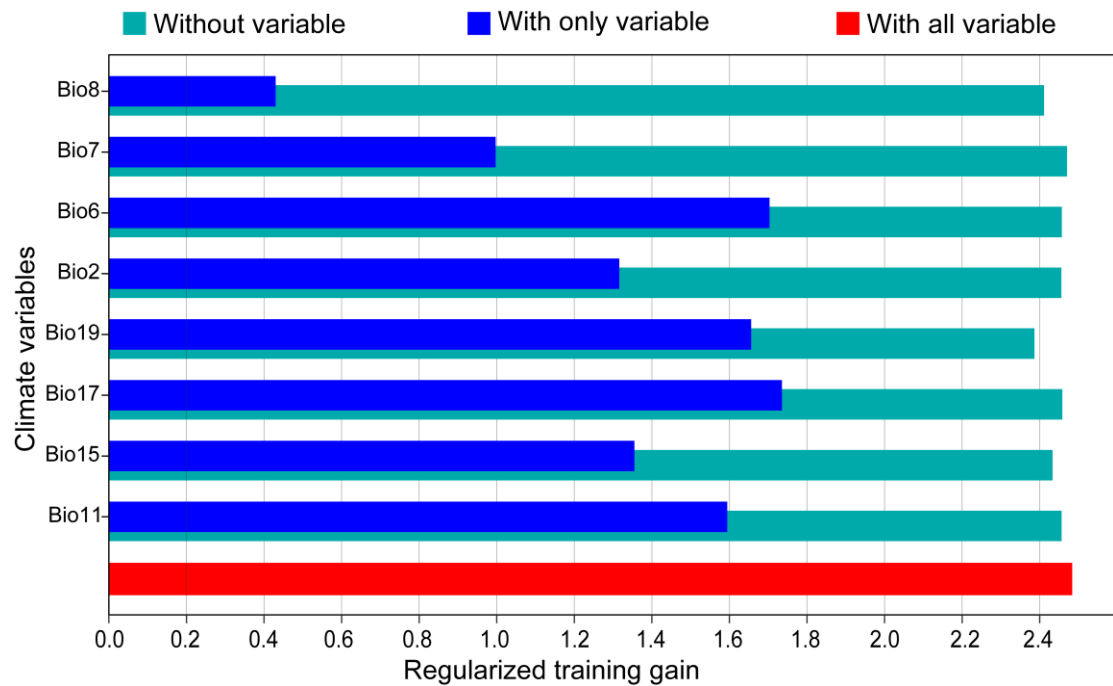


附图1 SNP转换与颠换统计

Appendix figure 1 Transition and transversion statistics of SNP



附图2 MaxEnt模型中的ROC预测
Appendix figure 2 Prediction of the ROC in the MaxEnt model



附图3 气候变量对短穗竹潜在分布模型的Jackknife检验得分
Appendix figure 3 Jackknife test scores of climate variables on potential distribution model of *Brachystachyum densiflorum*