



细叶云南松种实性状变异与地理气象因子的关联

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摘要 细叶云南松(*Pinus yunnanensis* var. *tenuifolia*)是分布于滇、黔、桂交界处的一个云南松变种, 其自然生境独特, 属典型的干热河谷气候, 具有重要的生态、经济价值。该研究以分布于南盘江-红水河流域沿线的8个细叶云南松天然种群为材料, 采用描述性统计及巢式方差分析比较种群间及种群内种实性状差异, 运用Pearson相关及典型相关分析探究种实性状与地理气象因子间的相关性, 最后对种群进行主成分聚类及Mantel检验, 揭示其种实性状地理变异模式。结果显示: 细叶云南松11个种实性状在种群间和种群内都存在极显著差异($p < 0.001$), 变异丰富。种实性状以种群内变异为主(平均表型分化系数 $V_{ST} = 18.65\%$), 球果性状种群间分化(24.22%–39.88%)高于种子及种翅性状(4.14%–13.80%), 表明球果性状受到更强的环境选择。尽管部分相关系数未达显著水平, 但整体上种实性状与经纬度、年平均气温呈正相关关系, 与相对湿度、年降水量呈负相关关系, 表明细叶云南松种实性状受到地理隔离、湿度和温度的协同选择作用, 使其能较好适应干热环境。主成分聚类将参试种群划分为3类, 位于东部的罗甸伍家坟(WJ)、罗甸大亭(DT)种群聚为一类, 其种实形态较大, 位于西南部的兴义坝汪(BW)种群单独一类, 其种实形态较小, 其他种群聚为一类, 种实形态介于前两类之间。总体上, 种实性状值有自西向东递增的趋势。Mantel检验表明, 参试种群存在明显的空间结构, 主要体现为渐变群模式。

关键词 细叶云南松; 球果性状; 种子性状; 地理变异; 生态适应性; 遗传资源

白天道, 余春兰, 甘泽朝, 赖海荣, 杨隐超, 黄厚宸, 蒋维昕 (2020). 细叶云南松种实性状变异与地理气象因子的关联. 植物生态学报, 44, 1224–1235. DOI: 10.17521/cjpe.2020.0269

Association of cone and seed traits of *Pinus yunnanensis* var. *tenuifolia* with geo-meteorological factors

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Abstract

Aims *Pinus yunnanensis* var. *tenuifolia* is an ecologically and economically important timber tree located at the junction of Yunnan, Guizhou and Guangxi, China. The natural distribution area represents a typical habitat of hot-dry valley. This paper aimed to describe the association between variation patterns of cone and seed traits (CST) and the geo-meteorological factors, explore its ecological adaptability, and provide a reference for the genetic resources conservation, evaluation and utilization.

Methods We sampled eight wild populations of *P. yunnanensis* var. *tenuifolia* distributed along the Nanpan-Hongshui River basin. The CST among and within populations were analyzed via descriptive statistics and nested ANOVA. Correlations between CST and geo-meteorological were evaluated based on Pearson and canonical correlation coefficients. Principal component analysis and Mantel test were applied to reveal the geographic variation pattern.

Important findings Abundant variations of eleven CST among and within populations were indicated by the extremely significant difference of nested ANOVA results ($p < 0.001$). The variation within population was the main source (the average coefficient of phenotypic differentiation $V_{ST} = 18.65\%$), and generally, the V_{ST} of cone traits (24.22%–39.88%) were larger than those of seed and wing traits (4.14%–13.80%), indicating more environment selection pressure on the cone traits. Majority of CST was positively correlated (though part of

收稿日期Received: 2020-08-06 接受日期Accepted: 2020-10-26

基金项目: 广西自然科学基金(2018GXNSFBA281110)和国家自然科学基金(31400575)。Supported by the Natural Science Foundation of Guangxi (2018GXNSFBA281110), and the National Natural Science Foundation of China (31400575).

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variable-pairs statistically insignificant) with latitude and longitude, annual average temperature, and negatively correlated with relative humidity and annual rainfall. This result suggests that the CST of *P. yunnanensis* var. *tenuifolia* is subjected to strong environmental selection, especially to temperature and relative humidity, prompting the species to adapt the hot-dry environment. Eight natural populations of *P. yunnanensis* var. *tenuifolia* were divided into three groups via principal component and cluster analysis. The two Luodian populations (WJ and DT) in the east were grouped into one group, and their cones and seeds were large. A population (BW) of Xingyi in the southwest belonged to a separate group, and its cones and seeds were small. The other populations were grouped together, and their CST fell between the first two groups. On the whole, the CST in *P. yunnanensis* var. *tenuifolia* increased from west to east. Mantel test exhibited a significant spatial structure among populations, and the variation pattern of populations was consistent with that of the cline.

Key words *Pinus yunnanensis* var. *tenuifolia*; cone trait; seed trait; geographic variation; ecological adaptivity; genetic resources

Bai TD, Yu CL, Gan ZC, Lai HR, Yang YC, Huang HC, Jiang WX (2020). Association of cone and seed traits of *Pinus yunnanensis* var. *tenuifolia* with geo-meteorological factors. *Chinese Journal of Plant Ecology*, 44, 1224–1235. DOI: 10.17521/cjpe.2020.0269

细叶云南松(*Pinus yunnanensis* var. *tenuifolia*)是云南松(*P. yunnanensis*)因南亚热带独特的河谷气候长期影响及适应下逐渐形成的一个地理变种,是我国特有种,其天然分布区域狭窄,仅限于黔、滇、桂交界处的南盘江流域、北盘江流域以及桂西北的红水河流域,属于微域分布的植被类型(徐学良, 1983; 王献溥, 1991)。细叶云南松生境狭窄,属于年平均气温较高,降水量小于蒸发量,总体较为干旱的河谷区域,焚风效应明显,气候独特。独特的生境使细叶云南松具有较高的生态研究价值(李治基和王献溥, 1981)。此外,细叶云南松干型直、树体高大,出材率高,木材强度和质量较好,具有较高的开发利用前景。但近年来,由于该区域其他经济林树种(油茶(*Camellia oleifera*)、八角(*Illicium verum*)等)的大力发展,对细叶云南松生境的人为干扰急剧加重,大量细叶云南松林遭到蚕食、破坏,原有的诸多大面积连续分布林分已消失殆尽,呈零星点状分布(吴东山等, 2016)。针对细叶云南松的遗传资源调查、收集、保存、评价迫在眉睫。

要开展细叶云南松遗传资源的收集和保护,首先要掌握其生态特性及种群遗传变异规律。目前,针对细叶云南松天然林的研究主要集中在林分结构、林下土壤特性等方面(潘婷, 2018; Yu *et al.*, 2018; 李远发等, 2019; 廖良宁等, 2019)。针对细叶云南松遗传资源评价的研究相对较少,仅见杨章旗等(2014)对广西西北部3个种群进行了SSR遗传多样性分析,认为遗传多样性与欧洲栓皮栎(*Quercus suber*)、黄杉(*Pseudotsuga menziesii*)等相比普遍不高,但种群间基因流动频繁,分化较小。表型多样性是

遗传与环境共同作用的结果,研究不同地理环境条件下的天然种群的表型性状分化程度和变异规律,不仅可在一定程度上反映其遗传变异水平,也可以有效揭示生物对不同环境的适应,进而探究其发展演化(Donohue *et al.*, 2001; Etterson, 2004; Gitonga *et al.*, 2008; Shirley & Vesk, 2009)。种实性状在物种自然演化过程中具有较高的遗传稳定性,不易受短期环境变化的影响。同时,作为主要繁殖器官,种实性状对物种的定居、繁衍及分布具有重要影响(Cilas *et al.*, 2009)。研究表明,果实形态、种子大小、质量、种翅的有无等都会影响其种子传播媒介(风、动物等)的传播效率,进而影响物种的分布范围(Wall, 2008; Zhang *et al.*, 2020)。本文通过对细叶云南松自然分布区的8个天然种群开展种实性状分析,以揭示细叶云南松种实性状在空间分布上的表型分化和变异规律,并探究其与细叶云南松特殊生境的关系,为进一步开展细叶云南松的种质资源保护与利用提供参考。

1 材料和方法

1.1 样本采集

根据中国植物志(<http://www.cvh.ac.cn/>)中细叶云南松的分布记录及实地调研情况,本试验采集的样品集中分布于南盘江-红水河流域贵州境内的8个代表性细叶云南松天然种群,采样时间为2019年10月中旬,种群信息详见表1。采样方法:每个种群选择15株生长正常、结实较多、树干通直、无明显病虫害的植株作为采种母树,分别测量母树胸径、海拔、经纬度等信息。为保证采种母树的代表性,降

表1 细叶云南松采样种群的地理位置和气象因子概况

Table 1 Locations and meteorological factors of the sampling populations of *Pinus yunnanensis* var. *tenuifolia*

种群 Population	经度 Longitude (E)	纬度 Latitude (N)	海拔高度 Altitude (m)	年平均气温 Mean annual air temperature (°C)	年平均相对 湿度 Mean relative humidity (%)	年降水量 Mean annual precipitation (mm)	地貌 Landform type	坡度 Slope degree (°)	土壤类型 Soil type	林分类型 Stand type	林分平均 胸径 DBH ± SD (cm)
兴义坝汪 Bawang, Xingyi (BW)	104.83°	24.70°	872.1	17.1	79.6	1 301.7	山地峡谷 Mountain gulch	10–15	砖红壤 Latosol	松栎混交林 Pine-oak forest	26.03 ± 7.94
册亨弼佑 Biyu, Ceheng (BY)	106.00°	24.78°	701.0	18.7	78.8	1 244.7	山地峡谷 Mountain gulch	25–30	砖红壤 Latosol	松栎混交林 Pine-oak forest	23.61 ± 8.44
兴义岔江 Chajiang, Xingyi (CJ)	104.68°	25.07°	1 250.8	16.0	79.8	1 413.0	山地峡谷 Mountain gulch	15–20	砖红壤 Latosol	松栎混交林 Pine-oak forest	24.94 ± 9.79
望谟大观 Daguan, Wangmo (DG)	106.27°	25.08°	870.0	18.7	78.1	1 211.6	山地峡谷 Mountain gulch	10–15	砖红壤 Latosol	松栎混交林 Pine-oak forest	32.64 ± 11.28
罗甸大享 Dating, Luodian (DT)	106.93°	25.30°	1 087.1	17.8	78.6	1 157.0	山地峡谷 Mountain gulch	15–20	砖红壤 Latosol	纯林 Pure stand	24.56 ± 5.73
安龙钱相 Qianxiang, Anlong (QX)	105.48°	25.20°	1 378.9	15.4	79.4	1 278.9	山地峡谷 Mountain gulch	5–10	砖红壤 Latosol	纯林 Pure stand	20.65 ± 8.23
安龙新桥 Xinqiao, Anlong (XQ)	105.28°	25.15°	1 315.0	16.1	79.6	1 266.9	山地峡谷 Mountain gulch	10–15	砖红壤 Latosol	松栎混交林 Pine-oak forest	26.29 ± 13.19
罗甸伍家坟 Wujiafen, Luodian (WJ)	106.93°	25.48°	776.2	17.5	78.7	1 157.3	山地峡谷 Mountain gulch	25–30	砖红壤 Latosol	纯林 Pure stand	35.74 ± 8.38

采样点年平均气温、相对湿度和年降水量通过克里格插值法获得, 原始数据为中国气象数据网(<http://data.cma.cn/>)发布的采样点周边区域77个县/市气象站1981–2010年累计的平均值。

Values of mean annual air temperature, relative humidity and mean annual precipitation were estimated (Kriging interpolation method) using the climate data during 1981 to 2010 from 77 climatic stations around the sampling locations. The original data were downloaded from <http://data.cma.cn/>. DBH, diameter at breast height.

低采种母树间的亲缘关系带来的系统误差, 每个种群内采种单株间距在80 m以上。使用高空采样器(20 m)采集树冠中上部的发育正常的成熟球果, 每株随机摘取球果20–30个, 装入布袋(35 cm × 25 cm)带回实验室。

1.2 性状测定

球果采集后, 于一周内完成球果形态指标测定; 后将球果暴晒干燥后脱粒, 再分别测量种子的相关性状。球果测定: 全测每个单株所采集的球果, 用电子天平称量单个球果鲜质量, 精确到0.01 g; 用游标卡尺测量球果长度及宽度, 精确到0.01 mm。种子及种翅测定: 每个单株随机选择50粒种子进行测定, 利用游标卡尺测定种子长度及宽度, 同时测定对应种子的种翅长度、宽度, 精确到0.01 mm; 种子千粒质量测定按二百粒法(去除种翅后, 按四分法选择200粒种子称质量, 4次重复, 换算为种子千粒质量), 测量精度为0.01 g。

1.3 数据处理

表型变异分析: 利用R 3.6.1 (R Core Team, 2018)计算各性状的种群平均值、标准偏差、种群内及种群间变异系数; 基于巢氏方差分析模型分析种群间及种群内差异, 线性模型为: $Y_{ijk} = \mu + \tau_i + \delta_{j(i)} + \varepsilon_{ijk}$, 其中, Y_{ijk} 为第*i*个种群第*j*个家系第*k*个观测值, μ 为总平均值, τ_i 为种群间效应值, $\delta_{j(i)}$ 为种群内单株(家系)随机效应值, ε_{ijk} 为随机误差(Logan, 2010); 利用表型分化系数(V_{ST})来反映种群间及种群内的表型分化状况, 其计算公式为: $V_{ST} = \frac{\sigma_{t/s}^2}{\sigma_{t/s}^2 + \sigma_s^2}$, 式中, $\sigma_{t/s}^2$ 为种群间方差分量, σ_s^2 为种群内(家系)方差分量(葛颂等, 1988)。

表型与环境相关分析: 基于采样区域及其周边气象站观测数据(附录I, II), 利用R相关数据包基于空间插值法(Kriging interpolation)获得各采样点气象数据估计值(Bivand *et al.*, 2013; Graler *et al.*, 2016;

Tennekes, 2018)。利用R数据包Hmisc 4.4计算Pearson相关系数及显著性 p 值(Harrell & Dupont, 2020), 并利用corrplot 0.84绘制相关性图(Wei & Simko, 2017)。采样地地理气象因子与参试性状间的典型相关分析采用CCA 1.2数据包(González & Déjean, 2012), 并采用ggplot2绘图(Wickham, 2016)。

地理变异规律分析: 采用数据包factoextra进行种实性状主成分分析, 获得综合反映种实性状的代表性主成分, 并以采样区域的气象插值数据作为背景, 分析种群主成分得分及典型相关性状值在采样区域内的变异趋势。采用平均轮廓系数确定最佳类别数 K , 并基于 K -质心法(K -Medoids)进行种群聚类(Kassambara, 2017)。采用Mantel检验分析种群间表型差异随地理距离的变化趋势(Jombart, 2008)。

2 结果

2.1 细叶云南松天然种群间和种群内种实性状变异特征

细叶云南松天然种群表型性状在种群间和种群内(植株间)两个层次的方差分析显示(表2), 种群的球果长(CL)、球果宽(CW)、球果长宽比(CR)、球果鲜质量(FM)、种子长(SL)、种子宽(SW)、种子长宽比(SR)、种子千粒质量(TSM)、种翅长(WL)、种翅宽(WW)、种翅长宽比(WR)共11个性状在种群间、种群内均存在极显著差异($p < 0.001$)。表明细叶云南松种实形态在种群间及种群内个体间均存在广泛差异。

多重比较(表3)表明, 细叶云南松天然种群种实性状在种群间存在着显著的差异。在球果性状方面, 罗甸伍家坟(WJ)种群 CL 、 CW 及 FM 均较大, 其次为罗甸大亨(DT)种群, 而兴义坝汪(BW)种群球果相对较小较轻; 在种子性状(SL 、 SW 及 TSW)方面也有相似趋势, 仍然以DT、WJ种群种子性状值较大, BW、安龙钱相(QX)种群种子性状值较小。种翅性状上, WL 以WJ种群最大, WW 则以望谟大观(DG)种群最大, BW最小。在长宽比上, CR 、 SR 及 WR 均以WJ种群最大, 以QX最小。综合所有性状, WJ种群各性状值普遍较大, BW种群总体较小。

由性状种群内变异系数(表4)可知, 不同性状变异水平有较大差异, FM 种群平均变异系数最大(36.64%), SW 最小(9.98%)。不同种群内变异系数也有明显不同, BW种群种子、种翅性状变异较大, DT种群则在多个性状上变异较小。从种群间变异系数来看, 变异系数最大仍然为 FM (21.91%), 但最小为 SR (2.91%), 总体上, 种群间、种群内均以质量性状(单果鲜质量、种子千粒质量)变异系数较大, 长度性状(CL 、 SL 、 WL)次之, 宽度性状(SW 、 WW)变异相对最小。

2.2 细叶云南松种群间表型分化

细叶云南松表型性状方差分量和 V_{ST} 显示(表5), 细叶云南松果实及种子性状 V_{ST} 的变异幅度为4.14%–39.88%, 表明不同性状在种群间和种群内个体间的方差分量占比有较大差异。其中球果性状

表2 细叶云南松天然种群间和种群内的种实性状巢氏方差分析
Table 2 Nested-ANOVA of cone and seed traits among and within populations of *Pinus yunnanensis* var. *tenuifolia*

性状 Trait	均方 Mean square			F			
	种群间 Among populations	种群内 Within populations	随机误差 Random error	种群间 Among populations	种群内 Within populations	种群间 Among populations	种群内 Within populations
CL	4 460.408	831.114	42.857	104.075***	19.393***		
CW	596.236	173.065	5.813	102.560***	29.770***		
CR	0.995	0.240	0.017	58.159***	14.041***		
FM	11 240.191	2 093.936	81.514	137.893***	25.688***		
SL	27.586	11.767	0.122	226.300***	96.532***		
SW	5.184	2.726	0.065	79.562***	41.835***		
SR	16.907	7.154	0.102	166.553***	70.471***		
TSM	97.442	48.754	0.418	233.050***	116.603***		
WL	647.766	335.707	2.428	266.774***	138.257***		
WW	25.997	19.652	0.375	69.362***	52.433***		
WR	1.045	0.658	0.020	52.216***	32.874***		

***, $\alpha = 0.001$ 。 CL , 球果长; CR , 果实长宽比; CW , 球果宽; FM , 球果鲜质量; SL , 种子长; SR , 种子长宽比; SW , 种子宽; TSM , 种子千粒质量; WL , 种翅长; WR , 种翅长宽比; WW , 种翅宽。
***, $\alpha = 0.001$ 。 CL , cone length; CR , cone aspect ratio; CW , cone width; FM , fresh cone mass; SL , seed length; SR , seed aspect ratio; SW , seed width; TSM , thousand-seeds mass; WL , seed-wing length; WR , seed-wing aspect ratio; WW , seed-wing width.

表3 细叶云南松天然种群种实性状平均值、标准偏差及种群间Duncan’s多重比较
Table 3 Mean, standard deviation (SD) and Duncan’s multiple range test of cone and seed traits of *Pinus yunnanensis* var. *tenuifolia*

种群 Population	CL (mm) (SD)	CW (mm) (SD)	CR (SD)	FM (g) (SD)	SL (mm) (SD)	SW (mm) (SD)	SR (SD)	TSM (g) (SD)	WL (mm) (SD)	WW (mm) (SD)	WR (SD)
兴义坝汪 Bawang, Xingyi	53.72 ^s (9.64)	31.52 ^d (4.07)	1.70 ^e (0.18)	26.07 ^f (11.94)	5.54 ^c (0.75)	3.18 ^d (0.38)	1.76 ^b (0.28)	11.88 ^e (2.73)	17.70 ^e (3.18)	5.78 ^e (1.01)	3.11 ^d (0.58)
册亨弼佑 Biyu, Ceheng	63.10 ^{de} (9.76)	34.18 ^c (3.90)	1.85 ^b (0.20)	40.37 ^d (14.13)	5.79 ^b (0.57)	3.41 ^b (0.36)	1.70 ^c (0.15)	14.81 ^{bcd} (2.93)	19.66 ^c (2.93)	6.00 ^d (0.94)	3.32 ^b (0.51)
兴义岔江 Chajiang, Xingyi	60.81 ^e (11.73)	34.78 ^c (5.32)	1.75 ^{de} (0.21)	39.62 ^d (17.98)	5.48 ^c (0.50)	3.40 ^b (0.35)	1.63 ^d (0.18)	14.91 ^{bc} (4.24)	19.70 ^c (2.93)	6.32 ^c (0.99)	3.16 ^d (0.46)
望谟大观 Daguan, Wangmo	63.61 ^{cd} (9.23)	36.51 ^b (4.55)	1.75 ^{de} (0.20)	44.69 ^c (14.86)	5.77 ^b (0.65)	3.41 ^b (0.32)	1.70 ^c (0.18)	14.42 ^{cd} (3.18)	19.49 ^c (3.38)	6.49 ^a (0.93)	3.03 ^e (0.49)
罗甸大亭 Dating, Luodian	67.83 ^b (7.01)	38.18 ^a (4.12)	1.78 ^{cd} (0.15)	50.32 ^b (14.76)	6.09 ^a (0.59)	3.49 ^a (0.26)	1.75 ^b (0.18)	16.78 ^a (2.82)	20.38 ^b (2.72)	6.37 ^{abc} (0.57)	3.23 ^c (0.57)
安龙钱相 Qianxiang, Anlong	57.51 ^f (12.42)	35.06 ^c (5.12)	1.63 ^f (0.16)	33.86 ^e (13.36)	5.36 ^d (0.58)	3.19 ^d (0.35)	1.69 ^c (0.13)	13.23 ^{cde} (4.46)	18.09 ^{de} (1.90)	6.45 ^{ab} (0.77)	2.83 ^f (0.35)
罗甸伍家坟 Wujiafen, Luodian	72.34 ^a (11.08)	37.22 ^{ab} (4.02)	1.94 ^a (0.16)	54.62 ^a (18.56)	6.04 ^a (0.49)	3.39 ^b (0.28)	1.79 ^a (0.16)	16.48 ^{ab} (2.71)	21.31 ^a (2.97)	6.28 ^c (0.69)	3.41 ^a (0.49)
安龙新桥 Xinqiao, Anlong	66.16 ^{bc} (9.92)	36.35 ^b (3.66)	1.82 ^{bc} (0.18)	47.80 ^{bc} (14.78)	5.54 ^c (0.54)	3.28 ^c (0.36)	1.70 ^c (0.15)	13.07 ^{de} (3.69)	18.27 ^d (2.79)	6.34 ^{bc} (0.83)	2.90 ^f (0.33)

下划线数值为对应指标种群最大平均值。平均值后的字母代表在 $\alpha = 0.05$ 水平上的种群间多重比较结果。
Values with underline denote the maximum of trait mean of each population. Letters after the means denote the significance of the multiple comparisons among populations.

表4 细叶云南松种群种实表型性状的变异系数
Table 4 Coefficient of variation (CV) of cone and seed traits from populations of *Pinus yunnanensis* var. *tenuifolia*

种群 Population	表型变异系数 CV (%)											
	CL	CW	CR	FM	SL	SW	SR	TSM	WL	WW	WR	Mean
兴义坝汪 Bawang, Xingyi	17.94	12.91	10.59	<u>45.80</u>	<u>13.54</u>	<u>11.95</u>	<u>15.91</u>	22.98	<u>17.97</u>	<u>17.47</u>	<u>18.65</u>	<u>18.70</u>
册亨弼佑 Biyu, Ceheng	15.47	11.41	10.81	35.00	9.84	10.56	8.82	19.78	14.90	15.67	15.36	15.24
兴义岔江 Chajiang, Xingyi	19.29	<u>15.30</u>	<u>12.00</u>	45.38	9.12	10.29	11.04	28.44	14.87	15.66	14.56	17.81
望谟大观 Daguan, Wangmo	14.51	12.46	11.43	33.25	11.27	9.38	10.59	22.05	17.34	14.33	16.17	15.71
罗甸大亭 Dating, Luodian	10.33	10.79	8.43	29.33	9.69	7.45	10.29	16.81	13.35	8.95	17.65	13.01
安龙钱相 Qianxiang, Anlong	<u>21.60</u>	14.60	9.82	39.46	10.82	10.97	7.69	<u>33.71</u>	10.50	11.94	12.37	16.68
罗甸伍家坟 Wujiafen, Luodian	15.32	10.80	8.25	33.98	8.11	8.26	8.94	16.44	13.94	10.99	14.37	13.58
安龙新桥 Xinqiao, Anlong	14.99	10.07	9.89	30.92	9.75	10.98	8.82	28.23	15.27	13.09	11.38	14.85
平均值 Mean	16.18	12.29	10.15	36.64	10.27	9.98	10.27	23.56	14.77	13.51	15.07	15.70
种群间变异系数 CV_A	9.31	5.85	5.33	21.91	4.67	3.39	2.91	11.67	6.37	3.87	6.38	7.42

下划线数值为对应性状种群变异系数最大值。种群间变异系数(CV_A)为种群间性状标准偏差与总均值的比。
Values with underline denote the maximum of variation coefficient (CV). CV among populations (CV_A) were calculated as the standard deviation between the trait mean of populations divided by the total mean of all populations.

(CL、CW、CR及FM)在种群间的方差占比普遍较高, 种群间分化较大。而种子、种翅性状种群间分化明显低于球果性状, 其中又以翅宽(WW)在种群间分化最小($V_{ST} = 4.14\%$)。

总体来看, 长度(CL、SL)及质量(FM、TSM)性状在种群间分化比宽度性状(CW、SW及WW)要大。以多性状表型分化系数均值(18.65%)为参照, 发现所有种子、种翅相关性状的 V_{ST} 均小于平均值, 而球果相

关性状 V_{ST} 均高于平均值, 这可能意味着球果相关表型性状受环境因子的影响更大, 因种群间地理环境差异较大, 使不同种群间存在较大分化, 而同一林分环境相对一致, 使得其单株间的球果性状变异较小。

2.3 细叶云南松天然种群种实性状和地理生态因子相关性

为进一步分析细叶云南松种实性状和地理气候因子的关系, 对11个种实性状与采样地主要地理气

表5 细叶云南松方差分量及表型分化系数

Table 5 Variance components and differentiation coefficient of phenotypic traits of *Pinus yunnanensis* var. *tenuifolia*

性状 Trait	方差分量 Variance component			方差分量百分比 Percentage of variance component (%)			表型分化系数 Coefficient of phenotypic differentiation (%)
	种群间 Among populations	种群内 Within populations	随机误差 Random error	种群间 Among populations	种群内 Within populations	随机误差 Random error	
CL	45.405 5	68.437 6	42.767 7	28.99	43.70	27.31	39.88
CW	4.573 8	14.312 0	5.805 9	18.52	57.96	23.51	24.22
CR	0.011 0	0.017 6	0.017 0	24.04	38.65	37.31	38.35
FM	85.877 4	161.015 3	81.274 8	26.17	49.06	24.77	34.79
SL	0.037 4	0.233 9	0.121 9	9.52	59.48	31.00	13.80
SW	0.005 6	0.053 4	0.065 2	4.54	43.00	52.46	9.55
SR	0.000 9	0.012 8	0.020 0	2.53	38.06	59.41	6.23
TSM	1.427 1	12.075 3	0.418 1	10.25	86.74	3.00	10.57
WL	0.729 8	6.661 7	2.428 1	7.43	67.84	24.73	9.87
WW	0.016 6	0.383 8	0.374 8	2.14	49.51	48.35	4.14
WR	0.022 6	0.141 1	0.101 5	8.52	53.21	38.27	13.80
平均值Mean				12.97	53.38	33.65	18.65

性状缩写见表2。

Trait abbreviations see Table 2.

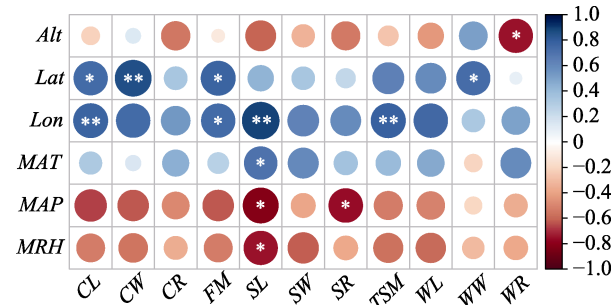


图1 细叶云南松表型性状与地理气候因子之间的Pearson相关性。*、**分别表示在95%、99%置信水平下显著相关。Alt, 海拔; CL, 果长; CR, 球果长宽比; CW, 果宽; FM, 单果鲜质量; Lat, 纬度; Lon, 经度; MAP, 年降水量; MAT, 年平均气温; MRH, 相对湿度; SL, 种子长; SR, 种子长宽比; SW, 种子宽; TSM, 种子千粒质量; WL, 种翅长; WR, 种翅长宽比; WW, 种翅宽。

Fig. 1 Pearson correlation between phenotypic traits and geo-meteorological parameters of *Pinus yunnanensis* var. *tenuifolia*. * and ** denote significant correlation between variables at $\alpha = 0.05$ and $\alpha = 0.01$. Alt, altitude; CL, cone length; CR, cone aspect ratio; CW, cone width; FM, fresh cone mass; Lat, latitude; Lon, longitude; MAP, mean annual precipitation; MAT, mean annual air temperature; MRH, mean relative humidity; SL, seed length; SR, seed aspect ratio; SW, seed width; TSM, thousand-seeds mass; WL, seed-wing length; WR, seed-wing aspect ratio; WW, seed-wing width.

候因子进行了Pearson相关分析(图1)。结果表明, CL、CW、FM与纬度(Lat)、经度(Lon)呈显著($p < 0.05$)或极显著($p < 0.01$)正相关关系, 与海拔(Alt)、年降水量(MAP)、年平均气温(MAT)及相对湿度(MRH)相关性不显著。SL与Lon、MAT(极)显著正相关($p < 0.05$), 与MAP、MRH显著负相关($p < 0.05$)。WL与Lon显著正相关。WW与Lat显著正相关。WR与Alt显著负相关。TSM与Lon显著正相关。需指出的是, 尽管

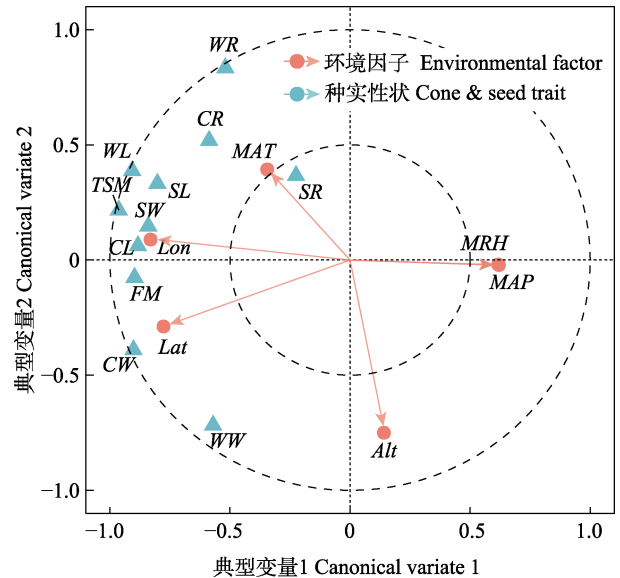


图2 种实性状与地理气候因子的典型相关性。Alt, 海拔; CL, 果长; CR, 球果长宽比; CW, 果宽; FM, 单果鲜质量; Lat, 纬度; Lon, 经度; MAP, 年降水量; MAT, 年平均气温; MRH, 相对湿度; SL, 种子长; SR, 种子长宽比; SW, 种子宽; TSM, 种子千粒质量; WL, 种翅长; WR, 种翅长宽比; WW, 种翅宽。

Fig. 2 Canonical correlation analysis (CCA) between phenotypic traits and geo-meteorological factors. Alt, altitude; CL, cone length; CR, cone aspect ratio; CW, cone width; FM, fresh cone mass; Lat, latitude; Lon, longitude; MAP, mean annual precipitation; MAT, mean annual air temperature; MRH, mean relative humidity; SL, seed length; SR, seed aspect ratio; SW, seed width; TSM, thousand-seeds mass; WL, seed-wing length; WR, seed-wing aspect ratio; WW, seed-wing width.

部分测定指标与MAP、MAT及MRH相关性未达显著水平,但总体趋势一致,即种实性状与经纬度、MAT主要呈正相关关系,而与MRH、MAP呈负相关关系。

种实性状与地理气象因子间的典型相关分析结果(图2)显示,地理气象因子均与典型变量1或2有较

高的相关性。其中 Lon 、 Lat 、 MAP 和 MRH 与典型变量1相关性较高, Alt 、 MAT 与变量2相关性较高。且从向量夹角来看, Lon 、 Lat 与 MAP 和 MRH 呈负相关关系,与 MAT 呈正相关关系。从种实性状来看,除 SR 外,其他指标均与典型变量1或2有较高相关性,其中大部分种实性状与变量1高度相关,而 WR 、 WW 与变量2相关性更大,绝大部分种实性状分布相对集中,表明彼此间存在明显的正相关关系。结合种实性状与地理气象因子来看,种实性状值均随 Lat 、 Lon 增加而增大,随 MRH 、 MAP 的增大而减小。这

与Pearson相关分析结果一致。

2.4 细叶云南松天然种群主成分及聚类分析

为进一步呈现种群种实性状随经纬度及主要气象因子的变异规律,将种实性状利用主成分分析进行降维,发现第一主成分(PC1)能较大程度反映细叶云南松种实性状综合特征(方差贡献率63.98%)(附录III, IV)。将种群 SL 值(与 MAT 、 MAP 及 MRH 均显著相关)、种群PC1得分(附录V)分别与通过空间插值获得的采样区域的气象因子梯度进行对应分析(图3),发现 SL 有随 MAT 增加而增大趋势,但

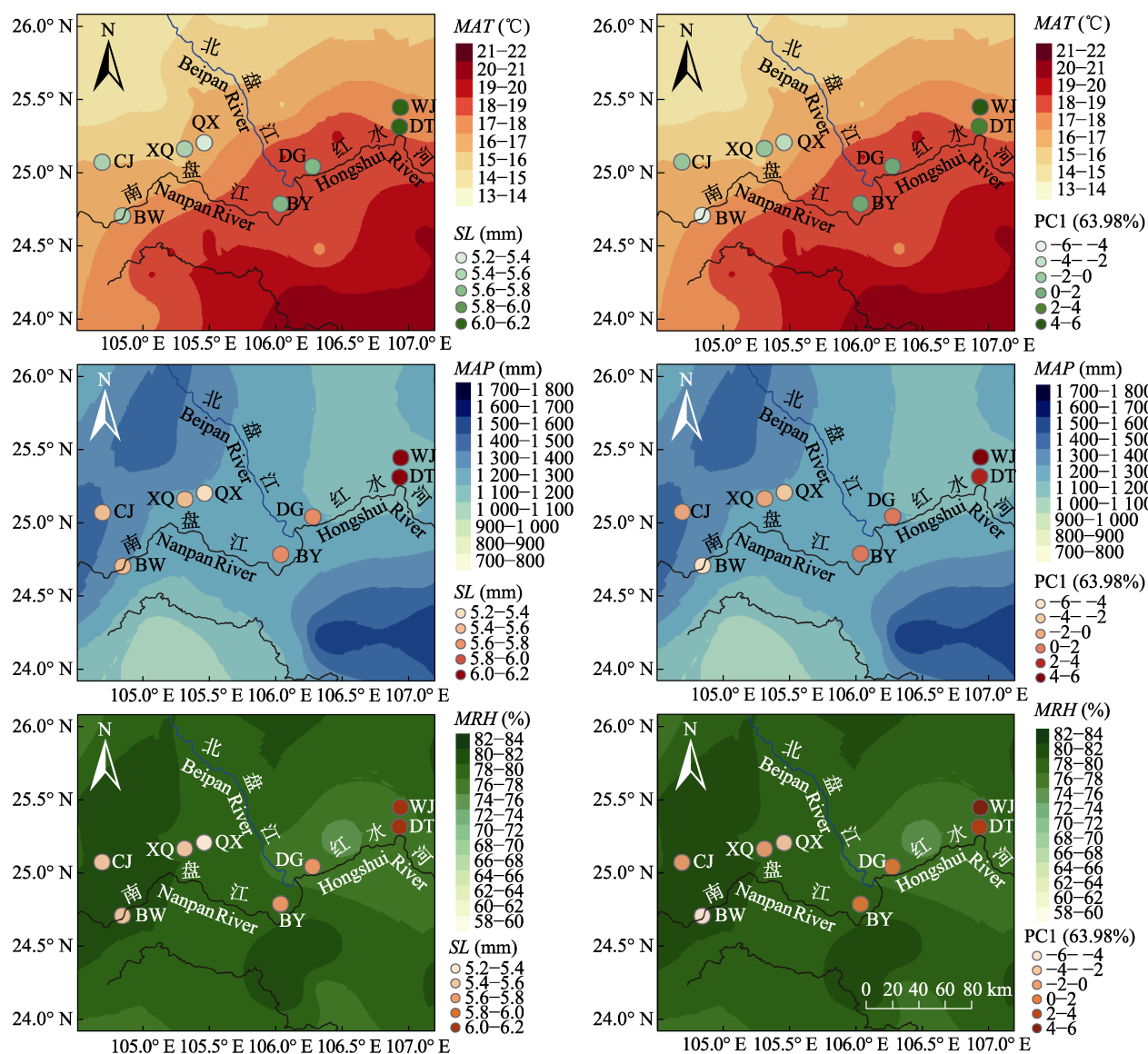


图3 细叶云南松8个天然种群种实性状随地理气象因子的变化模式。 MAP , 年降水量; MAT , 年平均气温; MRH , 相对湿度; SL , 种子长; $PC1$ 为各种种群实性状主成分分析中第一主成分得分值(第一主成分贡献率63.98%)。种群缩写(BW 、 BY 、 CJ 、 DG 、 DT 、 QX 、 WJ 、 XQ)同表1。

Fig. 3 Distribution model of the seed and cone traits of *Pinus yunnanensis* var. *tenuifolia* with the geo-meteorological factors. MAP , mean annual precipitation; MAT , mean annual air temperature; MRH , mean relative humidity; SL , seed length; $PC1$ (63.98%), the score of the first principal component of each population based on principal component analysis of seed and cone traits. See Table 1 for population abbreviation (BW , BY , CJ , DG , DT , QX , WJ , XQ).

两者不完全吻合,西部4个种群(CJ、XQ、QX及BW)位于MAT较低区域,SL值亦相对较小,中部两个种群(BY、DG)MAT最高,而SL处于中等,位于东部的WJ、DT具有中度MAT,但SL最大。基于种群PC1值与MAT的对应分析亦有相似结果。从MAP来看,SL及PC1值的增大与MAP下降的趋势较为一致,西部种群SL和PC1均较小,MAP较大,中部种群SL、PC1及MAP均为中等,东部种群SL、PC1较大,MAP较小。在MRH梯度图中,SL和PC1随MRH的增大而减小。从经纬度来看,除QX外,种实性状有自西向东、自南向北逐渐增大的趋势。

对8个种群的11个种实性状进行了主成分聚类

分析。基于平均轮廓系数最大原则,发现8个种群最佳聚类数(K)为3(图4A)。以聚类数 $K = 3$ 为基准,基于前两个主成分(累计方差贡献率83.87%)对种群进行聚类(图4B),结果显示位于东部的DT、WJ种群聚为一类,其种实性状特点为球果及种子大而重,种翅较长。位于西南部的BW种群单独聚为一类,其种实性状特点为球果、种子及种翅小、质量轻。其他种群(QX、XQ、CJ、BY、DG)聚为一类,其种实性状值介于前两类之间。

Mantel检验结果(图5A)显示,表型距离与地理距离间相关值(0.562 8)显著偏离零假设(无空间结构)下的拟合值($p = 0.009$),表明种群种实性状符合距

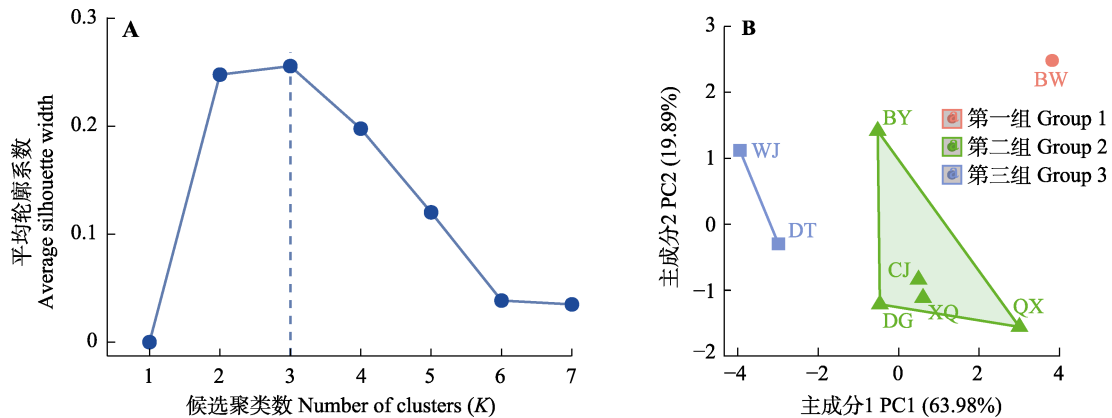


图4 细叶云南松天然种群种实性状的主成分聚类。A, 基于平均轮廓系数确定最佳聚类数。B, 种群聚类图(K-Medoids法)。种群缩写(BW、BY、CJ、DG、DT、QX、WJ、XQ)同表1。

Fig. 4 Principal component and cluster analysis based on the phenotypic traits of eight natural populations in *Pinus yunnanensis* var. *tenuifolia*. **A**, The optimal number of clusters determined by average silhouette width. **B**, Population clustering by K-Medoids algorithm. See Table1 for population abbreviation (BW, BY, CJ, DG, DT, QX, WJ, XQ).

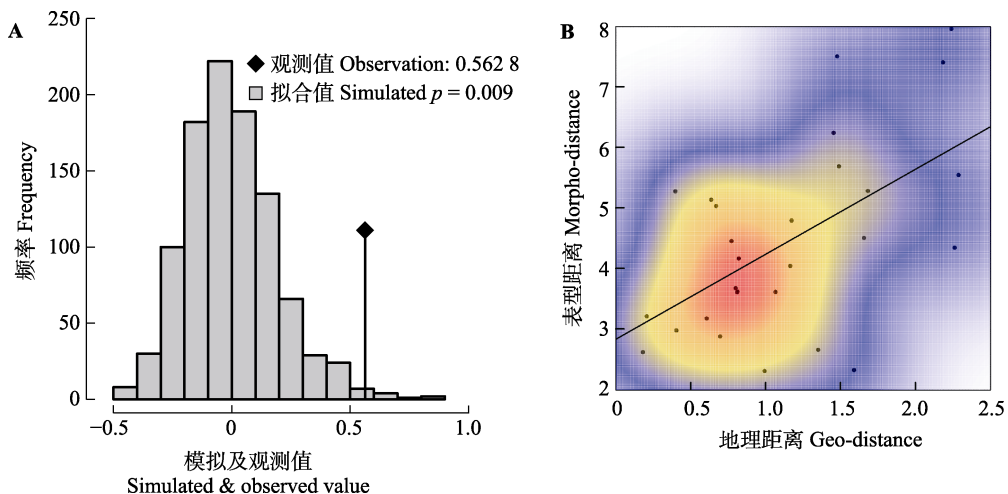


图5 基于表型距离与地理距离(欧式距离)的Mantel检验。A, 基于999次随机拟合Mantel检验结果,观测值(0.562 8)显著偏离零假设(无空间结构)下的拟合均值($p = 0.009$)。B, 表型距离与地理距离的相关性图,彩色斑块为基于距离值的二维核密度估计结果,单核表明符合渐变群模式。

Fig. 5 Mantel test between morpho-distance and geo-distance (Euclidean distance). **A**, Mantel test based on the 999 times of permutations. **B**, Correlation plot between morpho-distance and geo-distance. The single consistent cloud of point based on the 2-dimensional kernel density estimation indicates that the variation pattern of populations is a cline.

离隔离模式(IBM), 种群间存在明显的空间结构。性状的表型距离随地理距离的增大而增大, 二维核密度估计图显示表型距离为单核斑块, 证明种群空间结构近似符合渐变群(cline)模式(图5B)。

3 讨论

3.1 细叶云南松表型变异及分化

表型多样性是遗传多样性和环境多样性的综合表现。对种实性状进行种群差异及多样性研究, 可在一定程度上反映该物种的遗传变异大小和分布规律, 同时还能反映种实形态变异对长期环境的适应关系(Gitonga *et al.*, 2008; 刁松锋等, 2014; Sun *et al.*, 2017)。本研究发现细叶云南松种实性状在种群间、种群内均存在极显著差异($p < 0.001$), 细叶云南松种实性状变异以种群内为主($V_{ST} = 18.65\%$)。这与其近缘种云南松种实性状的研究结果一致($V_{ST} = 18.54\%$)(徐杨等, 2015), 高于思茅松(*Pinus kesiya* var. *langbianensis*)种群分化(11.95%)(李帅锋等, 2013), 低于其他近缘科属植物, 如白皮松(*P. bungeana*)(22.8%)(李斌等, 2002), 油松(*P. tabulaeformis*)(38.97%)(姬明飞等, 2013), 云杉(*Picea asperata*)(30.99%)(罗建勋和顾万春, 2005)、川西云杉(*Picea balfouriana*)(36.53%)(辜云杰等, 2009), 岷江柏(*Cupressus chengiana*)(43.4%)(冯秋红等, 2017)等的种群分化。总体上, 细叶云南松种群间总体分化水平属于中低水平。这可能因早年细叶云南松在该区域呈连续分布(李治基和王献溥, 1981; 徐学良, 1983), 种群间地理隔离不明显, 加之风媒植物传粉距离较远, 基因交流较为频繁, 降低了种群间的分化(Mosseler & Rajora, 2007)。同时, 由于种实主要采集自成年母树而非幼林, 从遗传上说, 其变异情况主要反映的是多年前的情况, 近年来人为干扰对种群分化造成的影响尚未体现。

3.2 细叶云南松种实形态地理变异规律及其生态适应性

不少研究表明, 海拔、年平均气温和经纬度是影响种实表型性状变异的主要因素(Shen *et al.*, 2015; 刘雄盛等, 2017; 何庆海等, 2018; Wu *et al.*, 2018; 刘莹等, 2019)。细叶云南松种实性状与地理气象因子相关分析结果可以看出, 绝大部分性状与地理气象因子的相关性表现出一致的趋势, 主要表现为与经纬度、年平均气温呈正相关关系, 与相对

湿度、年降水量和海拔呈负相关关系, 这意味着随降水量和相对湿度下降, 年平均气温升高, 其球果、种子、种翅及千粒质量有增大趋势。这与同属的白皮松(李斌等, 2002), 油松(姬明飞等, 2013)等有所不同。这说明不同的生境下的树种种实性状受到环境的选择压力不同, 其表型性状变异方向亦不同(Businsky *et al.*, 2014)。水分和温度是影响种子萌发、苗木生长的重要环境因素(McLaren & McDonald 2003; Bazin *et al.*, 2011), 因而其对种子及苗木生态适应性不可避免具有重要选择作用。一些研究(Andersson, 1996; Simons & Johnston, 2000)表明, 果实及种子大小、千粒质量与生活力和幼苗生长适应性有显著的正相关关系, 换言之, 较大果实及种子有利于其繁殖。因此, 综合以上可以推测, 在南盘江、红水河沿线特殊的干热河谷气候长期作用下(李治基和王献溥, 1981), 细叶云南松逐步演化出了适应干旱、高温生境的种实性状, 进而为其在特殊生境下的繁衍、更新奠定了基础。基于相关分析显著的性状(SL)和种群代表性主成分得分(PC1)与地理气象因子的对应分析发现, SL、PC1随经纬度呈现渐变趋势, 地理距离较近的种群种实形态更为相似, 这一方面可能源于地理距离较近种群间基因流动更为频繁, 遗传相似度更高, 另一方面其环境因素更为相似, 对种实性状选择作用趋于一致(图3)。此外, SL、PC1随MAP、MRH的变化比随MAT的变化具有更高的一致性, 表明该区域的干旱生境相对于温度对细叶云南松种实性状可能具有更强的选择作用。

基于种实性状的主成分聚类, 8个种群分为3组。结合地理距离(图3)来看, 分组呈西南-东北走向, 基本符合距离渐变模式, 但也有例外, 如QX种群种实较小, 与组内其他种群差异较大, 推测与该种群位于人为活动较频繁区域, 受到较强的人为干扰和破坏(如拔大毛式择伐)有关, 其样株胸径普遍小于其他种群也间接印证了该推测(表1)。总体上, 种群间地理距离越大, 分化越大。Mantel检验也证实了这一结论(图5)。综上可以推测, 地理距离造成的基因流大小及自然环境差异(湿度、温度等)的协同作用是引起细叶云南松表型分化的主要原因。尽管近年来受到其他经济林木种植的冲击, 使得细叶云南松生境受到较大程度的破坏, 呈现碎片化, 但因时间相对较短, 未对其现有种群分化水平造成明显影响,

使其遗传分化仍维持在中低水平。但随着人为干扰的进一步加剧, 种群规模缩小, 种群间的隔离增大, 种群内近交或自交加剧, 其种群分化水平、遗传漂变很可能进一步增大。

致谢 感谢贵州省望谟县林业局、兴义市林业局、安龙县林业局、罗甸县林业局和册亨县林业局在样本采集工作中给予的帮助。

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附录I 细叶云南松天然种群采样点及用于空间插值分析的气象站点分布图

Supplement I Map of sampling sites and the weather stations for spatial interpolation of eight natural populations in *Pinus yunnanensis* var. *tenuifolia*

<https://www.plant-ecology.com/fileup/1005-264X/PDF/cjpe.2020.0269-S1.pdf>

附录II 用于空间插值分析的气象站点基本信息

Supplement II Basic information of the climatic stations for spatial interpolation

<https://www.plant-ecology.com/fileup/1005-264X/PDF/cjpe.2020.0269-S2.pdf>

附录III 细叶云南松种实性状在各主成分(PC1-PC7)中的贡献值

Supplement III Contribution of the seed and cone traits of *Pinus yunnanensis* var. *tenuifolia* to principle components (PC1-PC7)

<https://www.plant-ecology.com/fileup/1005-264X/PDF/cjpe.2020.0269-S3.pdf>

附录IV 细叶云南松种实性状主成分特征值及方差贡献率

Supplement IV Eigenvalues and the percentages of variance of principle components of the seed and cone traits of *Pinus yunnanensis* var. *tenuifolia*

<https://www.plant-ecology.com/fileup/1005-264X/PDF/cjpe.2020.0269-S4.pdf>

附录V 细叶云南松种实性状种群主成分得分值

Supplement V Scores of principle components of the populations of the seed and cone traits of *Pinus yunnanensis* var. *tenuifolia*

<https://www.plant-ecology.com/fileup/1005-264X/PDF/cjpe.2020.0269-S5.pdf>

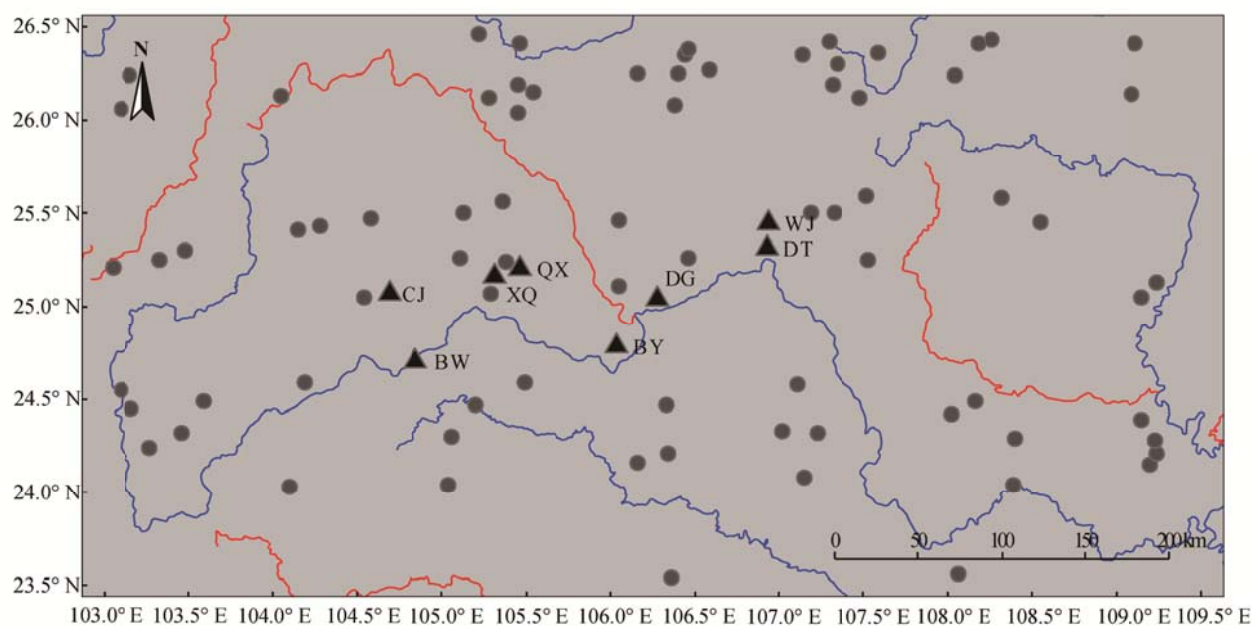
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<https://www.plant-ecology.com/CN/10.17521/cjpe.2020.0269>

附录I 细叶云南松天然种群采样点(▲)及用于空间插值分析的气象站点(●)分布图

Supplement I Map of sampling sites (▲) and the weather stations (●) for spatial interpolation of eight natural populations in *Pinus yunnanensis* var. *tenuifolia*



BW, 兴义坝汪; BY, 册亨弼佑; CJ, 兴义岔江; DG, 望谟大观; DT, 罗甸大亭; QX, 安龙钱相; WJ, 罗甸伍家坟; XQ, 安龙新桥。曲线代表区域内分布的二级(蓝色)及三级(红色)河流。

BW, Bawang, Xingyi; BY, Biyou, Ceheng; CJ, Chajiang, Xingyi; DG, Daguan, Wangmo; DT, Dating, Luodian; QX, Qianxiang, Anlong; WJ, Wujiafen, Luodian; XQ, Xinqiao, Anlong. The blue and red curves represent the rivers in the distribution area.

白天道, 余春兰, 甘泽朝, 赖海荣, 杨隐超, 黄厚宸, 蒋维昕 (2020). 细叶云南松种实性状变异与地理气象因子的关联. 植物生态学报, 44, 1224–1235. DOI: 10.17521/cjpe.2020.0269

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<https://www.plant-ecology.com/CN/10.17521/cjpe.2020.0269>

附录II 用于空间插值分析的气象站点基本信息

Supplement II Basic information of the climatic stations for spatial interpolation

区站号	Lon	Lat	MAT	MRH	MAP	区站号	Lon	Lat	MAT	MRH	MAP
59027	107.15	24.08	20.7	80	1 505.7	57926	107.53	25.25	18.5	77	1 211.9
59211	106.36	23.54	22.1	76	1 066.7	57807	105.28	26.12	14.8	80	1 479.9
59025	107.23	24.32	20.1	81	1 616.6	57913	106.59	26.27	15.0	80	1 077.3
59037	108.06	23.56	21.5	75	1 673.1	57916	106.46	25.26	19.8	75	1 124.8
59021	107.02	24.33	19.4	79	1 509.4	57828	107.35	26.30	14.6	82	1 309.8
59023	108.02	24.42	20.8	75	1 470.8	57800	105.22	26.46	13.7	81	1 202.9
59031	108.16	24.49	20.2	78	1 388.7	56793	104.28	25.43	15.3	77	1 347.9
59012	106.33	24.47	16.8	82	1 327.3	57814	106.16	26.25	14.3	81	1 244.3
59015	106.34	24.21	20.4	77	1 669.8	57921	107.19	25.50	17.0	79	1 157.8
59041	109.15	24.39	20.3	77	1 329.4	56792	104.58	25.47	13.9	81	1 353.8
59047	109.20	24.15	20.6	77	1 462.0	57808	105.45	26.19	15.2	78	1 340.7
59046	109.24	24.21	21.0	73	1 431.1	57900	105.13	25.50	14.2	82	1 492.0
59001	105.20	24.47	19.3	80	1 149.3	57932	108.32	25.58	18.4	80	1 180.3
57947	109.24	25.13	19.3	78	1 837.5	57923	107.52	25.59	18.2	80	1 326.1
57948	109.15	25.05	19.7	78	1 725.9	57834	108.18	26.41	15.9	81	1 096.7
59044	109.23	24.28	20.2	79	1 446.6	57906	106.05	25.11	19.5	77	1 241.0
57927	107.11	24.58	20.6	78	1 371.0	57915	106.46	26.38	14.9	81	1 083.4
59017	106.16	24.16	20.8	81	1 193.2	57902	105.11	25.26	15.5	80	1 322.0
59004	105.06	24.30	19.5	78	1 061.9	57907	104.54	25.05	16.4	80	1 450.9
59038	108.39	24.04	21.0	76	1 399.7	57905	105.38	25.24	16.6	79	1 318.3
59034	108.40	24.29	20.4	79	1 360.3	57809	105.45	26.04	15.3	79	1 346.9
57908	105.29	25.07	15.3	80	1 195.3	57805	105.46	26.41	14.3	81	1 355.5
57806	105.54	26.15	14.2	80	1 293.0	57910	106.05	25.46	15.5	80	1 250.0
57909	105.49	24.59	19.4	79	1 244.4	56688	103.10	26.06	19.9	58	741.3
57936	108.55	25.45	18.5	80	1 186.0	56790	104.15	25.41	14.3	74	1 064.7
57829	107.48	26.12	14.8	82	1 367.4	59007	105.04	24.04	17.0	78	994.8
57827	107.32	26.19	16.3	79	1 405.9	56684	103.15	26.24	13.0	70	791.3
57922	107.33	25.50	15.2	82	1 290.4	56886	103.46	24.32	15.2	76	878.5
57821	107.30	26.42	15.4	80	1 146.8	56891	104.19	24.59	15.3	83	1 595.6
57903	105.36	25.56	16.4	79	1 327.6	56782	103.33	25.25	13.8	73	979.5
57824	107.14	26.35	15.2	79	1 109.4	56885	103.27	24.24	17.3	74	913.3
57816	106.44	26.35	14.6	78	1 072.8	56889	104.10	24.03	16.7	77	1 143.2
57914	106.40	26.25	15.0	82	1 104.7	56783	103.48	25.30	15.1	69	944.6
57912	106.38	26.08	15.9	80	1 177.9	56883	103.59	24.49	14.3	79	1 147.1
57835	108.26	26.43	16.7	80	1 164.3	56881	103.16	24.45	16.3	73	939.6
57844	109.11	26.41	16.7	83	1 282.9	56785	103.05	25.21	14.4	73	1 006.9
57825	107.59	26.36	15.9	78	1 179.0	56697	104.05	26.13	13.7	71	973.8
57837	108.04	26.24	15.4	80	1 284.5	56880	103.10	24.55	16.6	74	860.1
57839	109.09	26.14	15.8	83	1 302.2						

Lat, 纬度; Lon, 经度; MAP, 年降水量; MAT, 年平均气温; MRH, 相对湿度。

Lat, latitude; Lon, longitude; MAP, mean annual precipitation; MAT, mean annual temperature; MRH, mean relative humidity.

白天道, 余春兰, 甘泽朝, 赖海荣, 杨隐超, 黄厚宸, 蒋维昕 (2020). 细叶云南松种实性状变异与地理气象因子的关联. 植物生态学报, 44, 1224–1235. DOI: 10.17521/cjpe.2020.0269

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附录III 细叶云南松种实性状在各主成分(PC1-PC7)中的贡献值

Supplement III Contribution of the seed and cone traits of *Pinus yunnanensis* var. *tenuifolia* to principal components (PC1-PC7)

性状 Trait	PC1	PC2	PC3	PC4	PC5	PC6	PC7
CL	12.598 20	0.738 13	4.595 75	9.290 87	0.000 23	2.859 34	0.570 66
CW	9.158 89	13.050 39	5.567 76	1.409 57	1.346 21	11.663 10	0.352 22
CR	9.026 69	5.172 41	0.464 24	44.723 58	0.021 95	2.967 91	14.601 70
FM	12.065 03	3.175 80	3.869 62	7.163 11	1.185 31	0.595 43	29.366 31
SL	11.402 59	3.867 98	1.216 21	12.152 74	15.890 73	4.110 82	23.668 50
SW	10.198 04	0.489 54	19.544 08	2.249 30	32.782 36	5.011 13	6.944 90
SR	1.922 60	16.374 20	44.169 49	12.727 56	0.908 61	1.744 37	4.660 93
TSM	12.408 21	0.214 85	5.003 21	7.793 23	7.955 81	34.139 63	8.201 31
WL	12.704 76	0.246 06	4.633 42	0.750 30	23.326 41	10.972 80	4.474 56
WW	1.723 75	37.952 57	1.001 69	1.707 17	9.193 69	25.933 86	4.814 20
WR	6.791 24	18.718 07	9.934 52	0.032 57	7.388 69	0.001 59	2.344 71

CL, 果长; CR, 球果长宽比; CW, 果宽; FM, 单果鲜质量; SL, 种子长; SR, 种子长宽比; SW, 种子宽; TSM, 种子千粒质量; WL, 种翅长; WR, 种翅长宽比; WW, 种翅宽.

CL, cone length; CR, cone aspect ratio; CW, cone width; FM, fresh cone mass; SL, seed length; SR, seed aspect ratio; SW, seed width; TSM, thousand-seeds mass; WL, seed-wing length; WR, seed-wing aspect ratio; WW, seed-wing width.

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附录IV 细叶云南松种实性状主成分特征值及方差贡献率

Supplement IV Eigenvalues and the percentages of variance of principal components of the seed and cone traits of *Pinus yunnanensis* var. *tenuifolia*

主成分 Principal component	特征值 Eigenvalue	方差百分比 Variance percentage (%)	累积方差百分比 Cumulative variance percentage (%)
PC1	7.037 529 83	63.977 543 90	63.977 543 90
PC2	2.187 953 03	19.890 482 07	83.868 025 97
PC3	0.982 485 99	8.931 690 83	92.799 716 79
PC4	0.547 708 96	4.979 172 38	97.778 889 17
PC5	0.197 733 63	1.797 578 43	99.576 467 60
PC6	0.041 157 20	0.374 156 32	99.950 623 93
PC7	0.005 431 37	0.049 376 07	100

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附录V 细叶云南松种实性状种群主成分得分值

Supplement V Scores of principal components of the populations of the seed and cone traits of *Pinus yunnanensis* var. *tenuifolia*

种群 Population	PC1	PC2	PC3	PC4	PC5	PC6	PC7
兴义坝汪 Bawang, Xingyi	-4.082 75	-2.650 94	0.460 22	0.399 03	-0.107 09	0.045 54	-0.066 12
册亨弼佑 Biyou, Ceheng	0.556 35	-1.511 09	-1.152 39	-0.504 00	-0.291 41	-0.049 65	0.139 98
兴义岔江 Chajiang, Xingyi	-0.529 08	0.895 68	-1.965 66	-0.355 61	0.337 35	-0.052 77	-0.098 51
望谟大观 Daguan, Wangmo	0.499 22	1.295 16	-0.042 93	0.376 67	-0.343 11	0.468 34	0.008 17
罗甸大亭 Dating, Luodian	3.195 89	0.317 28	0.104 39	1.222 39	-0.436 11	-0.260 47	-0.028 84
安龙钱相 Qianxiang, Anlong	-3.212 86	1.660 66	0.547 82	0.547 61	0.580 39	-0.108 38	0.088 16
罗甸伍家坟 Wujiafen, Luodian	4.223 06	-1.198 06	0.874 06	-0.350 84	0.718 68	0.083 80	-0.011 59
安龙新桥 Xinqiao, Anlong	-0.649 85	1.191 31	1.174 49	-1.335 25	-0.458 70	-0.126 41	-0.031 25