

云南高原的林火干扰：驱动机制、生态效应与响应

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2023.2.24

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0 研究背景

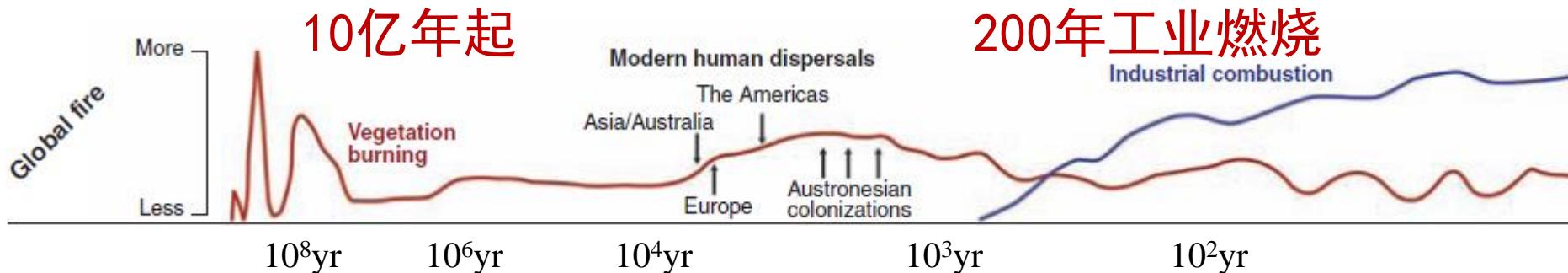
1 云南的林火格局与驱动机制

2 滇中高原森林的火后恢复与群落构建

3 滇中森林优势物种的火后更新策略

4 小结与展望

0、火的存在与意义



(Bowman et al. 2009, Science)



Review

TRENDS in Ecology and Evolution Vol.20 No.7 July 2005

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Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems

William J. Bond¹ and Jon E. Keeley^{2,3}

0、火的生态与进化意义

Received: 3 April 2019 | Accepted: 6 February 2020

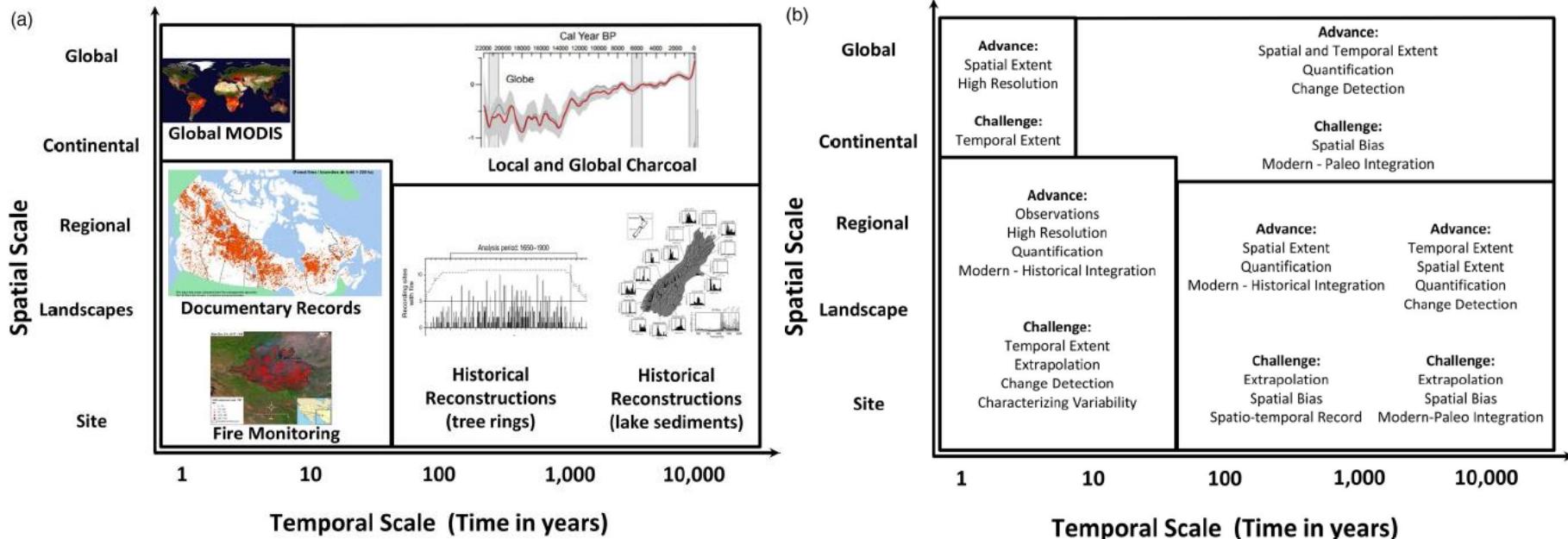
DOI: 10.1111/1365-2745.13403

ESSAY REVIEW

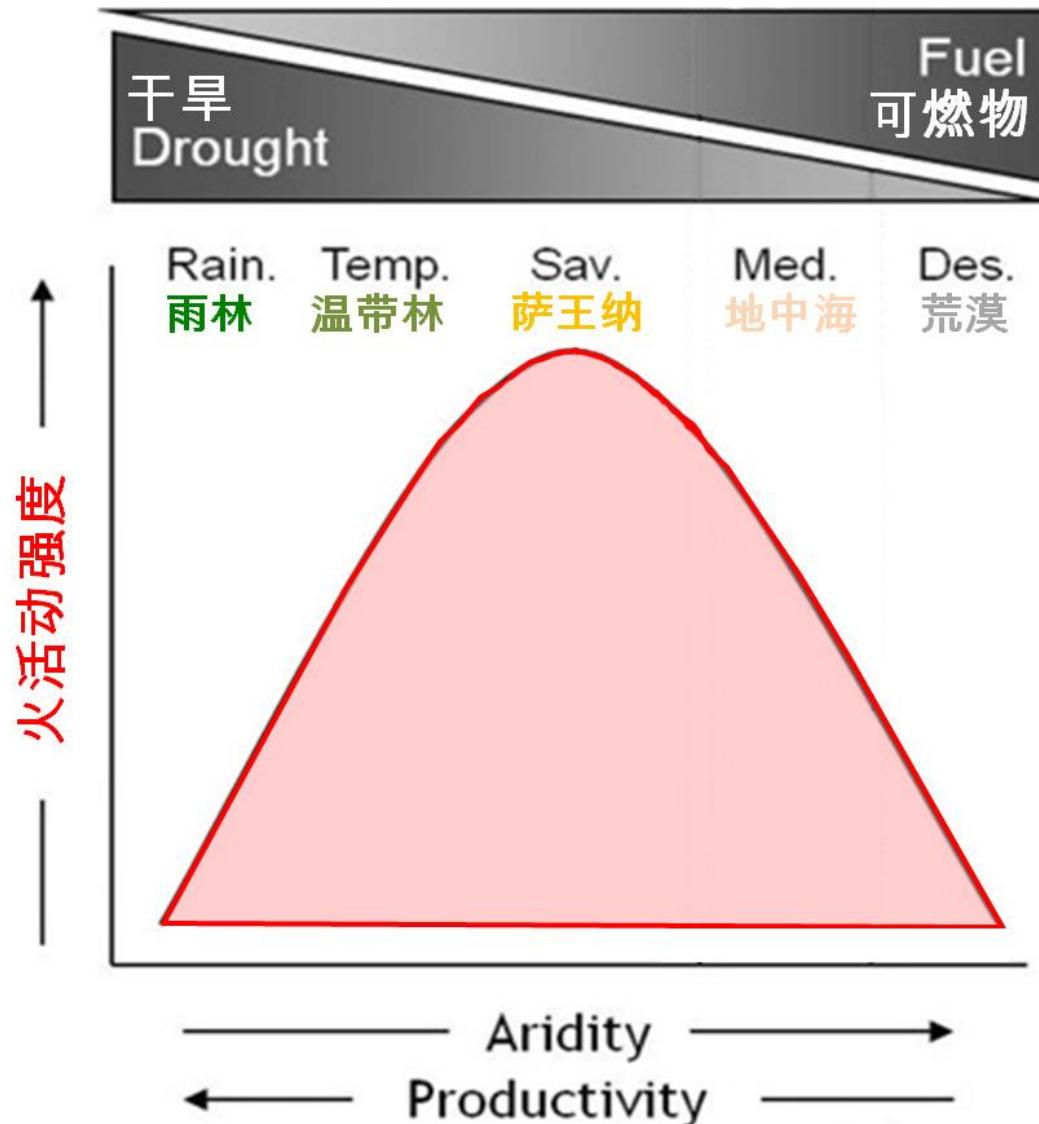
Journal of Ecology
BRITISH
ECOLOGICAL
SOCIETY

Fire as a fundamental ecological process: Research advances and frontiers

Kendra K. McLaughlan¹  | Philip E. Higuera²  | Jessica Miesel³ 

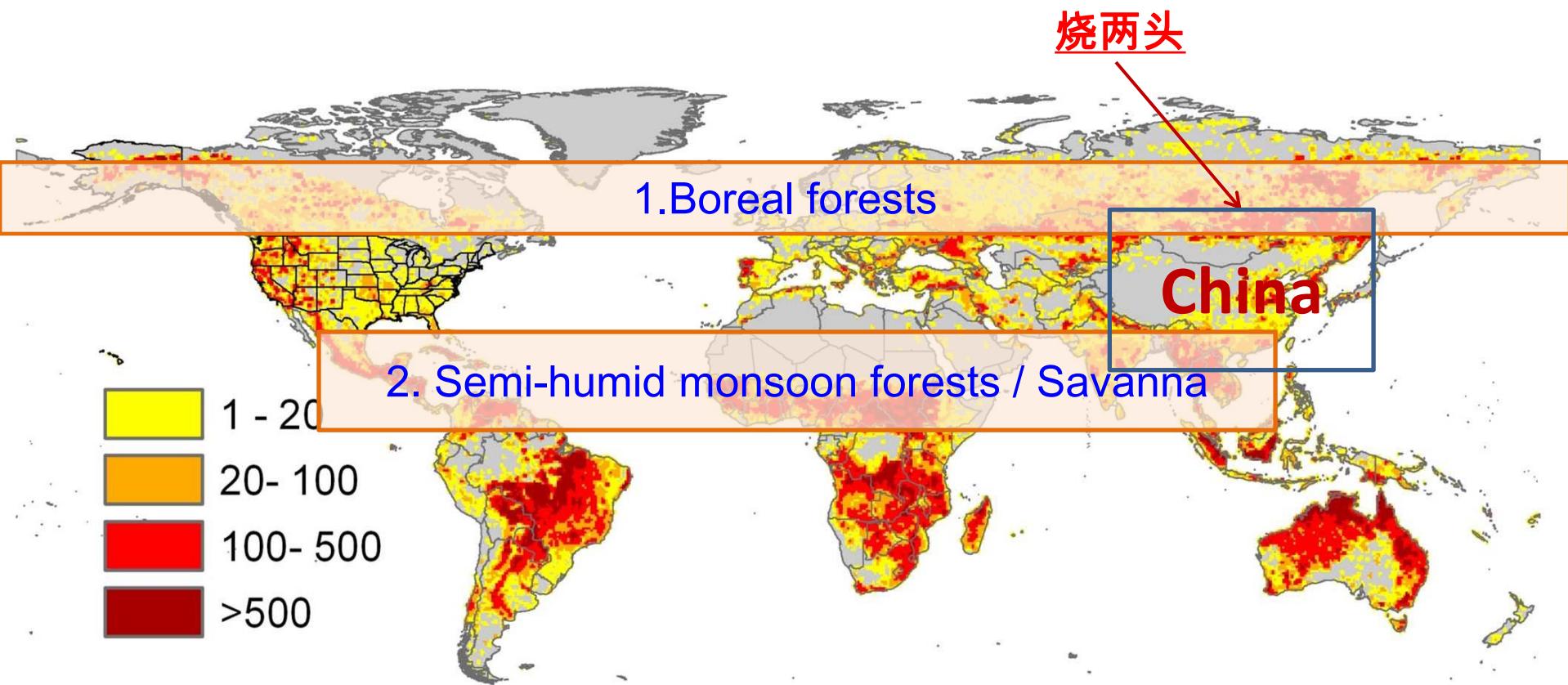


0 野火干扰体系的关键约束因子



(Pausas et al, 2012)

0、全球野火空间分布 Spatial patterns



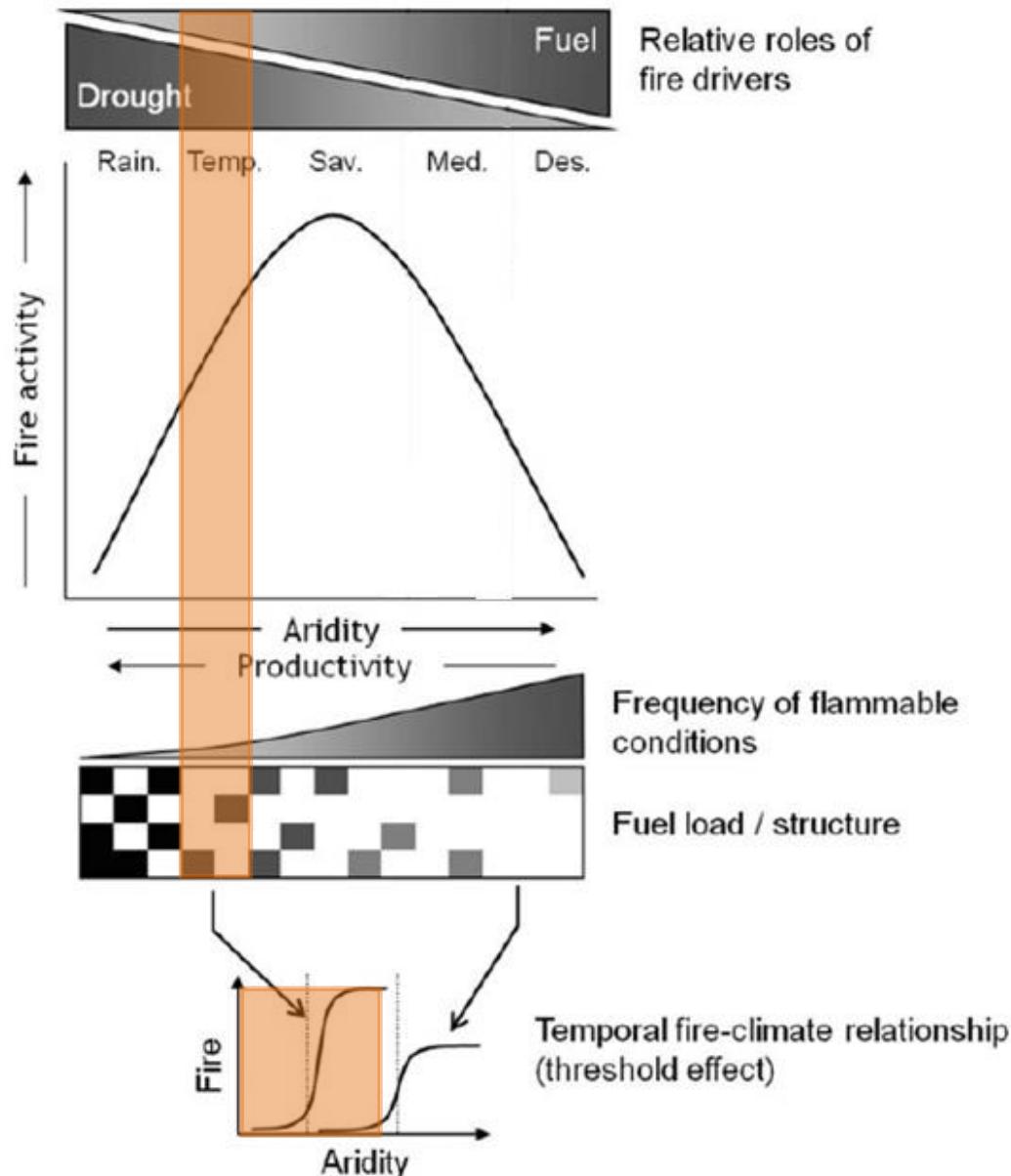
0 野火干扰体系的关键约束因子constraint

1) 燃料可燃性约束

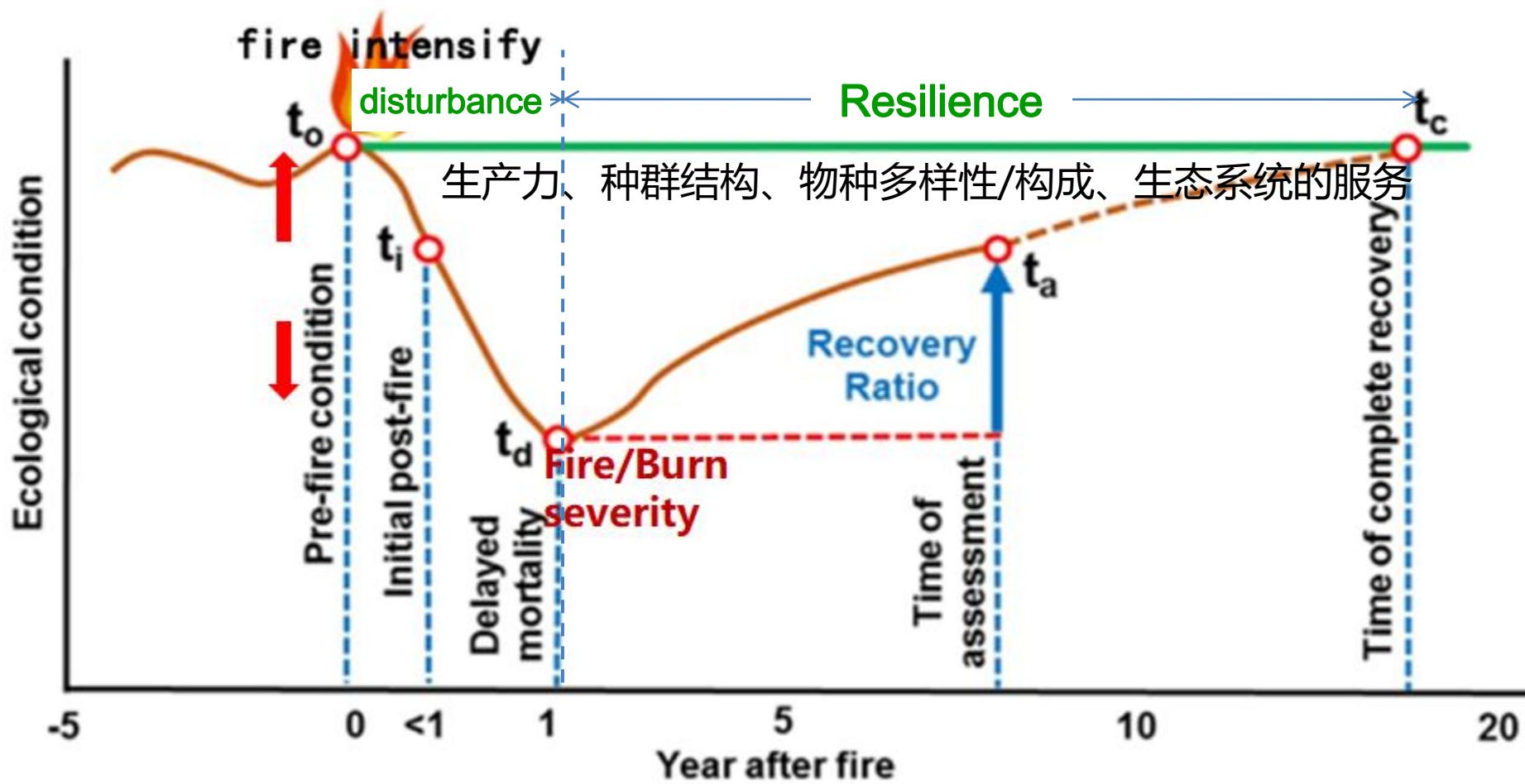
- 湿润多产气候
- 丰富而连续的可燃物
- 高温和/或干旱驱动为主

2) 燃料分布约束

- 更干旱的气候
- 生物量密度较低
- 可燃物有限且离散分布



0 林火的生态/进化响应Eco-Evo response



0 林火的生态/进化响应Eco-Evo response

火烧选择的植物功能性状traits :

1. 延迟果裂和林冠种子库 Serotiny & canopy seedbank
2. 火后开花、播种 Postfire flowering, seeding
3. 萌条能力 Resprouting
4. 厚的树皮 Thick bark
5. 易燃性树冠 Flammable canopy

火适应策略类型

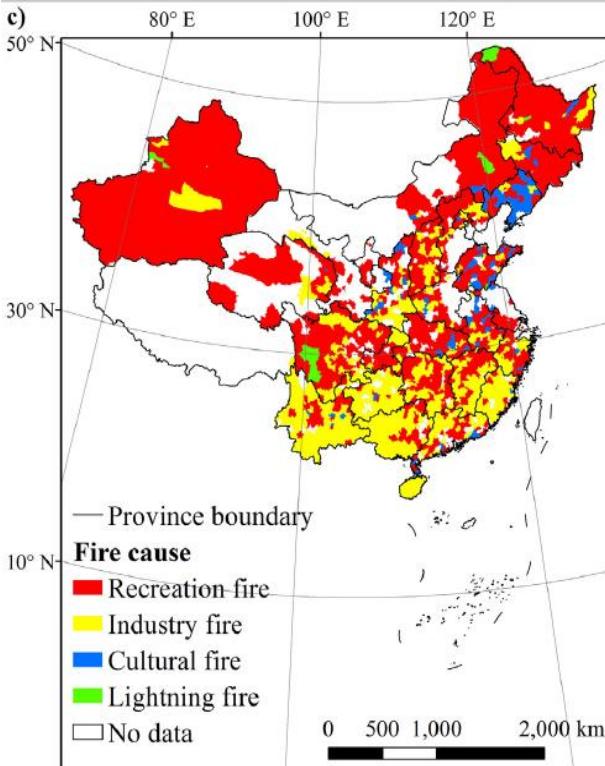
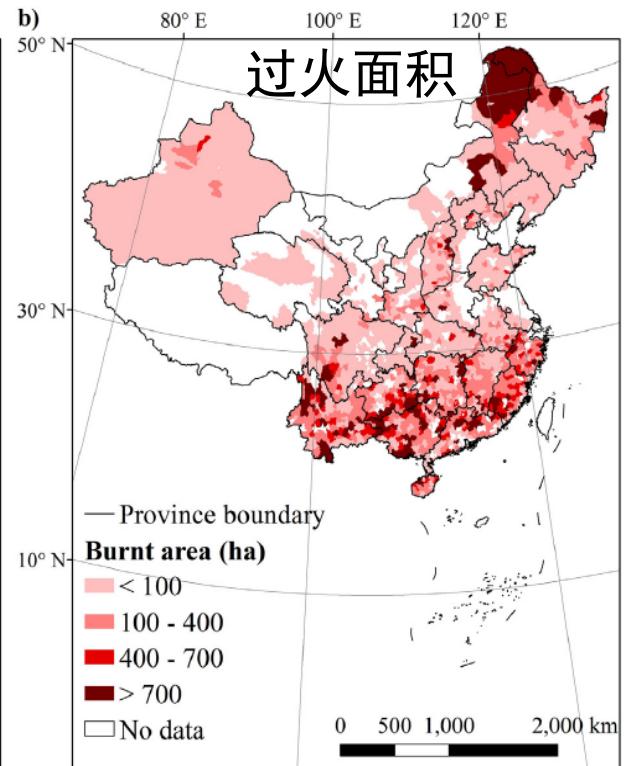
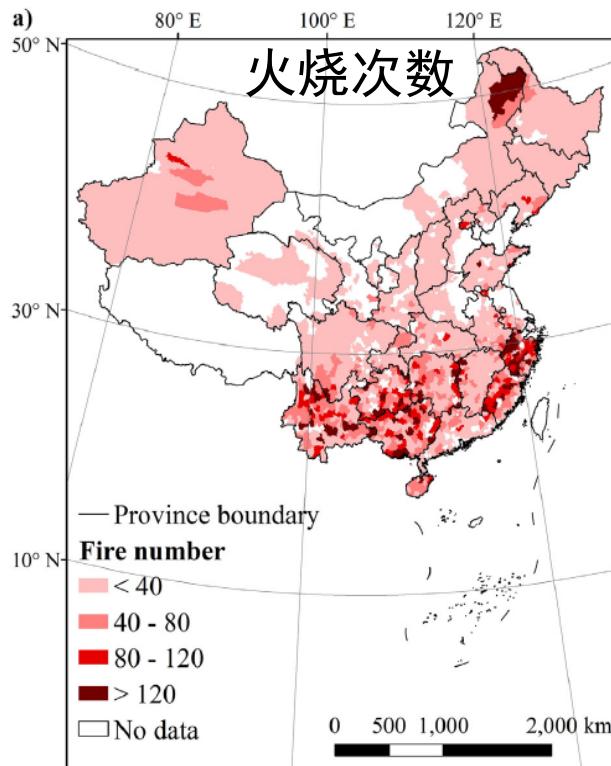
惹火型、耐火型、适(避)火型

Embracer, Tolerator, Evaders



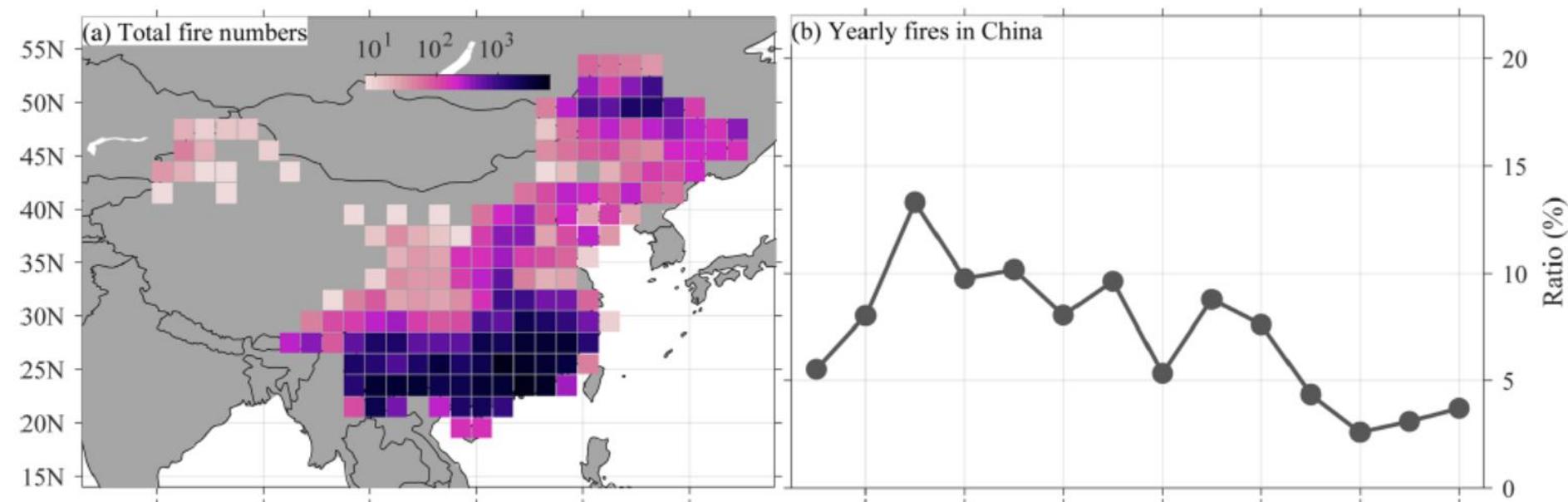
0 中国的林火格局与驱动因子的区域差异

1988–1991年全国县级林火统计



ENSO modulates wildfire activity in China

Keyan Fang^{1,2,12✉}, Qichao Yao^{3,4,12}, Zhengtang Guo^{5,6}, Ben Zheng⁷, Jianhua Du⁸, Fangzhong Qi⁴, Ping Yan³, Jie Li³, Tinghai Ou^{1✉}, Jane Liu^{1,9}, Maosheng He^{1,10} & Valerie Trouet^{11✉}



基于2005-2018年MODIS林火数据产品结合地面数据矫正

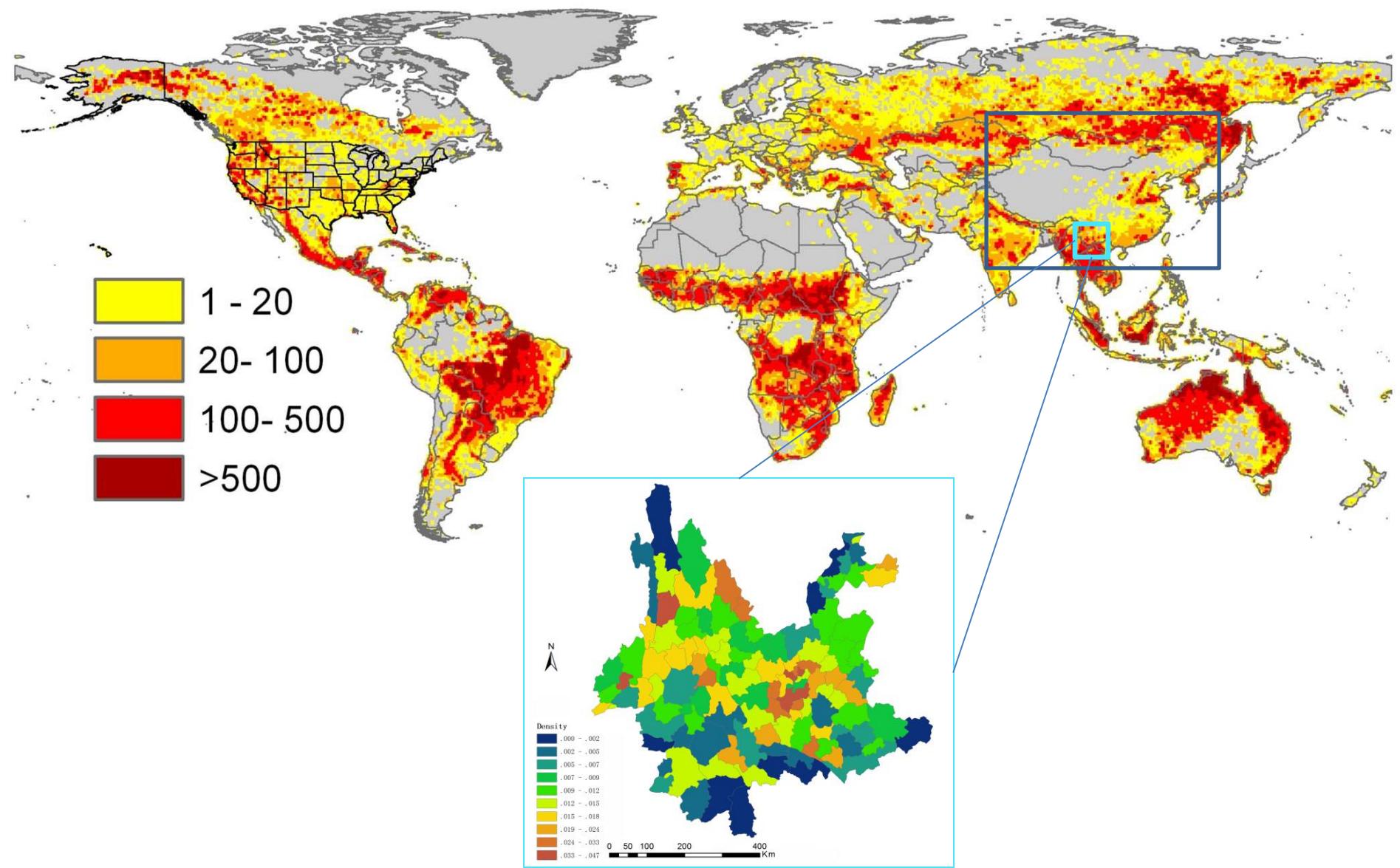
(Fang et al., 2021, NC)

1、云南林火格局与驱动机制

科学问题：

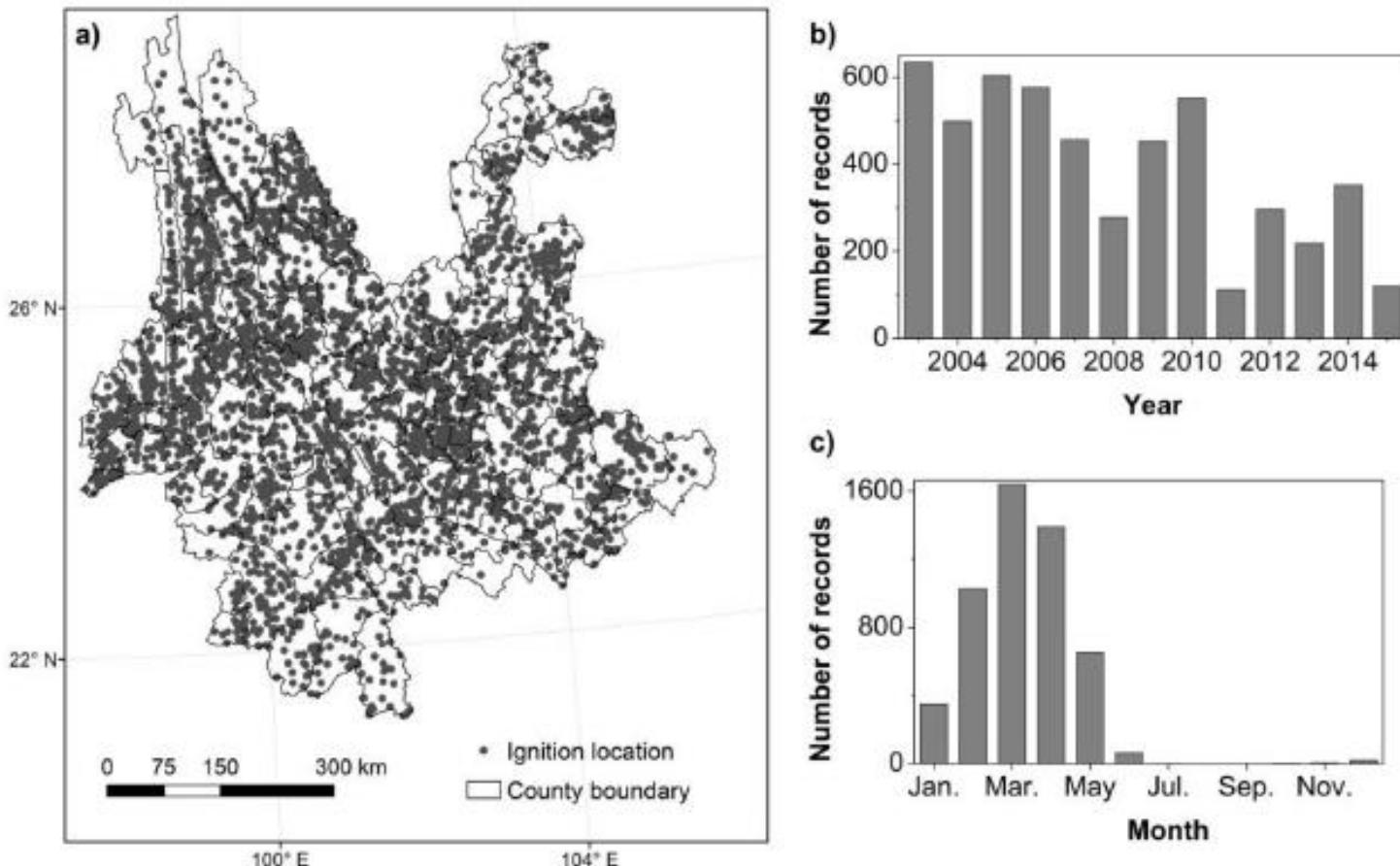
- 1) 不同数据源的林火评估结果比较 ?
- 2) 林火时空格局和域内驱动机制如何 ?
- 3) 域外环境对云南林火活动有何影响 ?

1、云南林火格局与驱动机制



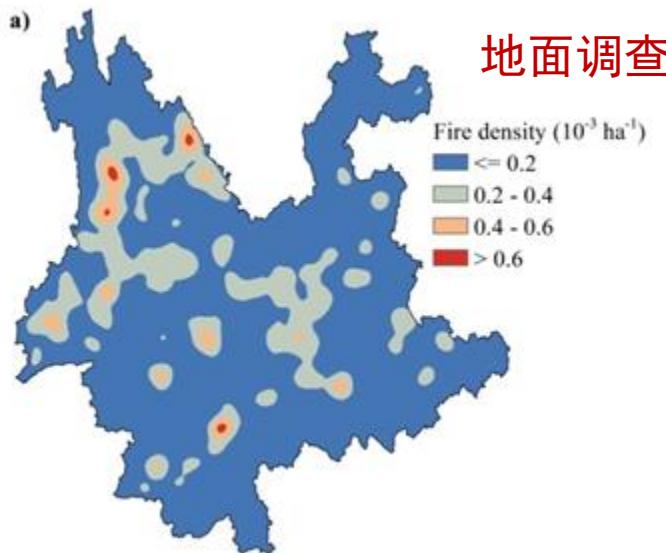
1、云南林火格局与驱动机制

2003-2015年县域林火事件Ignition统计 (5145起)

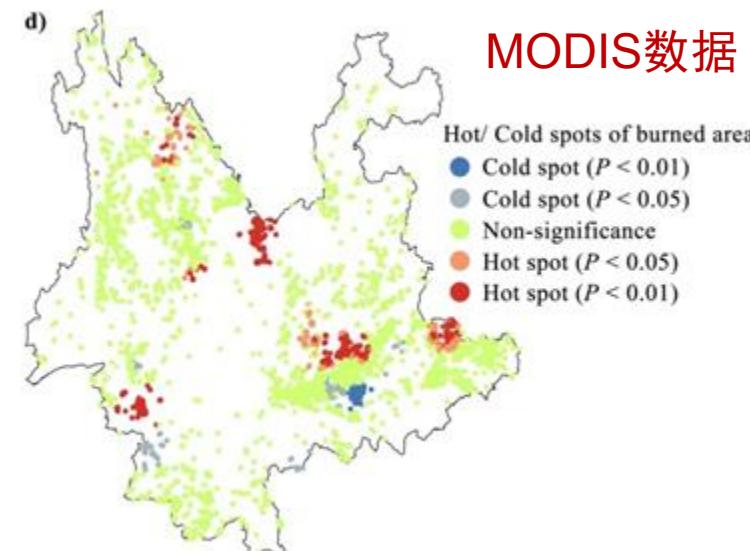
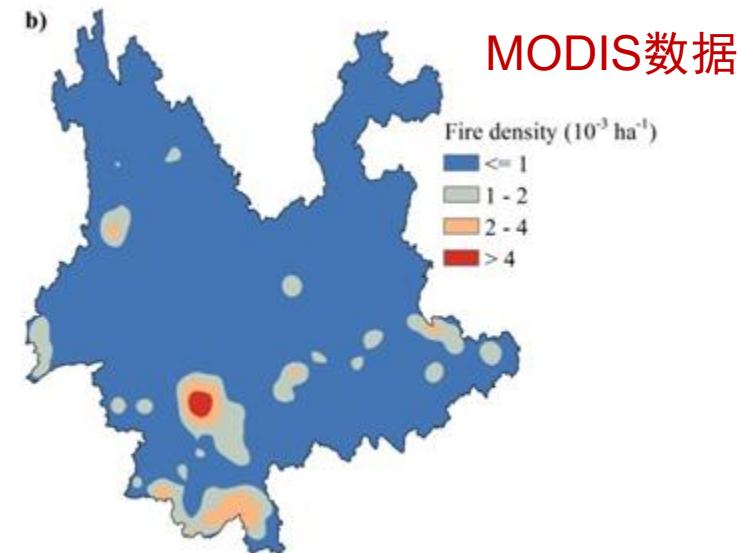
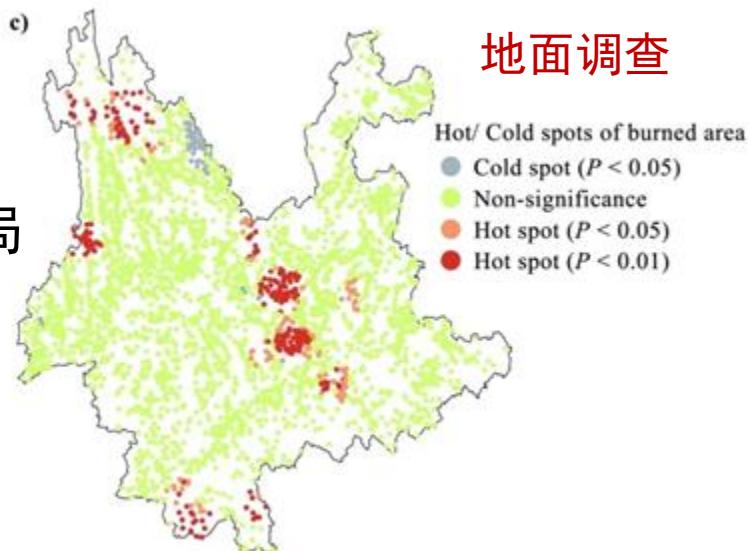


1、云南林火格局与驱动机制

火烧次数
核密度格局

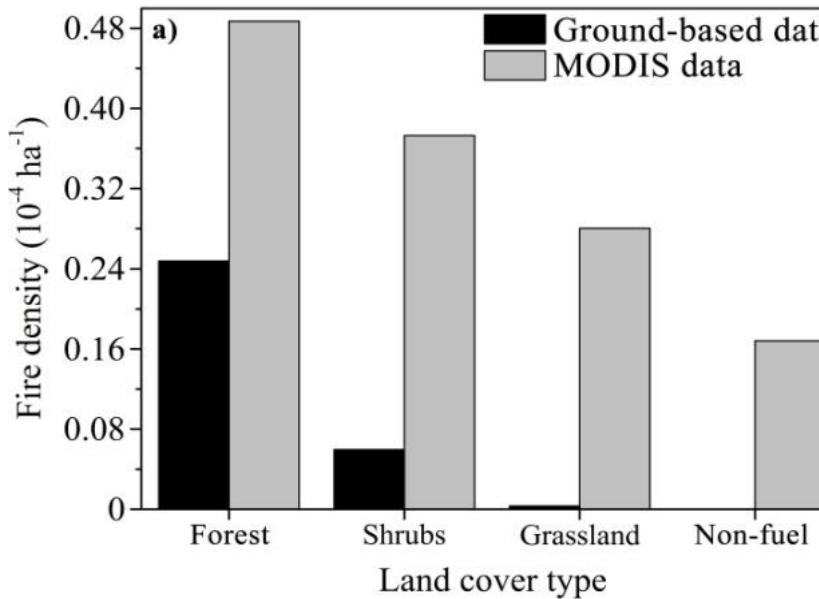


过火面积
热/冷点格局

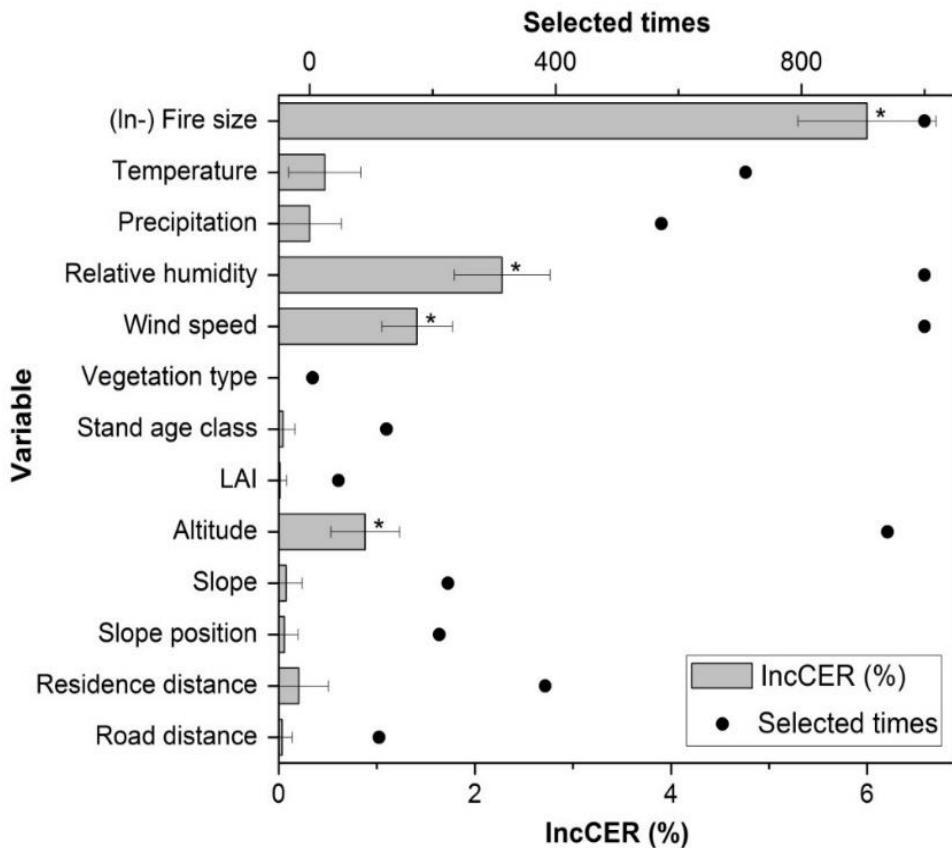


1、云南林火格局与驱动机制

□ MODIS和地面记录的林火发生

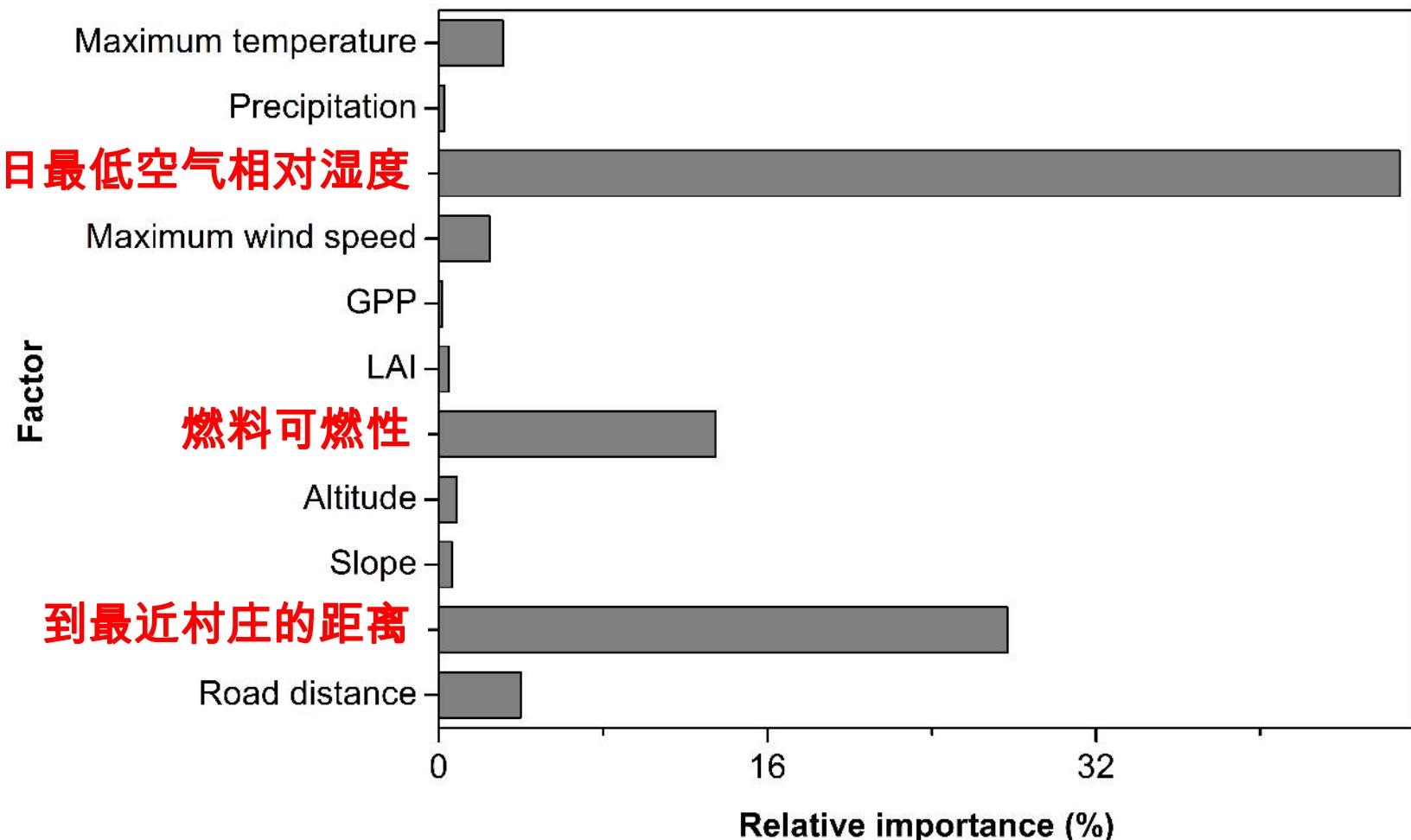


□ 林火探测差异的影响因子



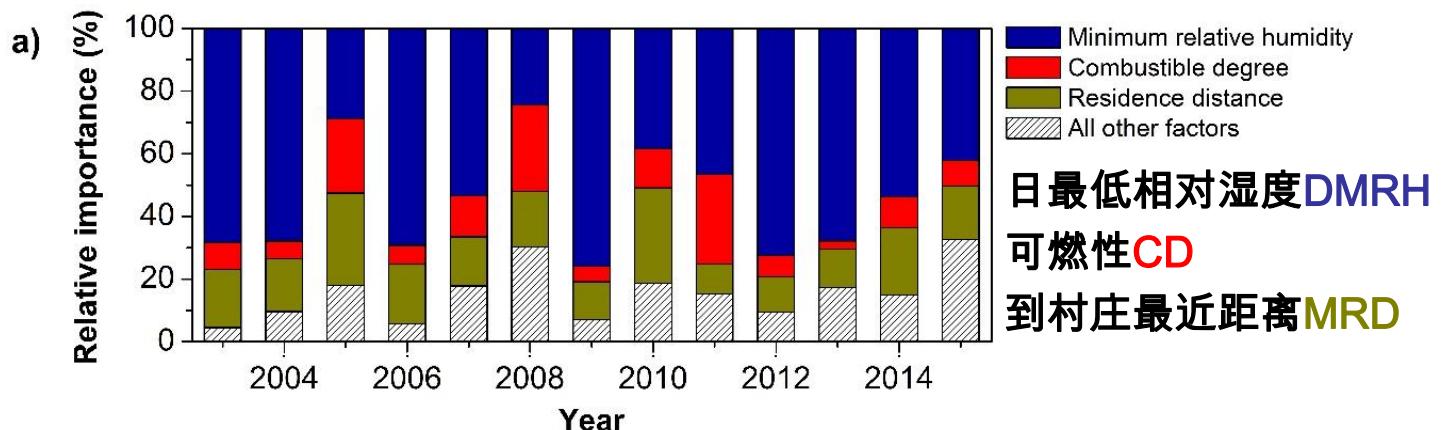
1、云南林火格局与驱动机制

基于Logistic模型的Ignition事件因子贡献

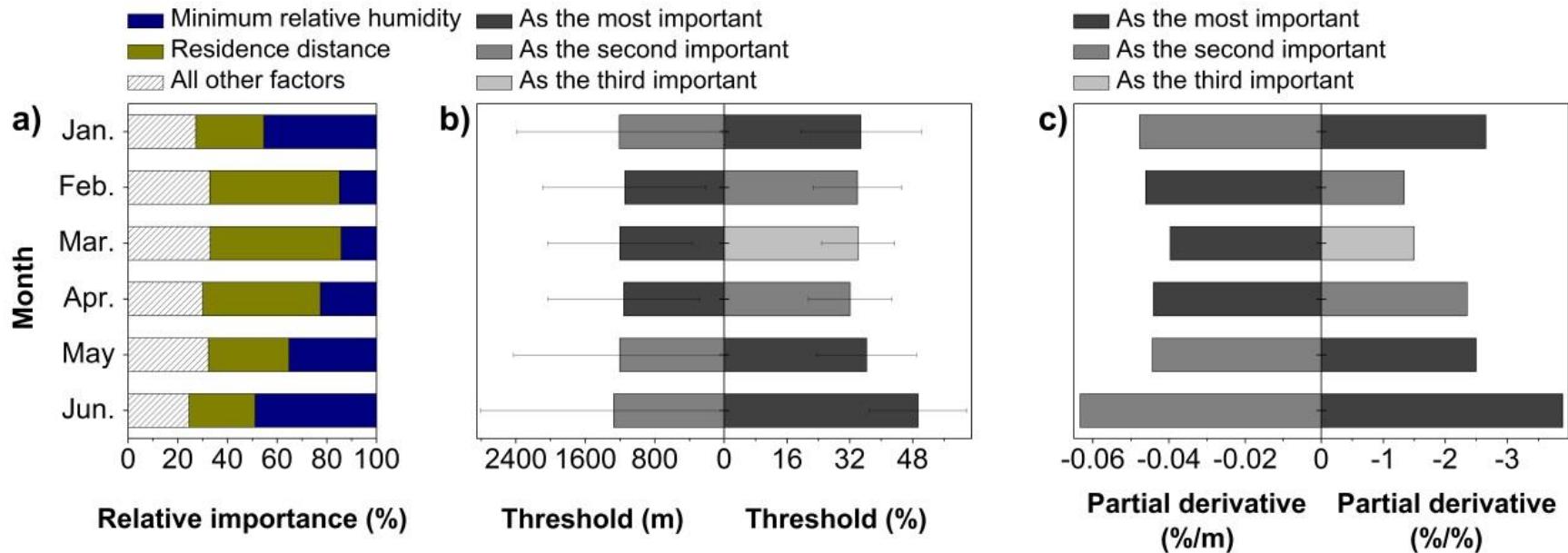


1、云南林火格局与驱动机制

逐年归因：

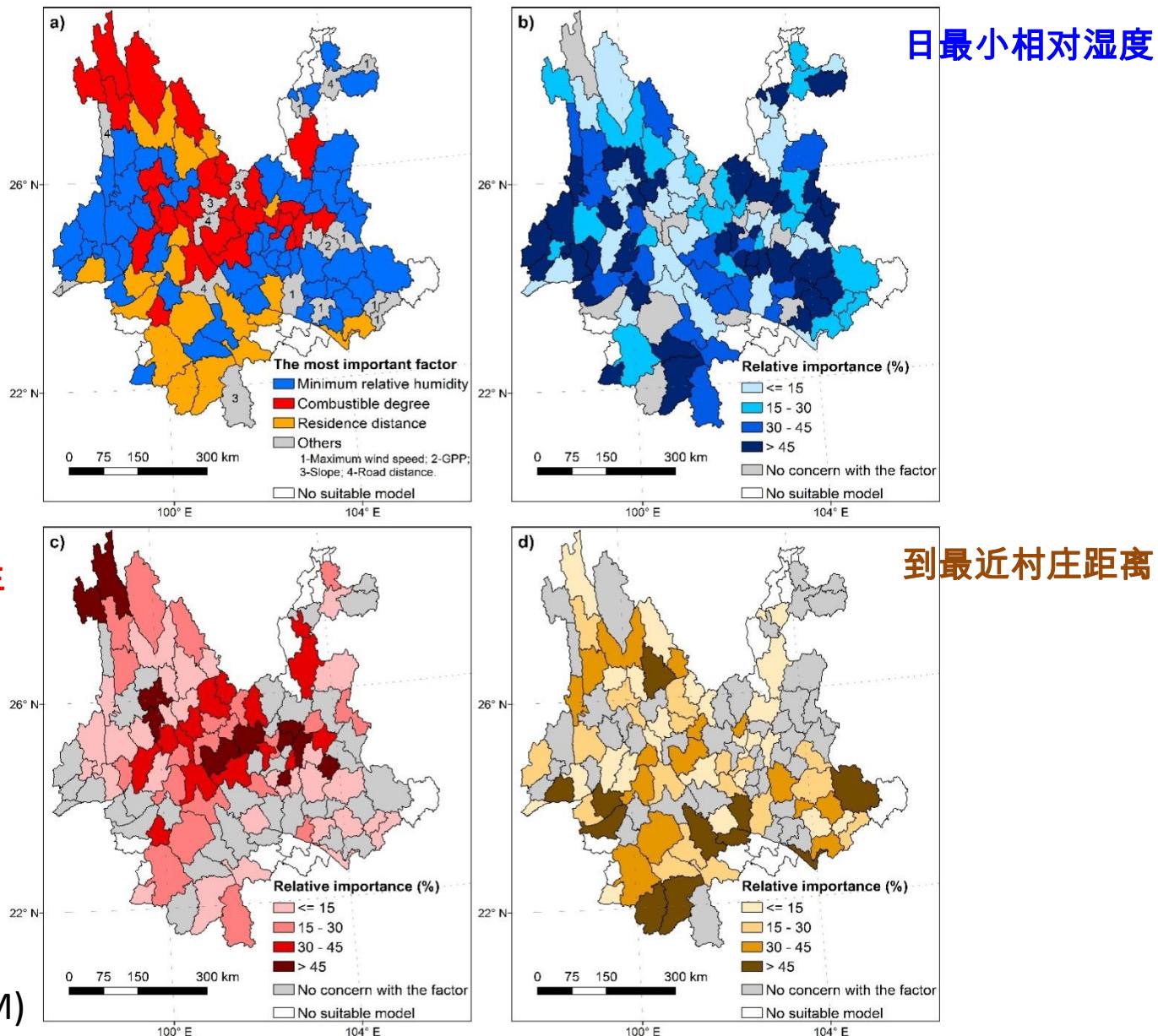


各月归因：



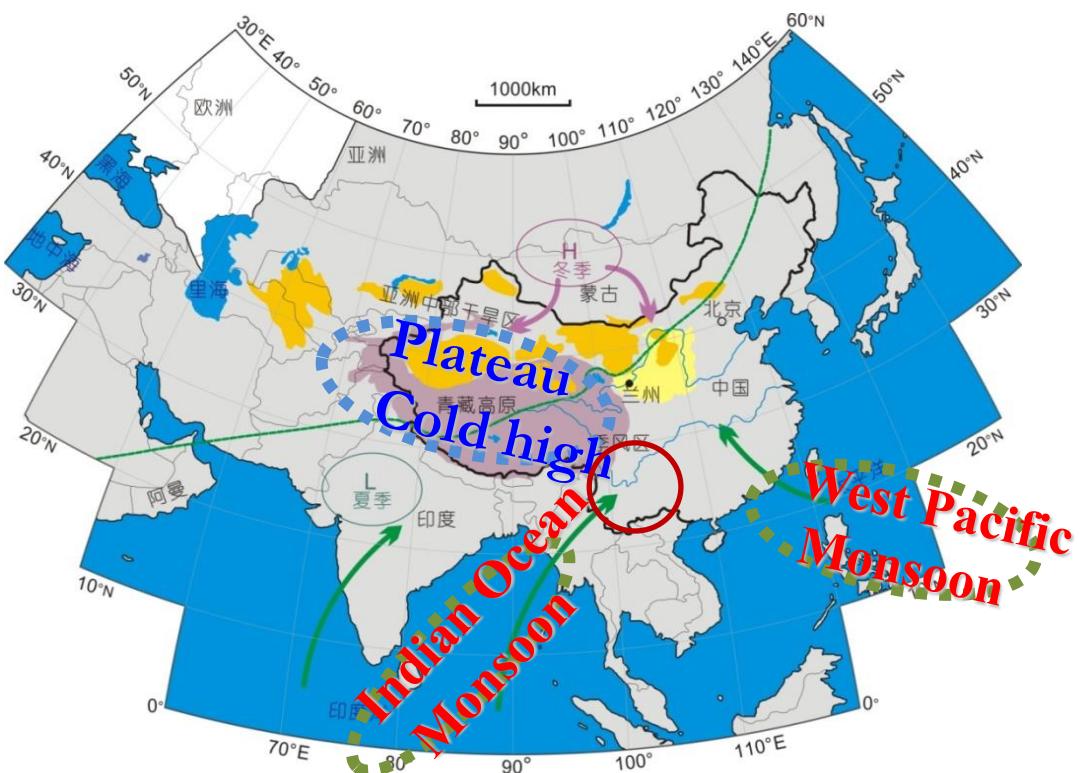
1、云南林火格局与驱动机制

首要因子
空间格局

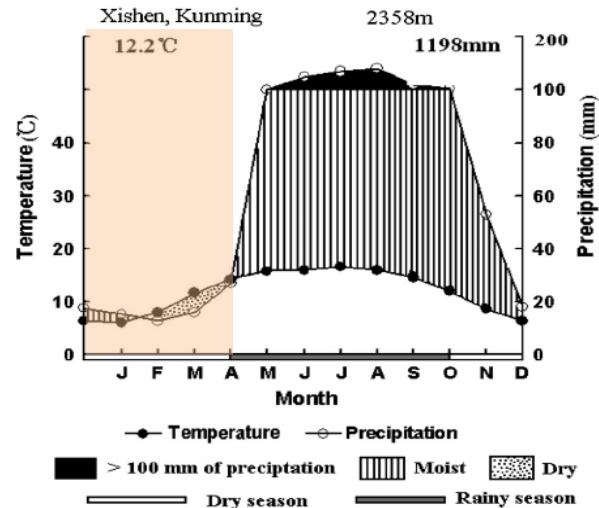


1、云南林火格局与驱动机制

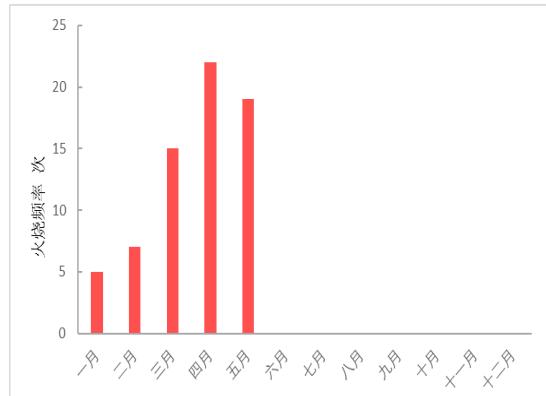
云南林火气候的域外因素——季风和大洋暖池



Climate-降水季节性

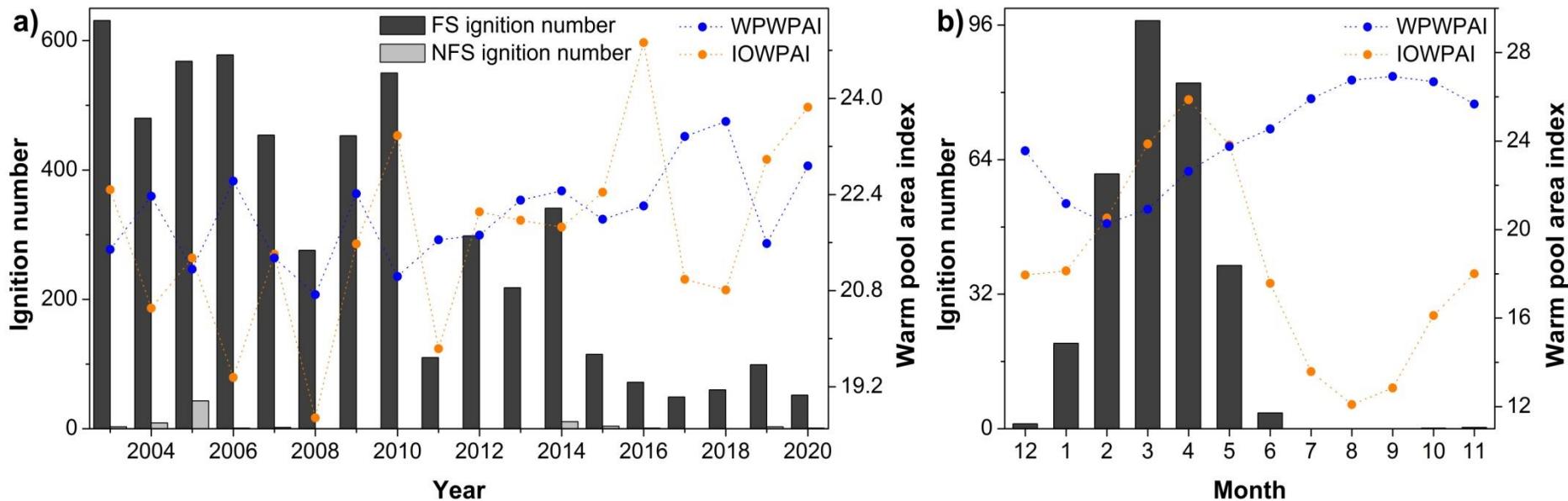


Fire-发生频率季节性



1、云南林火格局与驱动机制

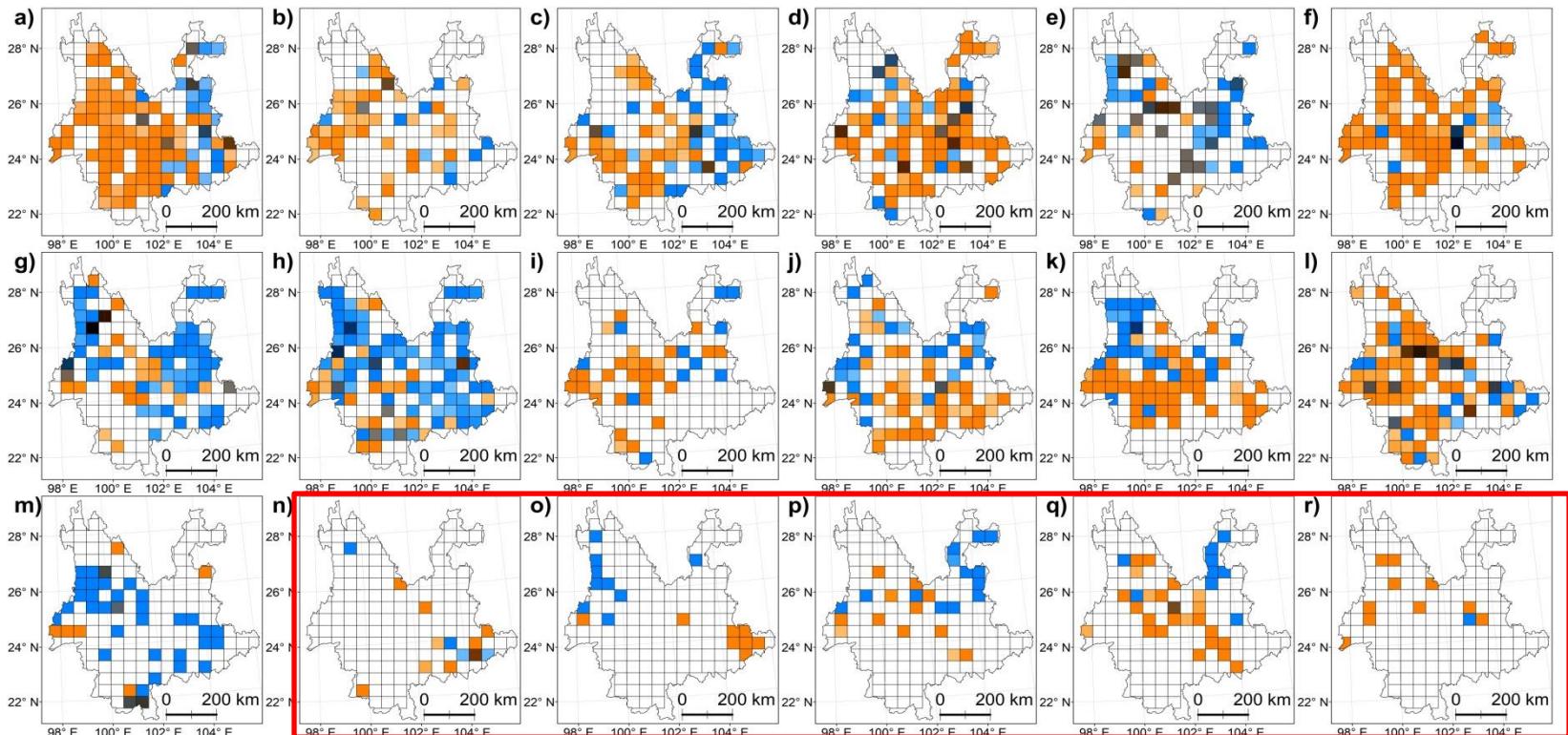
- 2003-2015年共发生5146次林火
- 平均每年396 次，过火面积 1.08×10^3 ha



- 林火频率与印度洋暖池指数IOWPAI的季节变化有显著的正相关
- 与西太暖池指数WPWPAI的年际变化的负相关较IOWPAI更明显

1、云南林火格局与驱动机制

- IO和WP暖池对林火年际变化(2003-2020)的影响在空间上相互消长，
- IO和WP暖池的影响以分别云南西南和东北为主；
- 近5年来，暖池效应在减弱



1、云南林火格局与驱动机制

认识1：

- 气候对云南高原的林火发生兼具直接（空气湿度）和间接（通过植被——可燃物）的影响

推论：云南林火多发区植被是fire-prone ecosystem

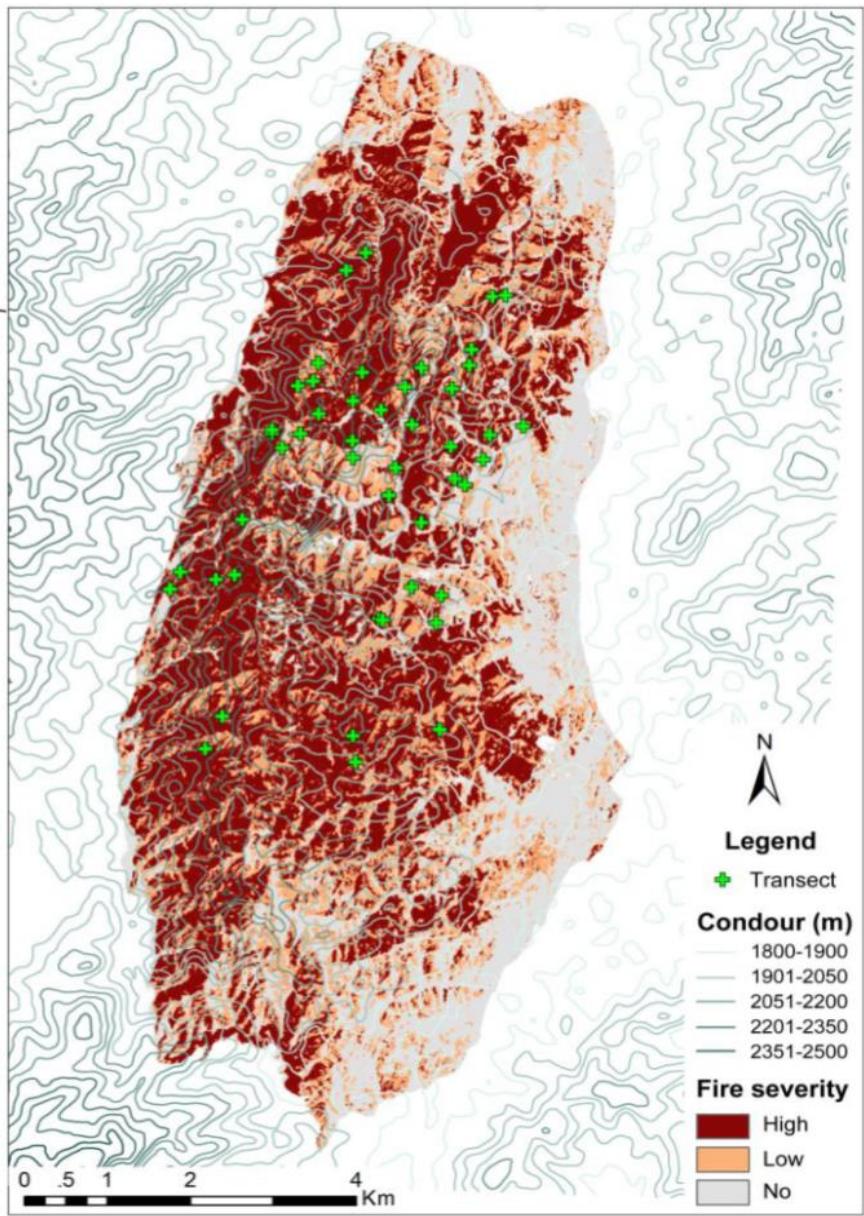
- 植被易受火干扰（气候和植被决定）
- 植被对火干扰具有稳定性和恢复力
- 植被的功能性状对火干扰具有关联性和适应性

2、云南高原森林火后群落构建

科学问题：云南高原森林群落对火干扰的稳定性如何？

- 火后森林植物种群更新速率
- 火后植被盖度和生物量的恢复速率
- 火后森林群落组成变化

2.1 种群、物种多样性恢复

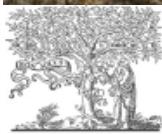


2013. 4. 23云南禄丰县勤丰镇特大火灾

- 约2000hm²过火面积
- 当年9~10月开始火后森林更新调查
- 10m×100m样带47条



Contents lists available at ScienceDirect



Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Early post-fire regeneration of a fire-prone subtropical mixed Yunnan pine forest in Southwest China: Effects of pre-fire vegetation, fire severity and topographic factors ☆

Jie Han ^a, Zehao Shen ^{a,*}, Lingxiao Ying ^a, Guixiang Li ^b, Anping Chen ^c

2.1 种群、物种多样性恢复

火后种群更新旺盛，恢复很快，当年更新群落相似性达到~53%

Table 3 Early post-fire regeneration of forests in different regions. AP, annual mean precipitation; MAT, mean annual temperature;

Vegetation type	Region	AP (mm)	MAT (°C)	Months after fire	Reg. density (stems ha ⁻¹)	Notes	References
Mixed pine forest	Semi-humid subtropic, China	912	14.3	5	$10^5 \pm 10^4$		This study
Chaco Serrano forest	Central Argentina	644	13.8	12	4567 ± 170	>90% are resprouts	Torres et al. (2014)
Woodland	Mediterranean	1400~1600	10~12.5	2	700~1200	resprouts	Maia et al. (2012)
Larix forest	Cool temperate North Japan	1560	7.1	18 24	$5800\text{--}13,900$ 1.0×10^5 1.7×10^5	Resprouts Seedlings	Goto (2004)

3.3. Pre- and post-fire community species composition similarity (SCS)

SCS between the early post-fire regeneration and pre-fire communities ranged from 0.07 to 0.914 with a mean \pm SD of 0.530 ± 0.222 for the Morisita–Horn index (with population density included). 84.8% of regenerating stems in all transects were composed of the six most abundant species, *P. yunnanensis*, *P. yunnanensis* var. *pygmaea*, *L. ovalifolia*, *Cyclobalanopsis glaucoidea*, *L.*

2.1 种群、物种多样性恢复

种群密度和物种构成恢复的调控因子

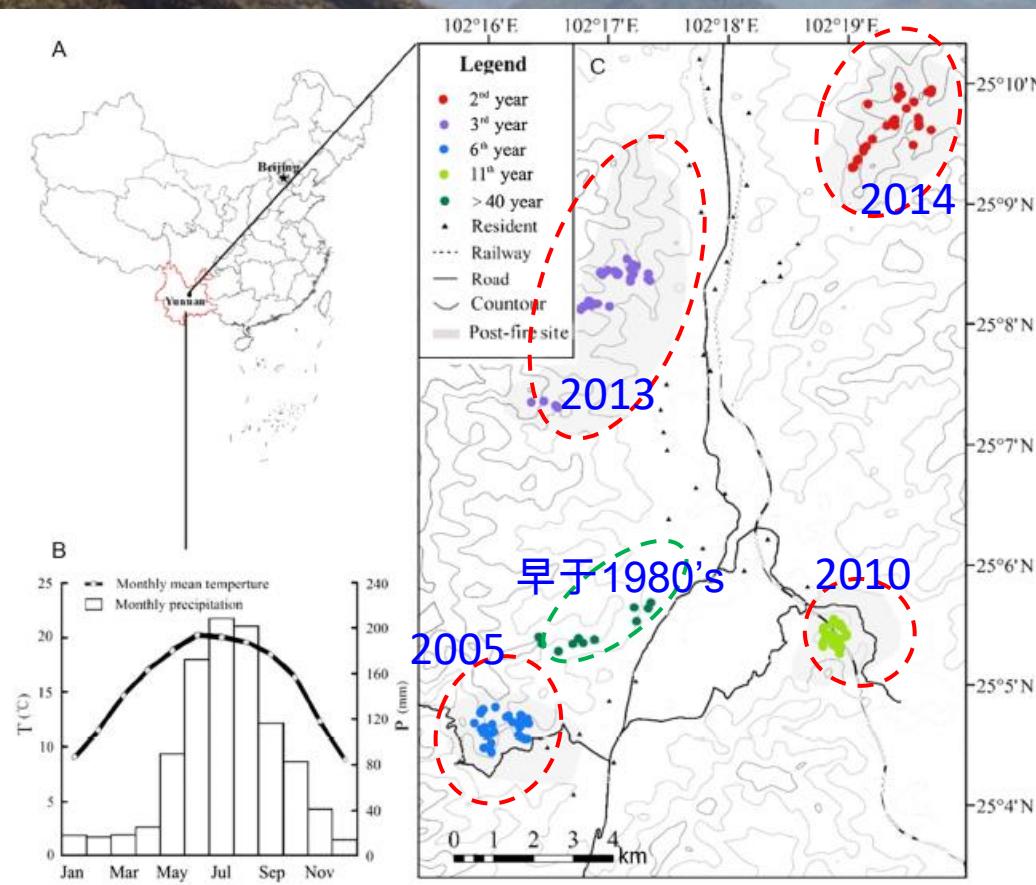
Variable	Density		SCS		Density		SCS	
	%IncMSE	rank	%IncMSE	Rank	R ²	P	R ²	P
Elevation	15.60	1	13.07	1	0.549	2.4e-09	0.272	0.0001
Type [†]	16.36	2	10.92	2	0.550	1.5e-07	0.294	0.001
Position [†]	3.44	3	6.79	4	0.367	5.6e-05	0.215	0.004
Slope	2.76	4	7.52	3	0.117	0.012	0.157	0.004
Aspect	2.02	5	-2.08	7	0.026	n.s.	-	n.s.
TBA	1.65	6	4.96	5	0.201	0.002	0.144	0.012
Shape [†]	1.56	7	-2.02	6	-	n.s.	-	n.s.
f.ratio	0.66	8	-2.90	8	-	n.s.	-	n.s.
Vari.exp%	56.2%		28.7%					

- 滇中植被对火烧表现了种群更新和物种构成上较快的恢复速率
——即对火干扰的弹性；
- 生境和火前群落类型，而非火烧烈度，决定火后的植被恢复力

2.2 群落物种组成变化

火后群落更新的群落组成变化

- 火后更新群落Beta多样性格局与及环境和空间因素的影响
- 火干扰与环境的历史效应对植物群落构建的贡献



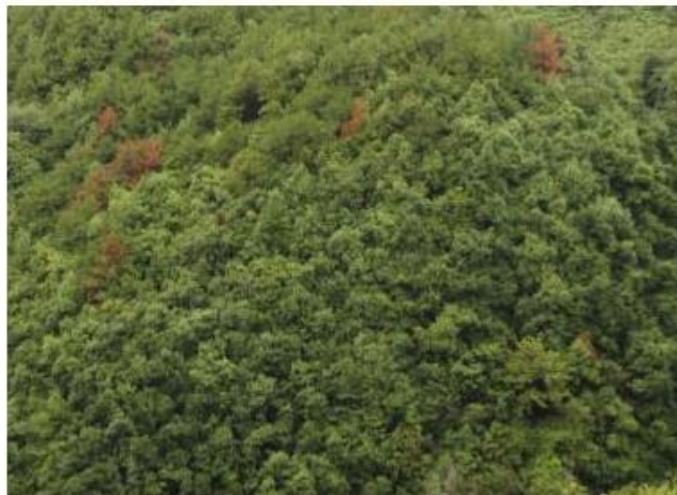
2.2 群落物种组成变化



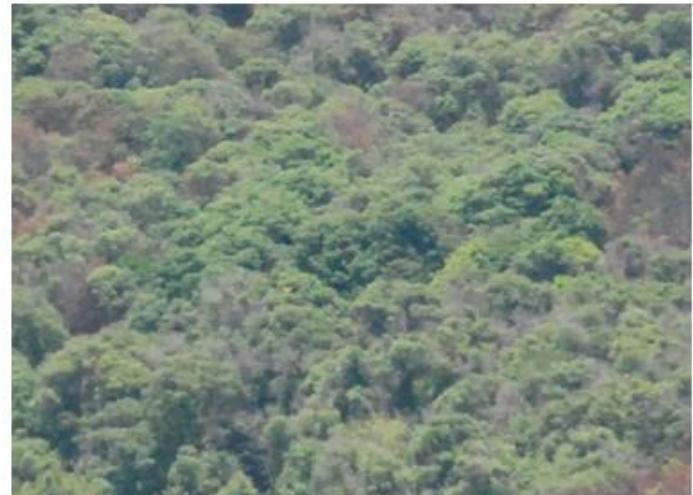
2 year-since-fire

3 year-since-fire

6 year-since-fire



11 year-since-fire



> 40 year-since-fire

2.2 群落物种组成变化

4) 多样性分析方法 :

- α diversity: Species richness per plot
- β diversity: Sorenson = turnover + nestedness

$$\beta = \beta_{sor} = \frac{\max(b,c) + \min(b,c)}{2a + \max(b,c) + \min(b,c)}$$

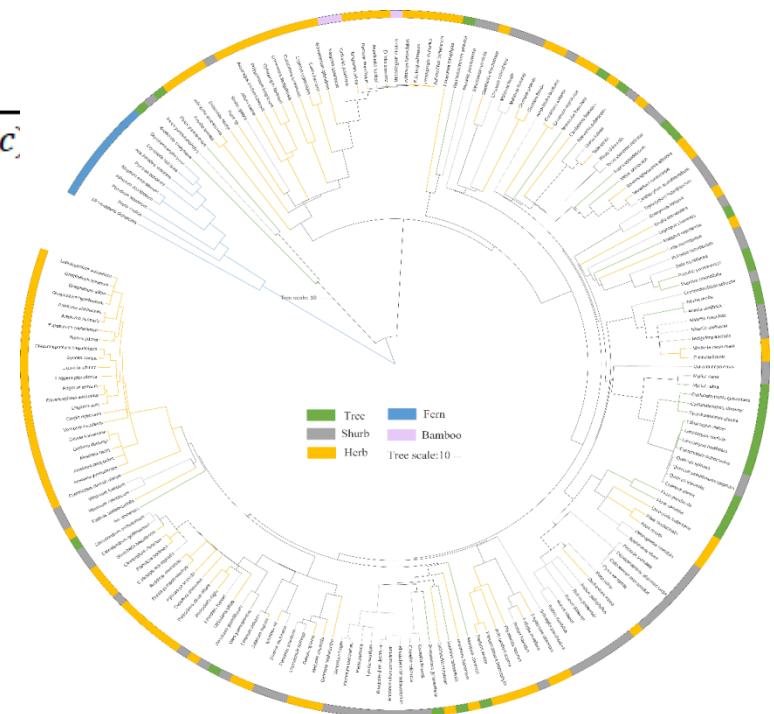
$$\beta_{nes} = \frac{\max(b,c) - \min(b,c)}{2a + \min(b,c) + \max(b,c)} \times \frac{a}{a + \min(b,c)}$$

$$\beta_{turnover} = \frac{\min(b,c)}{a + \min(b,c)}$$

- Phylogenetic structure:

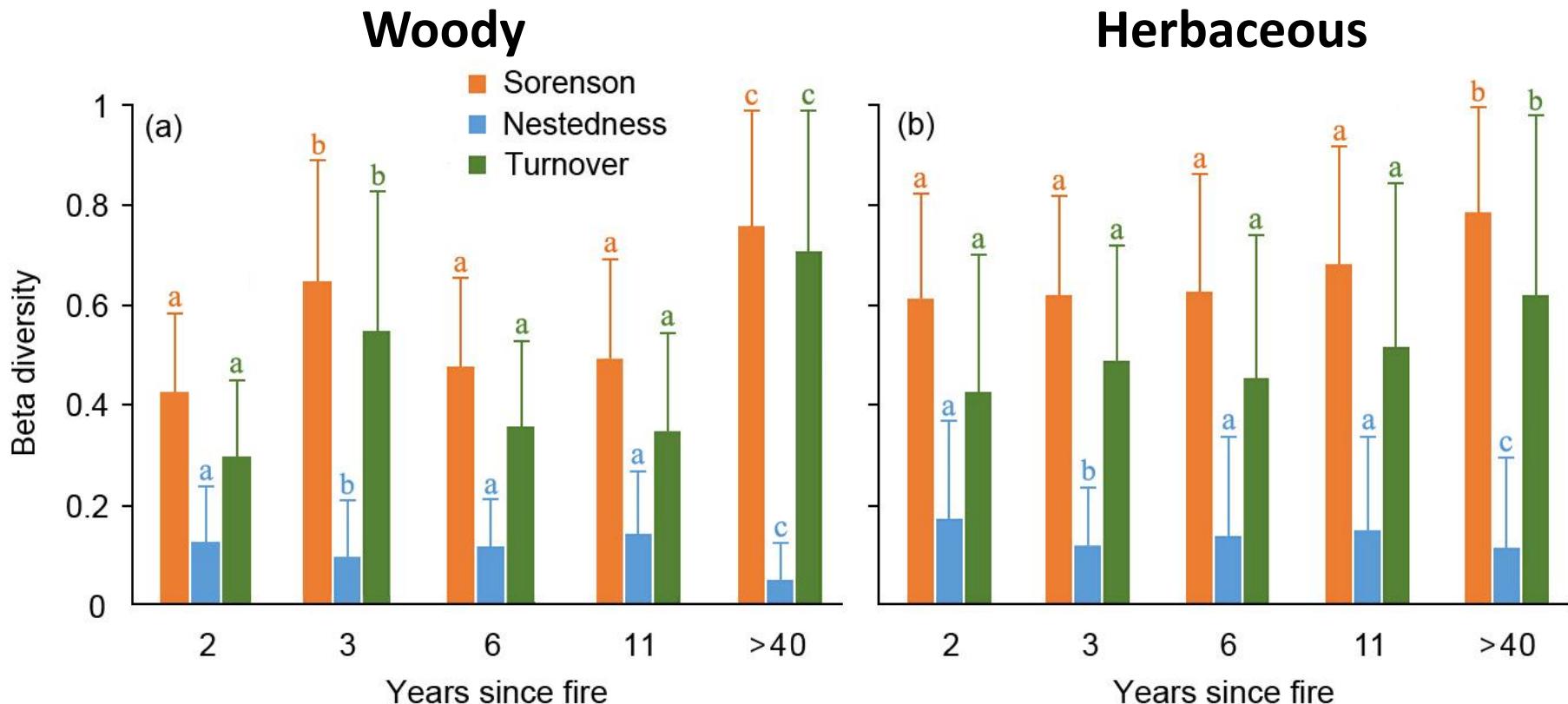
$$NRI = \frac{MPD_{observed} - \text{mean}(MPD_{null})}{sd(MPD_{null})}$$

- NRI < -1, overdispersed
- NRI > 1, clustering
- -1 < NRI < 1, random



2.2 群落物种组成变化

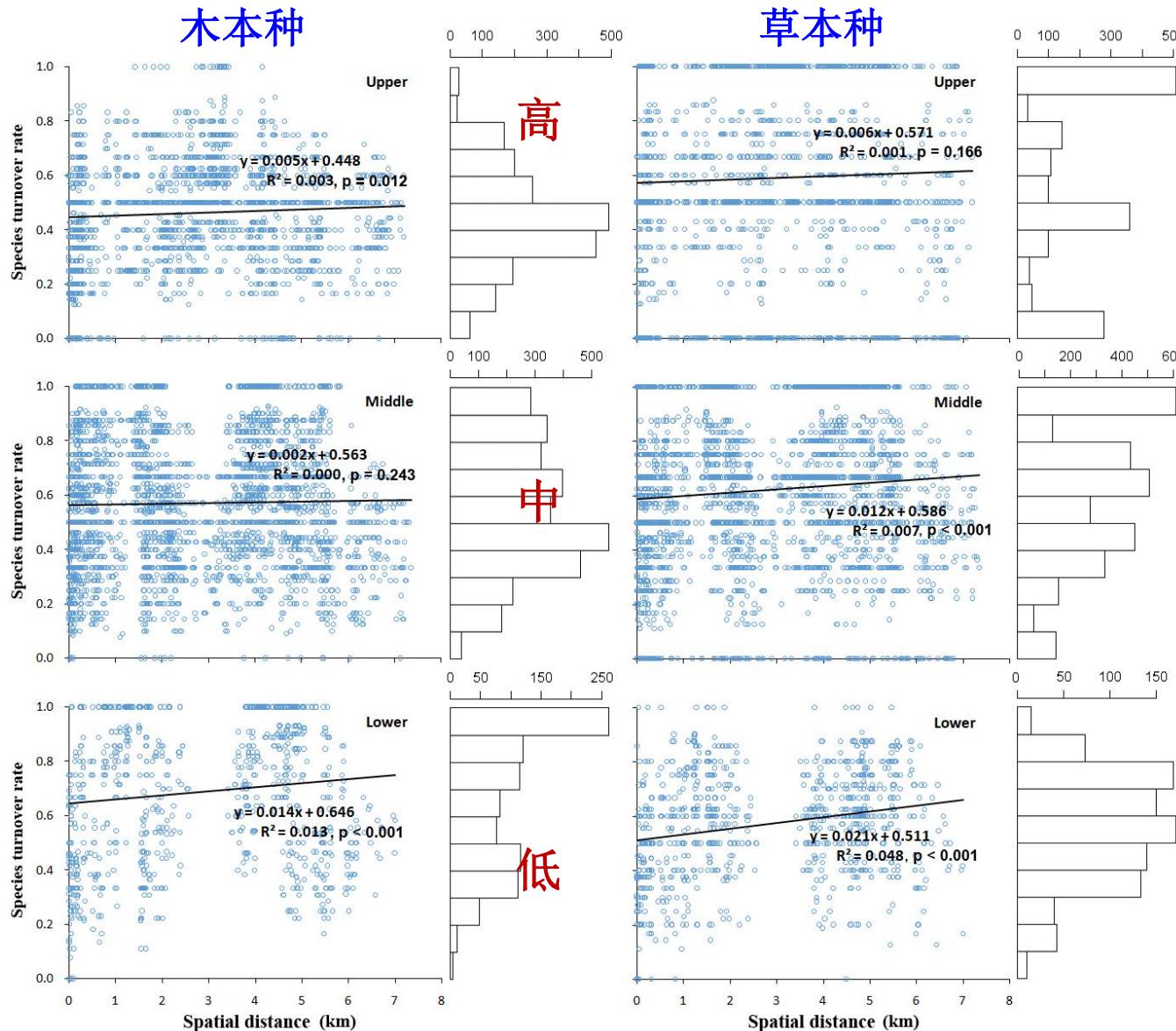
1) 火后植物群落间 β 多样性的年际差异



火后更新群落的物种更替随火后年份而增加但差别不大，草本物种更替更明显，且有增大趋势

2.2 群落物种组成变化

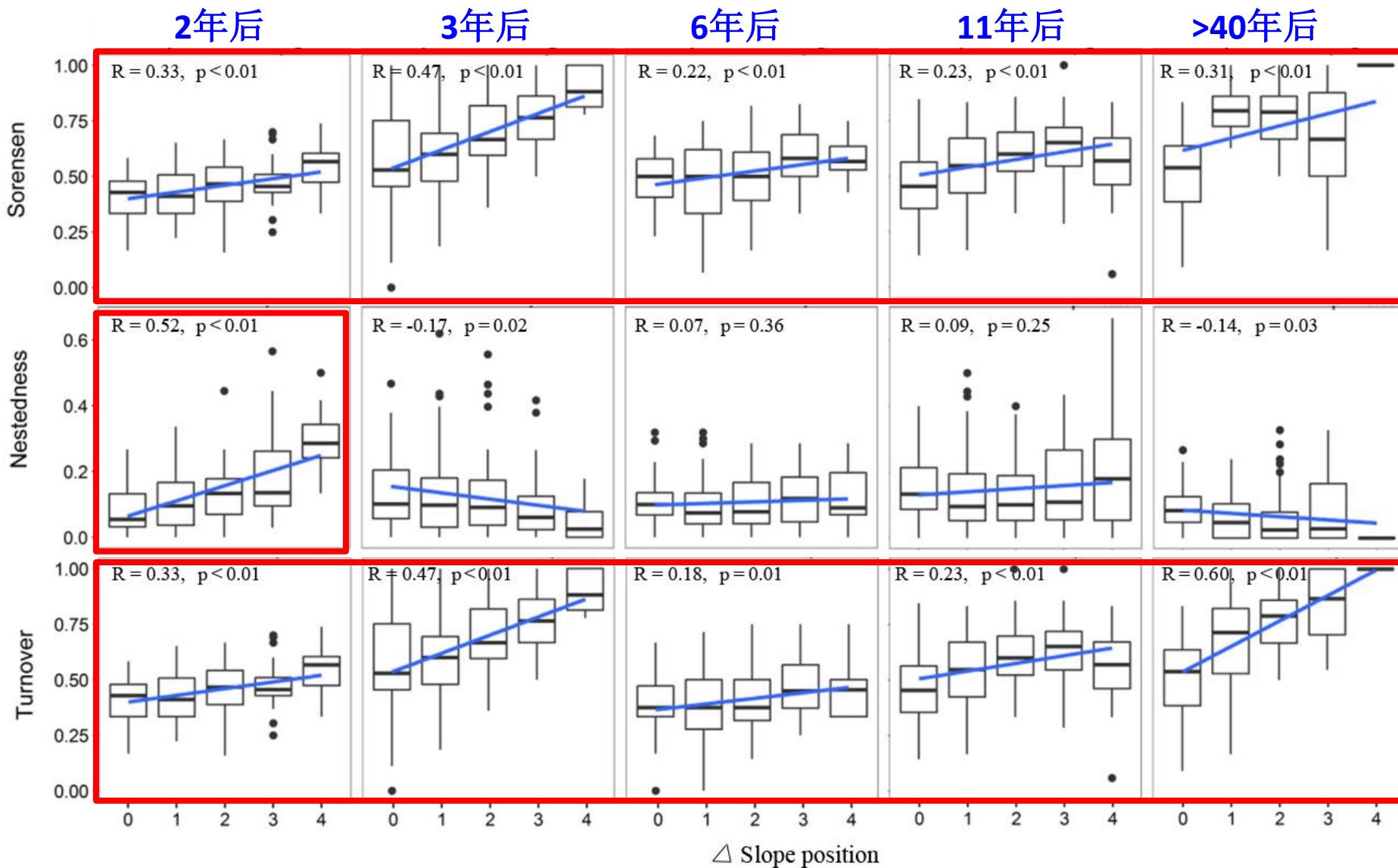
2) 不同坡位群落物种更替与空间距离的关系



- 木本物种随空间距离增大的替换速率低于草本种；
- 随坡位上升，物种替换速率降低

2.2 群落物种组成变化

3) 坡位差与群落 β 多样性的关系(木本)



2.2 群落物种组成变化

初步结论：

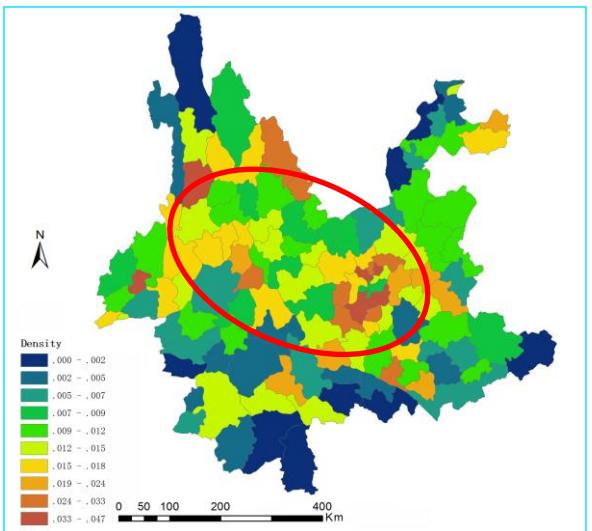
- 1) 地形梯度影响火后群落更新的空间格局和更替速率
- 2) 火干扰强化了地形主导的环境过滤和初始植物区系驻留机制，决定了火后植被结构的确定性和随机性构建过程

3、云南高原森林植物性状火干扰适应

科学问题：

- 植被的功能性状如何适应火干扰？
- 群落木本物种更新的火干扰适应策略

滇中高原常见木本植物的干扰适应策略普遍存在



Scientific name	Growth form	Presence	Post-cut resprouting	Post-fire resprouting	Serotiny
<i>Castanopsis delavayi</i>	Tree	V	Yes	Yes	No
<i>Castanopsis orthacantha</i>	Tree	V	Yes	Yes	No
<i>Cyclobalanopsis delavayi</i>	Tree	V	Yes	Yes	No
<i>Cyclobalanopsis glaucoidea</i>	Tree	V	Yes	Yes	No
<i>Lithocarpus dealbatus</i>	Tree	V	Yes	Yes	No
<i>Keteleeria evelyniana</i>	Tree	V	Yes	Yes	No
<i>Olea yunnanensis</i>	Tree	V	Yes	Yes	No
<i>Quercus aliena</i> var. <i>aculeserrata</i>	Tree	IV	Yes	Yes	No
<i>Albizia mollis</i>	Tree	III	Yes	Yes	No
<i>Cupressus duclouxiana</i>	Tree	III	No	No	Yes
<i>Lithocarpus confinis</i>	Tree	III	Yes	Yes	No
<i>Lithocarpus craibananus</i>	Tree	III	Yes	Unconfirmed	No
<i>Morus australis</i>	Tree	III	Yes	Unconfirmed	No
<i>Prunus conradinae</i>	Tree	III	Yes	Unconfirmed	No
<i>Pinus armandii</i>	Tree	III	No	No	No
<i>Pinus yunnanensis</i> var. <i>yunnanensis</i>	Tree	III	No	No	Yes
<i>Pistacia chinensis</i>	Tree	III	Yes	Yes	No
<i>Pistacia weinmannifolia</i>	Tree	III	Yes	Yes	No
<i>Quercus acutissima</i>	Tree	III	Yes	Yes	No
<i>Quercus variabilis</i>	Tree	III	Yes	Yes	No
<i>Quercus gilliana</i>	Tree	III	Yes	Yes	No
<i>Alnus nepalensis</i>	Tree	II	No	No	No
<i>Quercus senescens</i>	Tree	II	Yes	Yes	No
<i>Eurya nitida</i>	Tall shrub	V	Yes	Yes	No
<i>Lindera communis</i>	Tall shrub	V	Unconfirmed	Unconfirmed	No
<i>Lyonia ovalifolia</i>	Tall shrub	V	Yes	Yes	No
<i>Ternstroemia gymnanthera</i>	Tall shrub	V	Yes	Yes	No
<i>Toxicodendron succedaneum</i>	Tall shrub	V	Yes	Yes	No
<i>Vaccinium sprengelii</i>	Tall shrub	V	Yes	Yes	No
<i>Schima argentea</i>	Tall shrub	IV	Yes	Yes	No
<i>Diospyros mollifolia</i>	Tall shrub	III	Yes	Unconfirmed	No
<i>Pyrus pashia</i>	Tall shrub	III	Yes	Yes	No
<i>Schoepfia jasminodora</i>	Tall shrub	III	Yes	Yes	No
<i>Styrax grandiflora</i>	Tall shrub	III	Yes	Yes	No
<i>Zanthoxylum esquiralii</i>	Tall shrub	III	Yes	Yes	No
<i>Ilex micrococca</i>	Tall shrub	II	Yes	Yes	No
<i>Zanthoxylum armatum</i>	Tall shrub	II	Yes	Yes	No
<i>Fargesia</i> sp.	Shrub	V	Yes	Yes	No
<i>Hypericum uralum</i>	Shrub	V	Yes	Yes	No
<i>Michelia yunnanensis</i>	Shrub	V	Yes	Yes	No
<i>Myrsine africana</i>	Shrub	V	Yes	Yes	No
<i>Nothonanox delavayi</i>	Shrub	V	Yes	Unconfirmed	No
<i>Pinus yunnanensis</i> var. <i>pygmaea</i>	Shrub	V	Yes	Yes	Yes
<i>Rhododendron microphyton</i>	Shrub	V	Yes	Yes	No
<i>Rhododendron spinuliferum</i>	Shrub	V	Yes	Yes	No
<i>Smilax siderophylla</i>	Shrub	V	Yes	Yes	No
<i>Camellia reticulata</i>	Shrub	IV	Yes	Unconfirmed	No
<i>Campylotropis polyantha</i>	Shrub	IV	Yes	Yes	No
<i>Elsholtzia rugulosa</i>	Shrub	IV	Yes	Yes	No
<i>Reinwardtia indica</i>	Shrub	IV	Yes	Unconfirmed	No
<i>Rhododendron decorum</i>	Shrub	IV	Yes	Yes	No
<i>Rhamnus virgatus</i>	Shrub	IV	Yes	Yes	No
<i>Vaccinium figile</i>	Shrub	IV	Yes	Yes	No

^a I, II, III, IV, and V indicate a range of frequency of each species from most rare (I) to most common (V).

滇中植物火适应特征



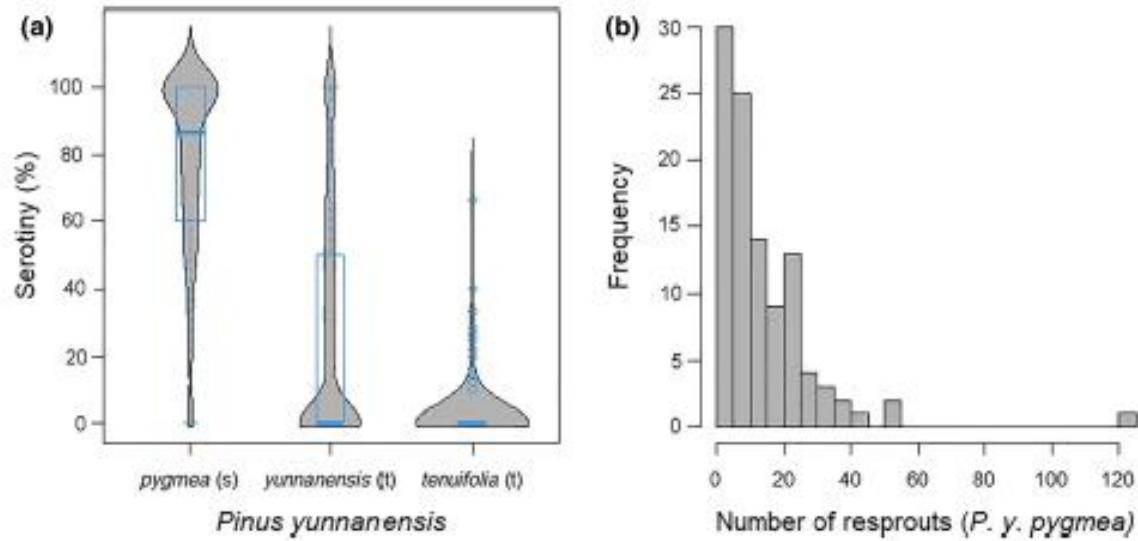
3.1 云南松的火适应特征

Pinus yunnanensis 典型的fire-prone species



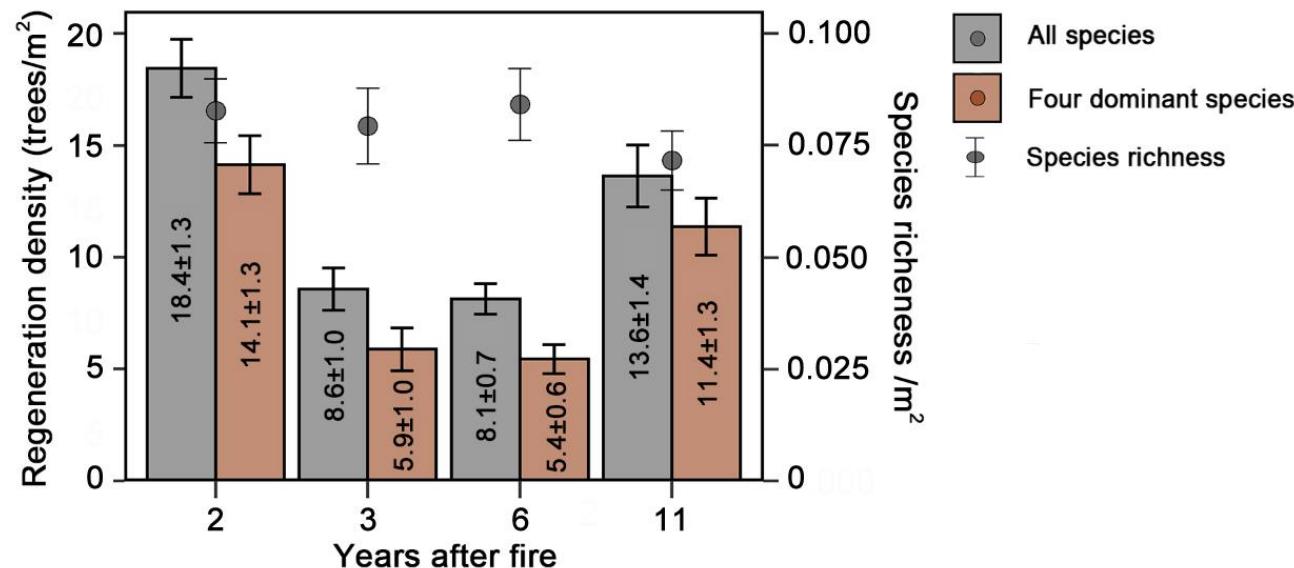
关键性状：

- 分化出亚种—地盘松*P. yunnanensis* var. *pygmaea*
- 球果延迟开裂Serotiny
- 火后有性繁殖早熟
- 强烈萌枝resprouting
- 林冠矮化



(Pausas, ..., Shen*, 2021, Ecology)

3.2 火干扰适应的木本物种更新策略



云南松 *Pinus yunnanensis*



毛叶珍珠花 *Lyonia villosa*



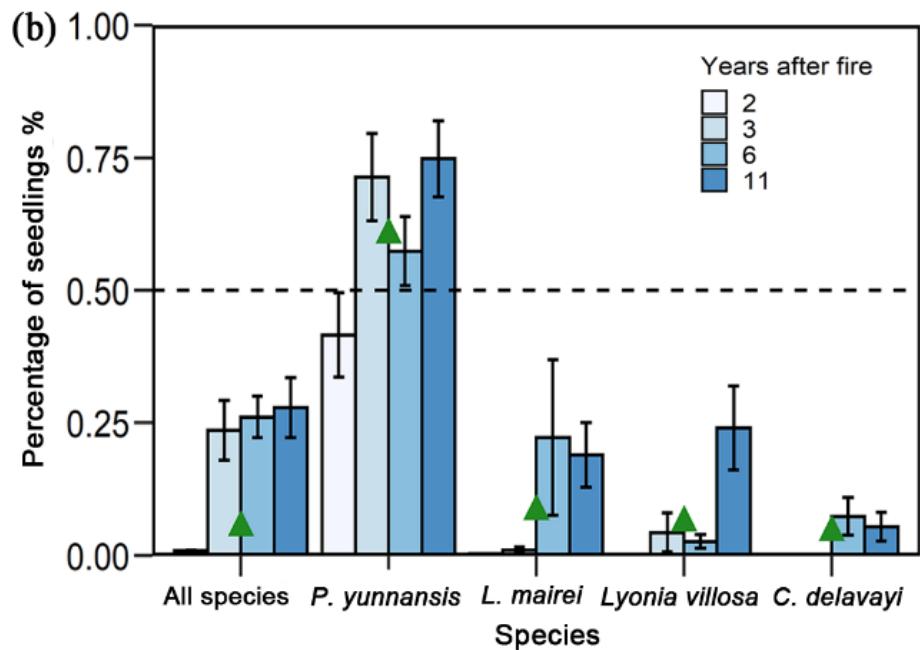
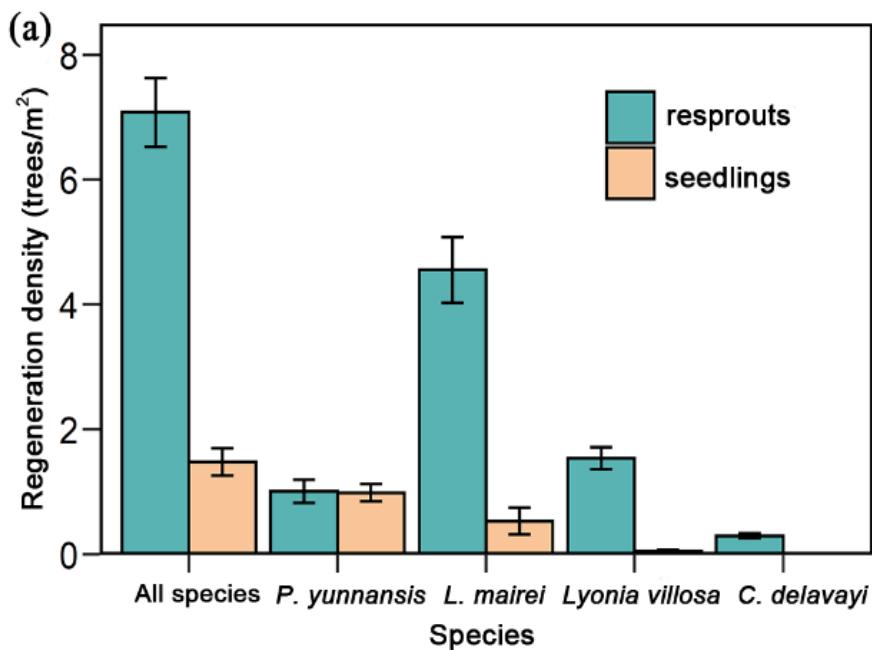
滇石栎 *Lithocarpus mairei*



黄毛青冈 *Cyclobalanopsis delavayi*

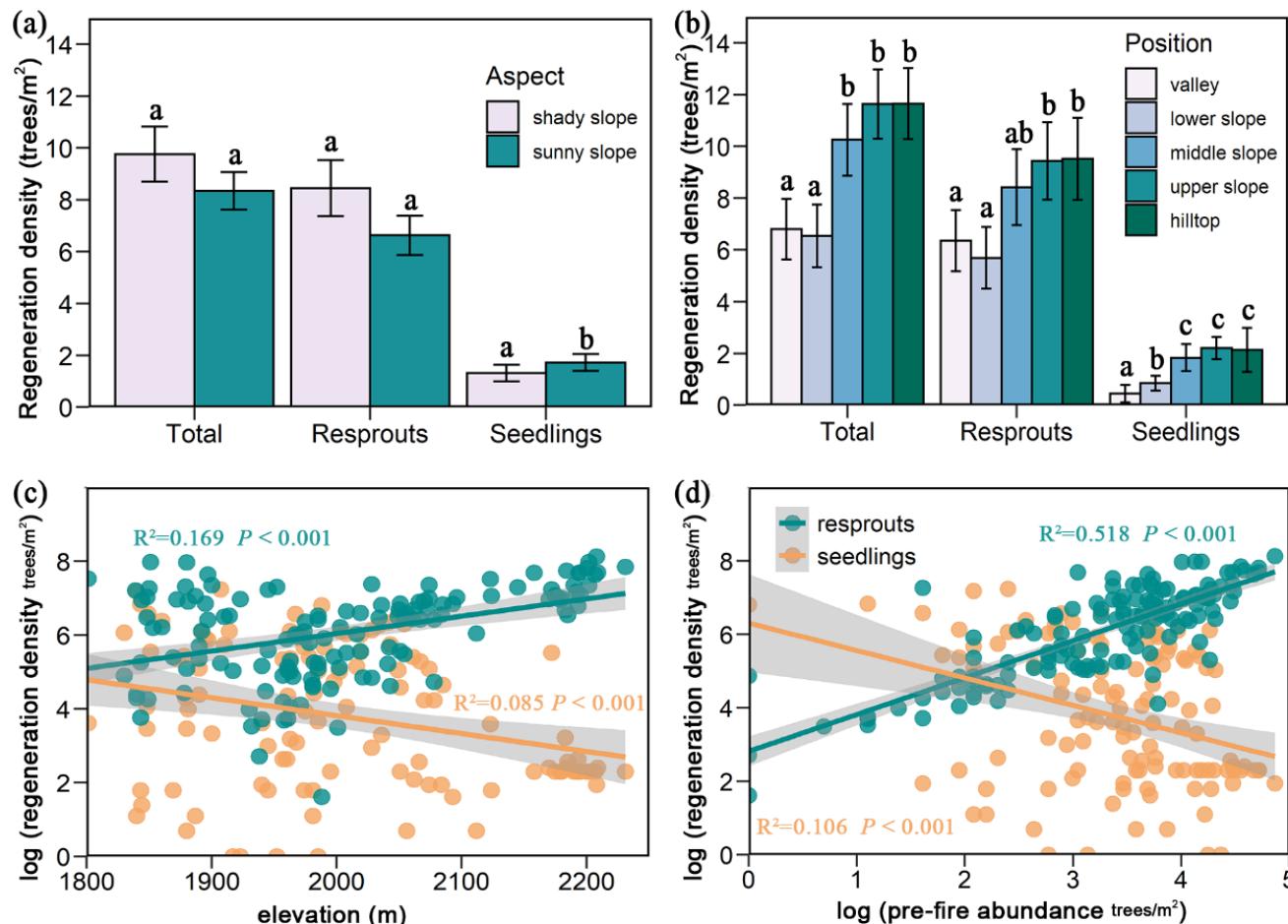
3.2 火干扰适应的木本物种更新策略

- 云南松种子更新、萌发更新各占一半；阔叶树以萌发更新为主；
- 萌发更新居先、种子更新随后



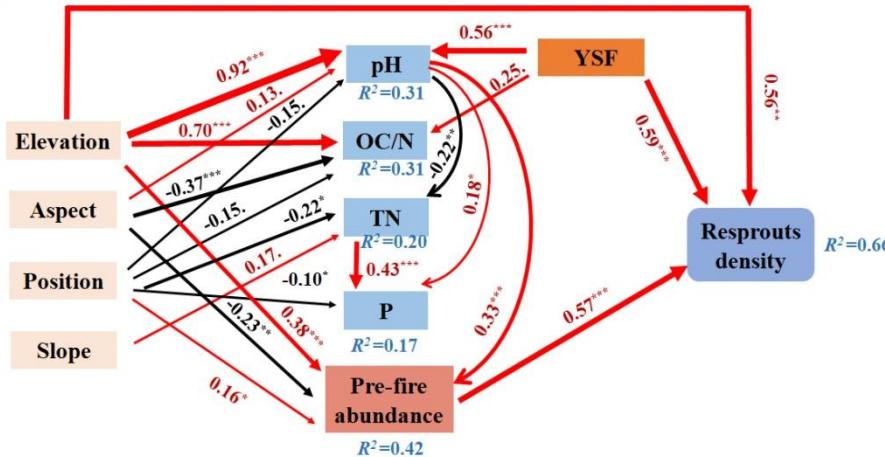
3.2 火干扰适应的木本物种更新策略

- Seeding和Sprouting更新密度的坡向坡位格局差异明显
- 海拔和火前植被多盖度的对更新密度的效应相反

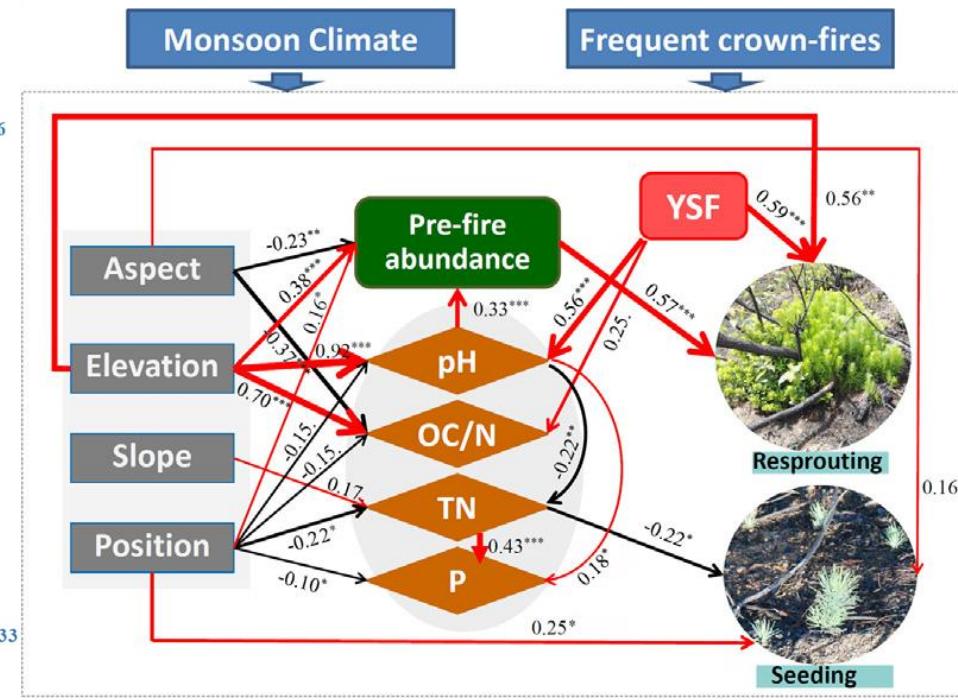
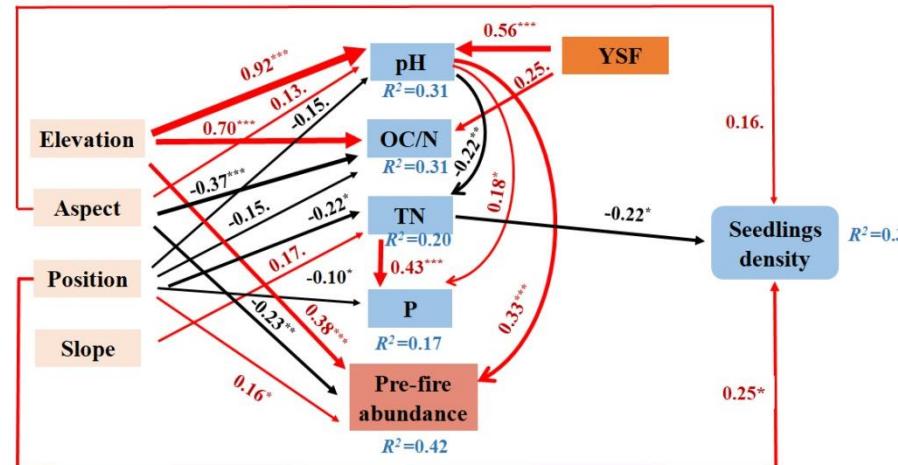


3.2 火干扰适应的木本物种更新策略

(b) N=120, Fisher's C = 27.17, AIC= 105.17, P=0.855



(c) N=120 Fisher's C = 27.17 AIC= 105.17 P=0.855

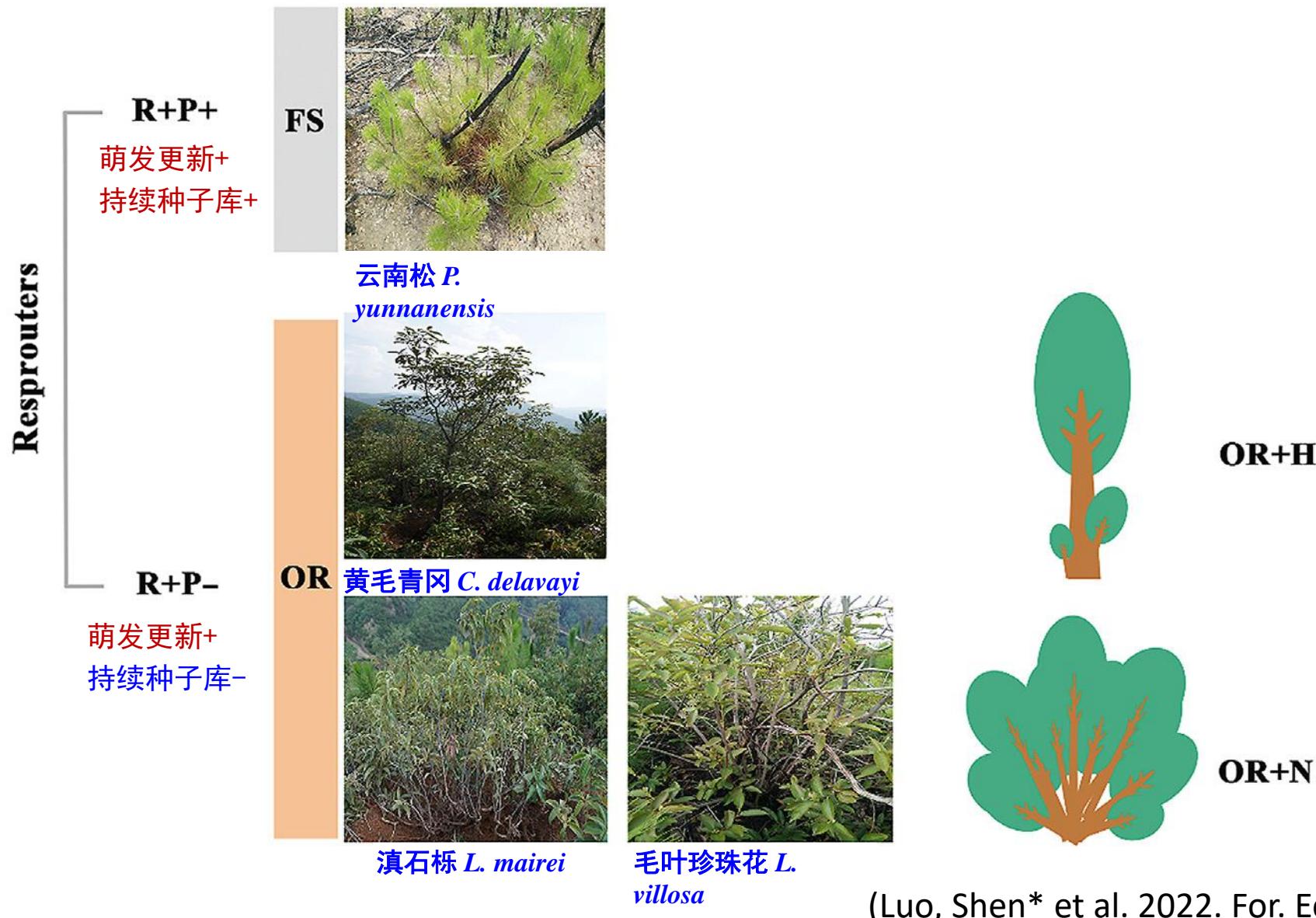


3.2 火干扰适应的木本物种更新策略

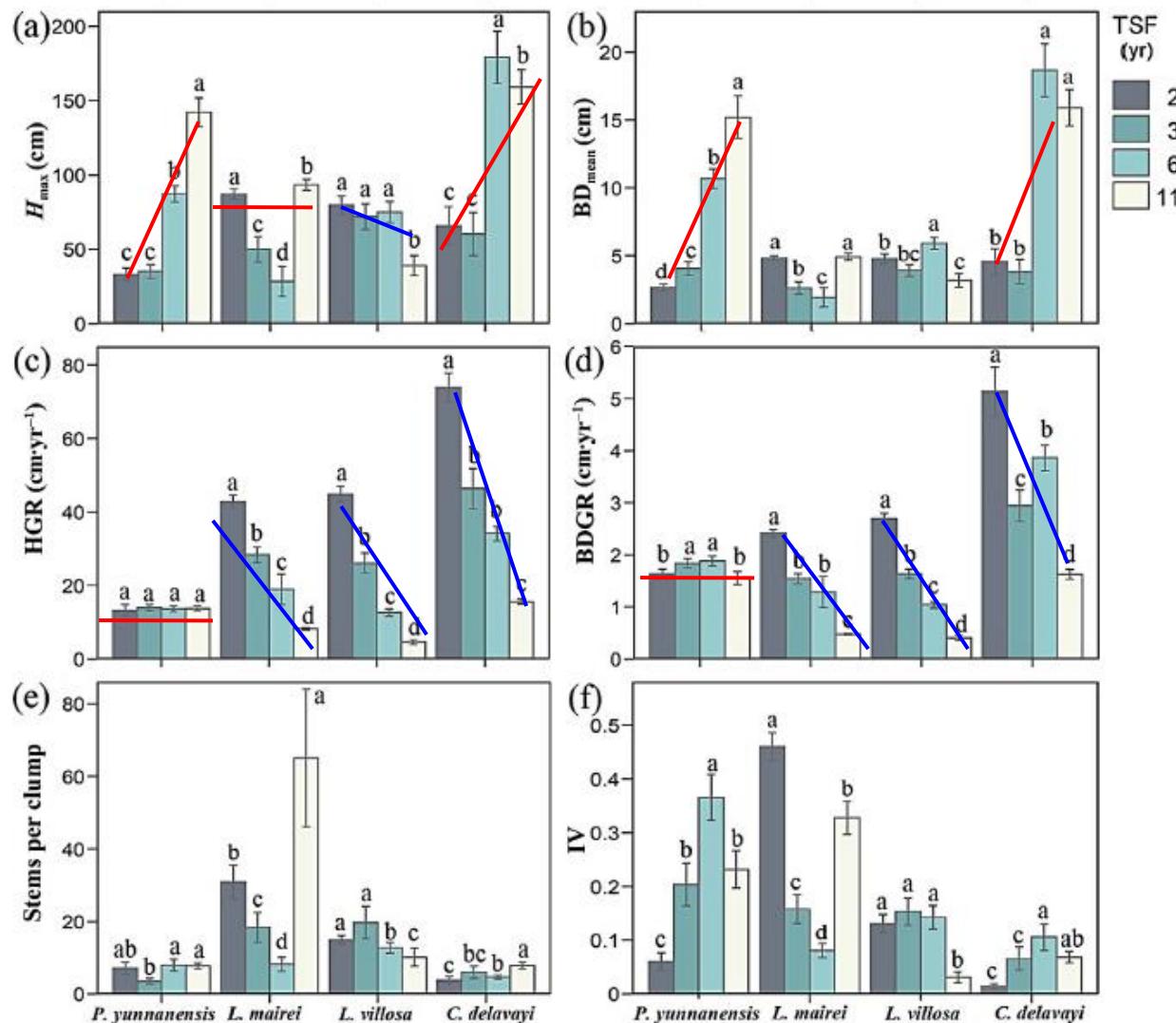
初步结论：

- 火后更新以萌发苗为主，实生苗较少且出现较晚；海拔、火前丰度和土壤pH值较高的生境，火后更新密度较大。
- 萌发苗密度受火前丰度、海拔、土壤pH值和火后年份的显著影响；实生苗优先出现在贫瘠的生境中，主要受地形位置和土壤养分的影响。
- 环境对萌发($R^2=0.66$)的约束强于播种($R^2=0.33$)，显示了确定性和随机性过程对火后更新不同策略的影响差异性。
- 火后萌发与播种更新的生境占据具有时空上的互补性。

3.3 物种更新的火后空间拓殖策略



3.3 物种更新的火后空间拓殖策略



云南松、黄毛青冈、光叶石栎有完全不同的高生长、径生长和分支比变化特征

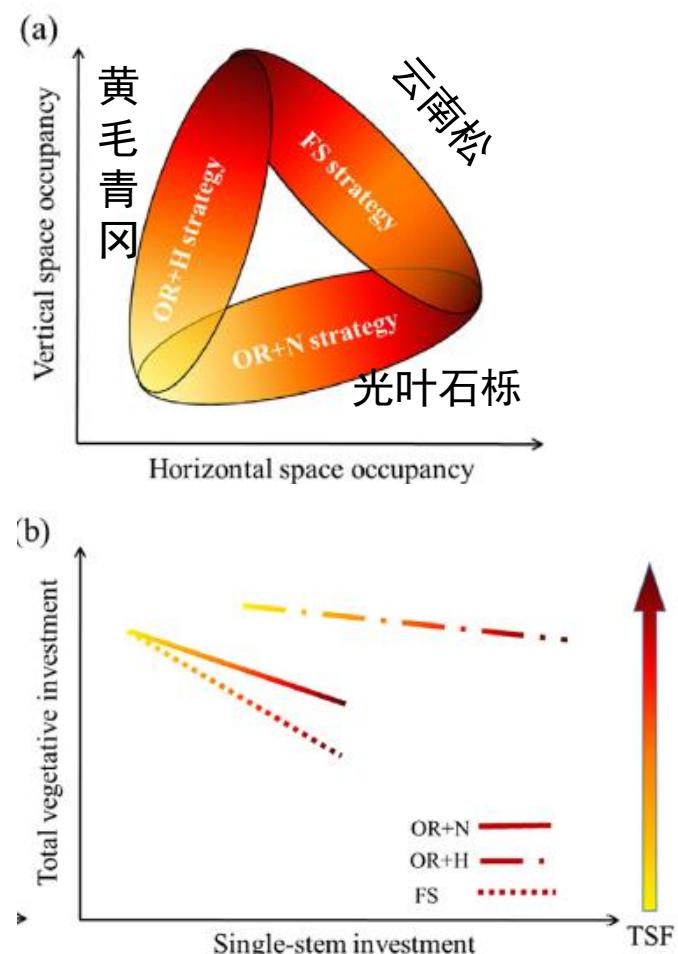
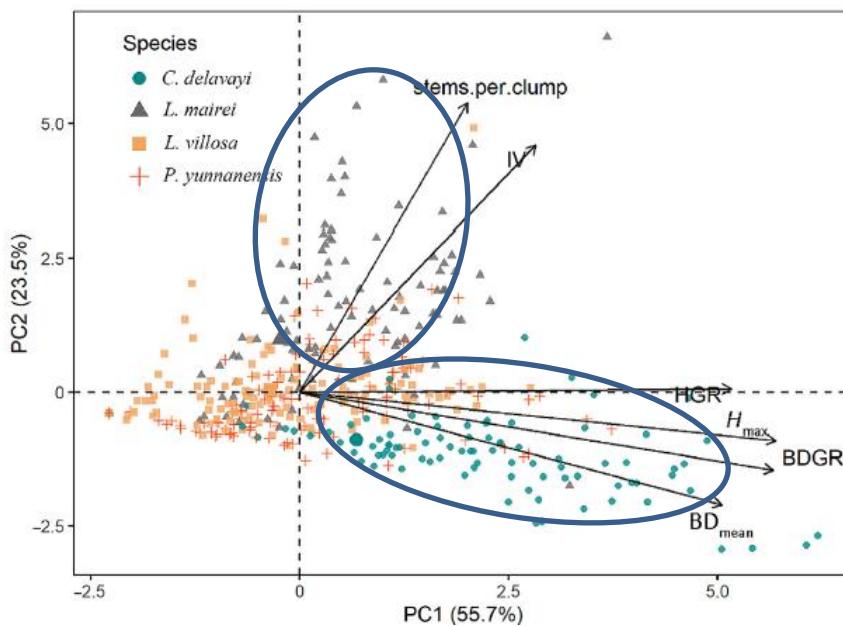
单株：黄毛青冈占优
种群：云南松、光叶石栎占优

3.3 物种更新的火后空间拓殖策略

云南松、黄毛青冈、光叶石栎有完全不同的高生长、径生长和分支比变化特征

单株——高空间：黄毛青冈占优

种群——水平空间：云南松、光叶石栎占优



4、小结

主要认识：

- 1) 滇中高原典型森林（包括云南松林及其混交林）是一种**fire-prone 生态系统**；常见物种已形成多种火适应特征；
- 2) 火后植物**种群群更新、物种构成和植被覆盖**的迅速恢复，展现了滇中高原森林对火干扰的恢复力；
- 3) 火烧后植被快速恢复的外在决定因素可能是丰沛的**季风降雨**；
- 4) 火烧烈度对火后**植被盖度恢复**起决定性作用；火前植被物种构成对火后植物**群落物种变化**起主导作用；
- 5) **萌发和实生苗更新的互补**，是滇中森林树种火后快速恢复的响应策略，和森林适应火干扰的主要弹性机制；萌发更新也分化了对**水平和垂直空间优先占据**的策略；
- 6) 异质地形主导和**火干扰强化的更新选择与植物适应策略**，是物种生态位分化和群落多样性维持的关键机制。

谢谢 !

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<https://www.ues.pku.edu.cn/szdw/qbjs/s/311935.htm>