

第19届中美碳联盟 (USCCC) 年会

# 寻求森林生态系统 固碳与水资源维持的协调之路

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# I 基本依据和思考

- 生态系统固碳和对水资源调控是生态系统对人类社会需求和生物圈稳定所贡献的两项最基本服务。
- 这是生态学研究永恒主题。
- 从生态学角度来讲，所有生态服务及其所涉及的过程是相互耦合的，它们并不会因为“双碳”需求对生态固碳的加持而处于从属地位。

- 因为对森林生态系统所提供的综合服务的需求增大，①全球森林面积无论预测和观测都指出在增大，但很快达到面积增长的天花板；而“碳中和”的需求和生物圈的平衡是长期的。
- 基于气温和CO<sub>2</sub>升高，劳动力成本上升而人工管理强度下降，af-/ re- forestation的可用地减少，②森林自然成熟会加快且成熟森林的比列快速提高

——考虑到成熟森林生态系统具有更强大的生态服务功能（eg, Yu and Zhou *et al*, 2021, GCB; Hua and Bruijnzeel *et al.*, 2022, Science），其实，过去几十年来相较于这之前，生物圈综合生态服务是在提高的。但固碳和水资源怎么样呢，却是要考究的。

- 那么，随着森林生态系统越来越成熟，其碳汇如何变化？

有一条基于逻辑推理得出的“生态系统演替理论”指出：

生态系统由“先锋阶段”“成熟阶段”向“地带性顶级阶段”演替，系统C贮量逐渐稳定，净C积累量降低，达到平衡状态。

我认为该推理存在一个缺陷：“生态系统演替”中的“植物群落演替”和“SOC变化”分属于生物过程和地质过程(至少是生物地球化学过程)，其时间尺度相差1-2个数量级，不可能同步。

这意味着“生态系统演替理论”应该这样写：

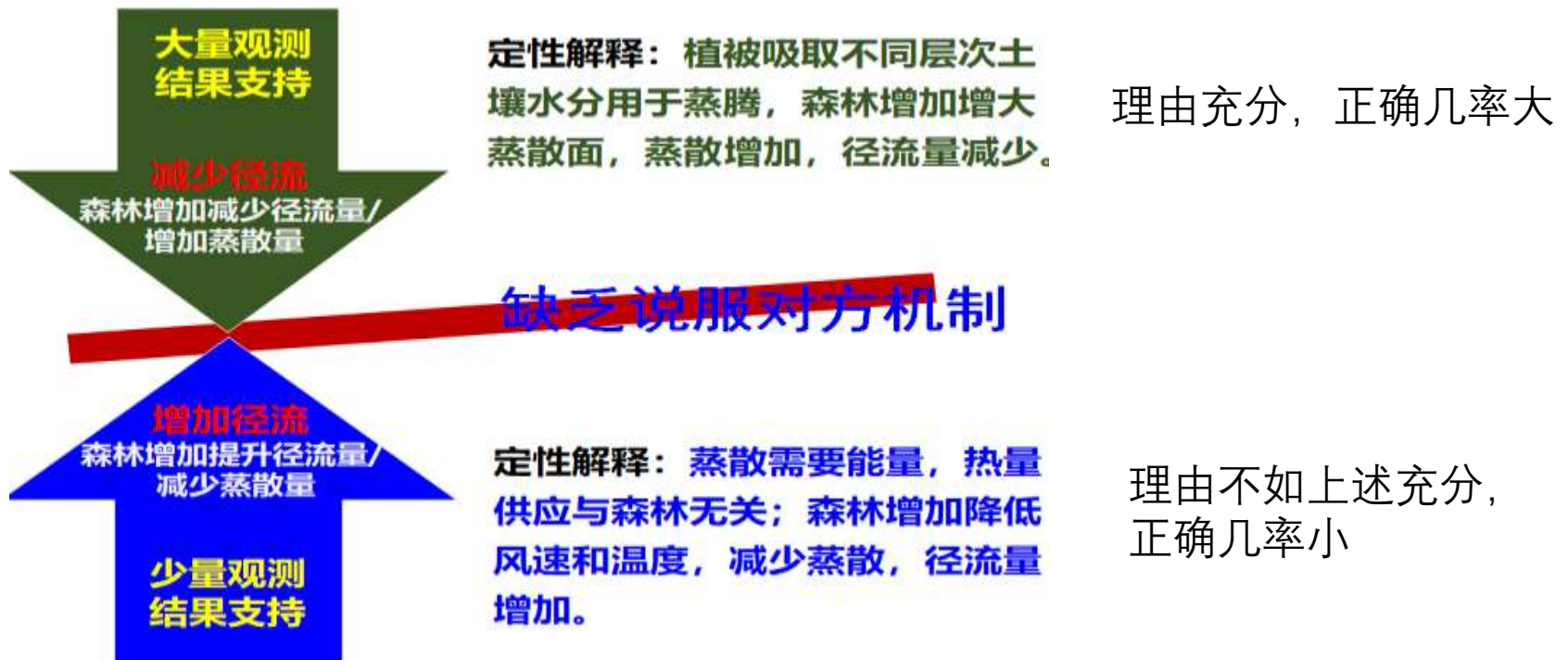
生态系统中的植物群落由“先锋阶段”“成熟阶段”向“地带性顶级阶段”演替，相应地，生物量逐渐稳定，净积累量趋于0；SOC积累也遵守该规律，但时间大大滞后。

- 如果森林生物量C和SOC积累随森林成熟是不同步的，那么它们各自的积累过程如何，上限在哪里？
- 有没有其它途径保持森林长期处于成熟前的状态从而高速积累生物量？哪怕是牺牲一些成熟森林的其它服务功能。

- 同时，随着森林面积逐渐接近80亿人生活所允许的天花板，水资源又会如何变化？

自古以来，全球就有两派对立观点，近几十年来有所好转。

- 1 森林覆盖会减少径流—违背人们情感，且人类无所作为
- 2 森林覆盖会增加或不显著减少径流—合乎人们情感，人类可以作为



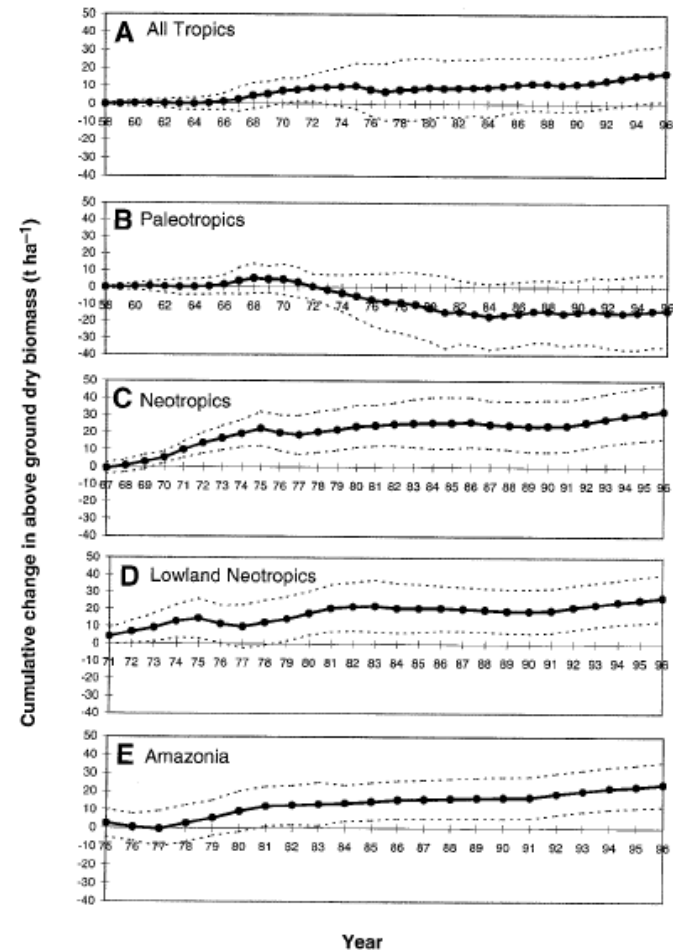
那么，在地球上的哪些地方森林增加（不减少）径流的几率会大些呢？

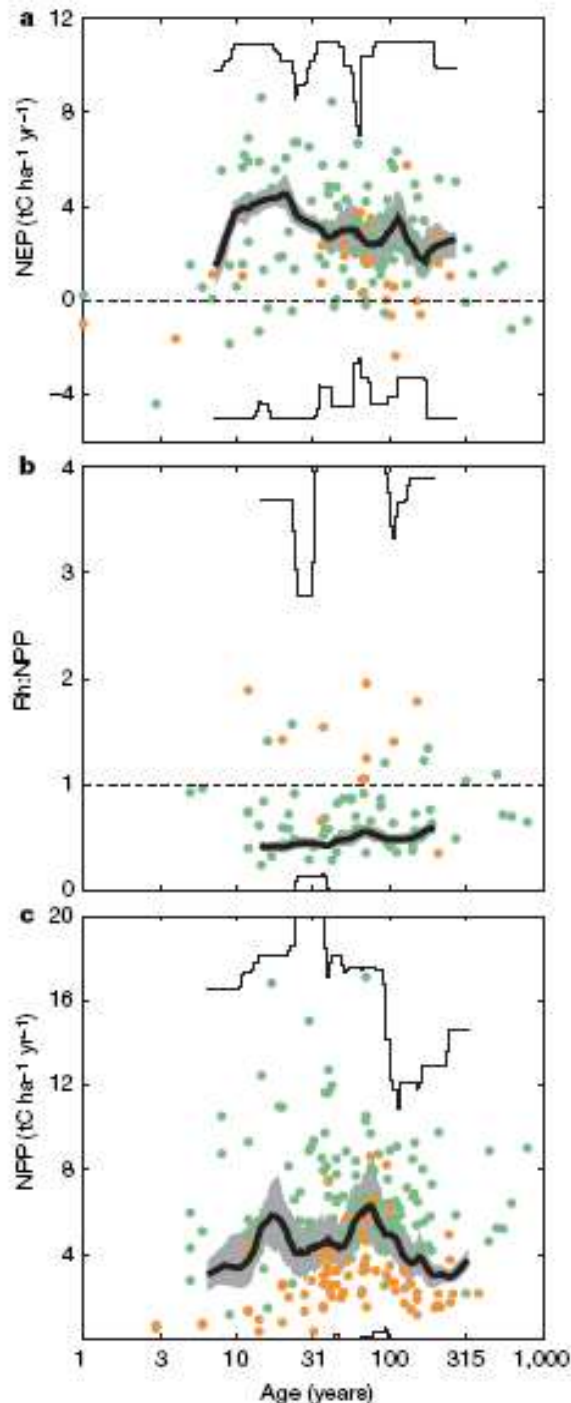
## II 一些研究实例

### 1 成熟森林生态系统生物量碳库能否起到持续碳汇作用？

#### (1) 正面的

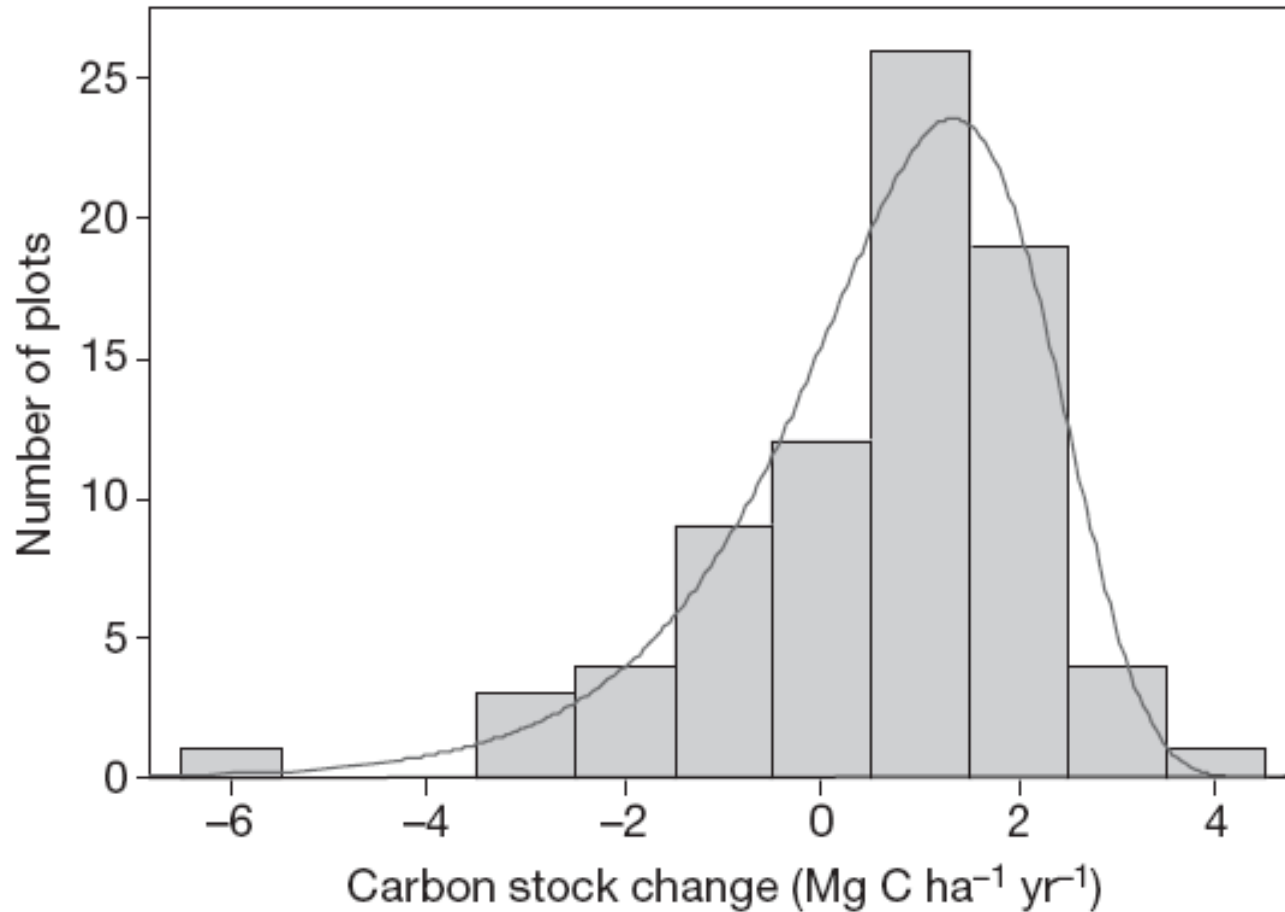
Phillips et al. (1998) 总结了不同热带区域森林生物量的多年变化，发现近年来热带湿润性区域地带森林生物量净积累了  $0.71 \pm 0.34 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ 。





Luysaert et al. (2008) 通过对全球大量文献的综述，发现林龄从15a到800a森林的NEP（Net Ecosystem Productivity，生态系统净生产力）通常都为正值，异养呼吸（指非生命有机碳分解）与NPP（Net Primary Productivity，净初级生产力）的比值小于1以及NPP不随年龄下降等规律。





Lewis et al (2009) 通过79块样地的连续调查，发现非洲热带森林地上部分的碳贮量在1968-2007这段期间的净增量为0.63Mg C ha<sup>-1</sup>yr<sup>-1</sup>

刘迎春等（2010）从文献发表和野外调查的中国森林生物量数据中选取了338个林龄在80 a及以上的森林样点，发现以中国成熟林生物量碳密度为参考水平，未来通过自然生长过程的固碳潜力约为13.86 Pg C。

Pan et al.（2011）总结了全球各个区域的森林生物量变化情况，发现普遍存在生物量碳持续积累的现象。

基于这些发现，全球出现了一片近乎乐观的情绪。普遍认为20世纪90年代到21世纪初全球陆地碳汇的一半左右要归功于热带未受干扰森林的碳吸存，约占同期内人类CO<sub>2</sub>排放的15%（Pan et al.,2011;Sitch et al.,2015;Gaubert et al.,2019）。气候植被模型（climate-driven vegetation models）预计热带森林的碳汇作用将持续数十年（Huntingford et al.,2013;Mercado et al.,2018）。

## NEWS &amp; VIEWS

## CARBON CYCLE

## Sink in the African jungle

Helene C. Muller-Landau

Apparently pristine African tropical forests are increasing in tree biomass, making them net absorbers of carbon dioxide. Is this a sign of atmospheric change, or of recovery from past trauma?

The lush vegetation of tropical forests is a large and globally significant store of carbon<sup>1</sup>. Because tropical forests contain more carbon per unit area than any alternative land cover, cutting them down releases carbon into the atmosphere. For the same reason, growing forests take up carbon from the atmosphere. Of course, trees cannot grow for ever, and neither can forests in the absence of disturbances that kill trees en masse — such as fires, hurricanes or logging — every forest will eventually reach a point at which tree growth and death are in equilibrium, and at which the average change in tree carbon stocks is zero.

It is thus surprising that undisturbed tropical forests currently do not seem to be at equilibrium. If you measure the size of trees in a given area, calculate their carbon stocks, and then repeat the process some years later, you will on average find that the forest holds more carbon than it did before. This was first reported for Amazonian tropical forests<sup>1</sup>, and on page 1003 of this issue Lewis *et al.*<sup>2</sup> show that African forests also have increasing stocks of tree carbon.

So how much carbon are we talking about? Using data collected in Africa between 1968 and 2007, the authors find that trees have added an average of 0.63 tonnes of carbon per hectare each year. Given that approximately half the dry matter in trees is carbon, the amount of wood added annually in each hectare of African forest is equivalent in mass to a small car. For comparison, the average rate of carbon accumulation in tropical forests around the globe was 0.49 tonnes of carbon per hectare per year<sup>2,3</sup>. Extrapolating from their data<sup>2</sup> by assuming parallel changes in the carbon pools of roots and dead trees, Lewis *et al.* estimate that 'old-growth' tropical forests are taking up  $1.3 \times 10^{11}$  tonnes of carbon per year worldwide.

There are two possible explanations for this finding. One is that the tropical forests that



**Figure 1** Getting bigger. Lewis *et al.*<sup>2</sup> show that apparently undisturbed African tropical forests are currently increasing in tree biomass each year, and act as carbon sinks. But it is impossible to say how long this will continue.

we think of as intact actually suffered major disturbances in the not-too-distant past, and are still in the process of growing back<sup>4</sup>. This recovery process is known as succession, and takes hundreds — or even thousands — of years. Succession involves not only initial growth to full canopy height, but also subsequent gradual shifts in species composition. The past disturbances could have been natural or anthropogenic; possible explanations include droughts and fires related to huge El Niño events, and changes in land use that

allowed previously cleared land to revert to forest<sup>5</sup>.

In fact, palaeoecological and archaeological evidence increasingly documents the long disturbance histories of today's 'undisturbed' tropical forests<sup>6</sup>. There have been many large fires in Amazonian forests over the past few millennia, the timings of which are related to both climate and the size of human populations<sup>7</sup>. Far from being pristine wildernesses little influenced by their human inhabitants, many areas were cleared or otherwise intensively used in centuries past<sup>8</sup>. Given the timescales of tropical forest succession, these disturbances are almost certainly contributing to carbon accumulation in many tropical forests today.

The second explanation for Lewis and colleagues' findings<sup>1</sup> is that tropical forests have been knocked from their previous equilibrium by global climate and/or atmospheric change<sup>9</sup>, so that they are currently in transition to a higher carbon state. Perhaps, for example, the increase in atmospheric carbon dioxide is effectively fertilizing tropical tree growth. Under these circumstances, if tree mortality doesn't keep pace with increases in growth, then trees will on average grow larger before they die (Fig. 1), and tree carbon stocks will increase<sup>10</sup>. Carbon stocks in mature tropical forests vary enormously depending on climate, soil type and topography; temporal changes in climate and resource availability would therefore be expected to have parallel influences in the long run.

The two mechanisms that might account for Lewis and colleagues' observations<sup>1</sup> would be expected to produce different spatial and temporal patterns of carbon uptake by trees, but our current knowledge does not allow us to predict what these patterns are, or to say which mechanism is operating in Africa. Over the course of succession, tree carbon stocks increase at an ever-slower rate as stands age. Thus, we

在Lewis *et al.* (2009) 发表那篇文章以后，nature还为此写了个评论。认为外部环境变化，如：气温升高、CO<sub>2</sub>的施肥效应甚至是全球氮沉降上升等，是驱动非洲丛林生物量积累的直接动因。

我不知道这篇评论的本意是推荐还是贬低 Lewis *et al.* (2009) 文章对“碳中和”的贡献，但效果都是贬低其价值。

试想，如果非洲丛林生物量积累的驱动力是气温升高，大气CO<sub>2</sub>、全球氮沉降上升，那么对“碳中和”又有什么意义呢？

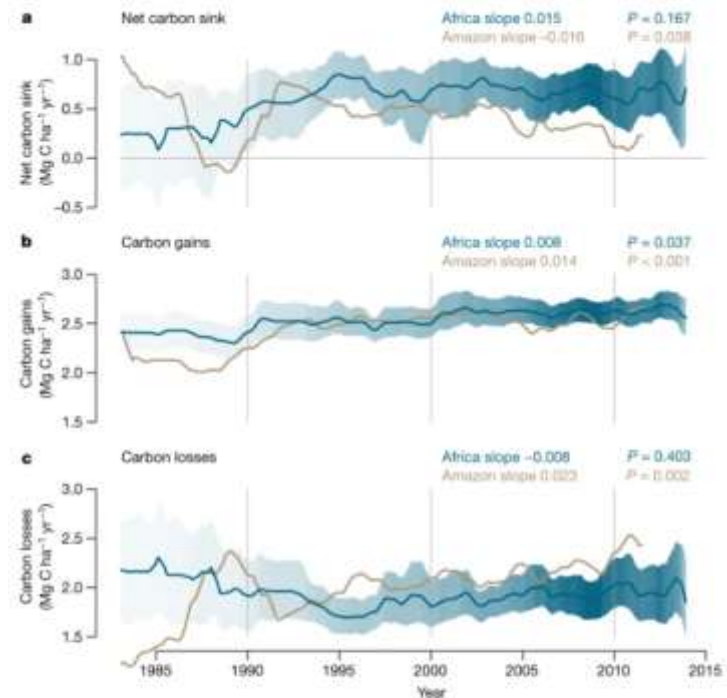
正如一只猫咬着自己的尾巴奔跑一样，原地转圈

## (2) 负面的

Baccini et al. (2017) 基于对地上生物量消长的实际测定，得出结论为热带森林是一个净碳源。

Rammig (2020) 认为热带森林生物量碳汇是不同步的。

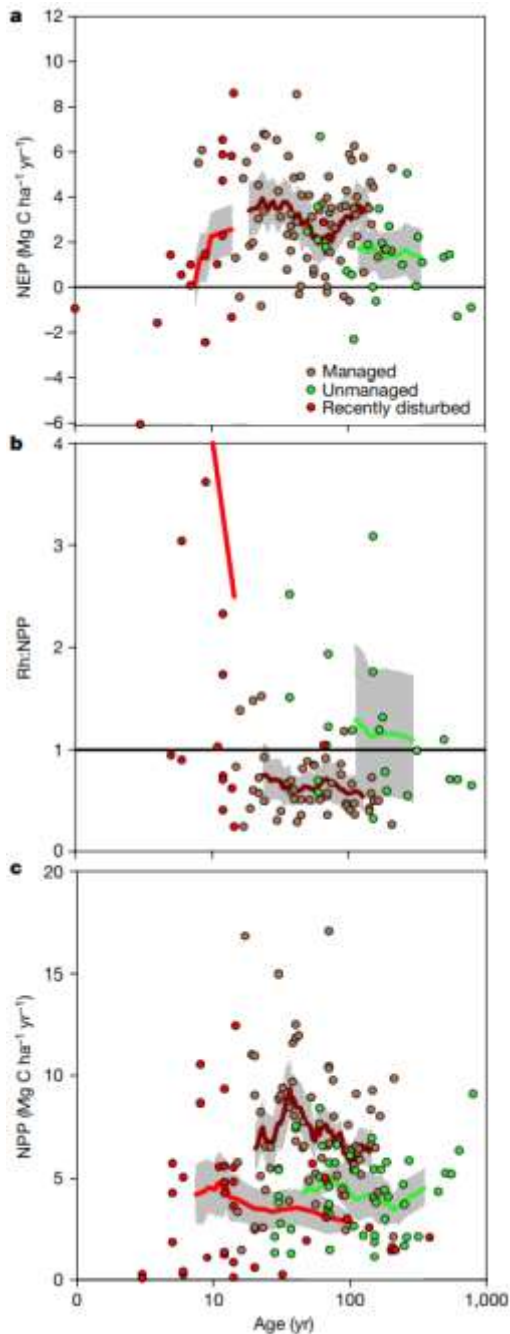
**Fig. 1: Long-term carbon dynamics of structurally intact old-growth tropical forests in Africa and Amazonia.**



**a–c.** Trends in net aboveground live biomass carbon (**a**), carbon gains to the system from wood production (**b**), and carbon losses from the system from tree mortality (**c**), measured in 244 African inventory plots (blue lines) and contrasting published<sup>6</sup> Amazonian inventory data (brown lines; 321 plots). For Africa we show complete years with at least 25 plots monitored; for Amazonia we show the published record<sup>6</sup>. Shading corresponds to the 95% CI, with darker shading indicating a greater number of plots monitored in that year (the lightest shading indicates the minimum 25 plots monitored). The CI for the Amazonian dataset is omitted for clarity, but can be seen in Fig. 3. Slopes and *P* values are from linear mixed effects models (see [Methods](#)).

[Source data](#)

Hubau et al. (2020) 通过更广泛的数据比对得出非洲和亚马孙热带森林生物量碳汇正逐步趋于饱和，并指出非洲热带森林的地上部分生物量截至到2015年就已经稳定30a了，而亚马孙森林生物量处于衰退中。



Gundersen et al. (2021) 通过对前期数据的再分析，认为老龄林生物量碳汇被Luyssaert et al. (2008) 高估了

其实，我们的结果也一样，基于过去40多年对鼎湖山季风常绿阔叶林生物量的长期监测，发现成熟森林生物量总体上处于下降的趋势，年份之间有波动而已

(Zhou et al.,2013)；对热带亚热带常绿阔叶林13个永久样地长达30多年的监测表明，木材生物量都处于下降过程中 (Zhou et al.,2014)；有显著上升趋势的只是群落的枝叶等活跃生物量 (active biomass)

(Xiao and Zhou et al.,2014)，而这些活跃生物量因为滞留的时间较短对热带亚热带常绿阔叶林生物量固碳是没有贡献的，虽然可能贡献了土壤有机碳的积累

## 2 有没有其它途径保持森林长期处于成熟前的状态从而高速积累生物量？哪怕是牺牲一些成熟森林的其它服务功能

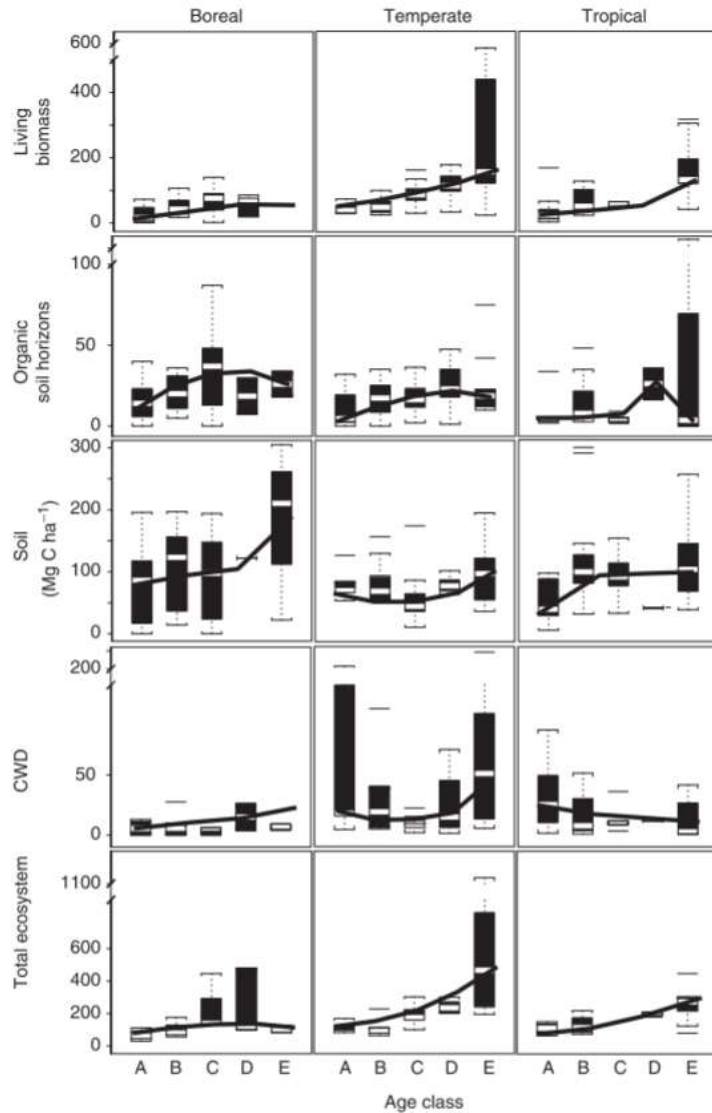
有！在科学上是可行的——用与经营木材生产类似的方法来经营碳汇，适度收获成熟树木以获取碳汇的同时获取木材。

但在技术和经济上是否可行则需要深入研究

技术上：收获成熟树木不能破坏土壤、同时保证自然更新

经济上：择伐的成本上升能否被木材价值补偿；碳足迹能否被木材的含碳量抵消

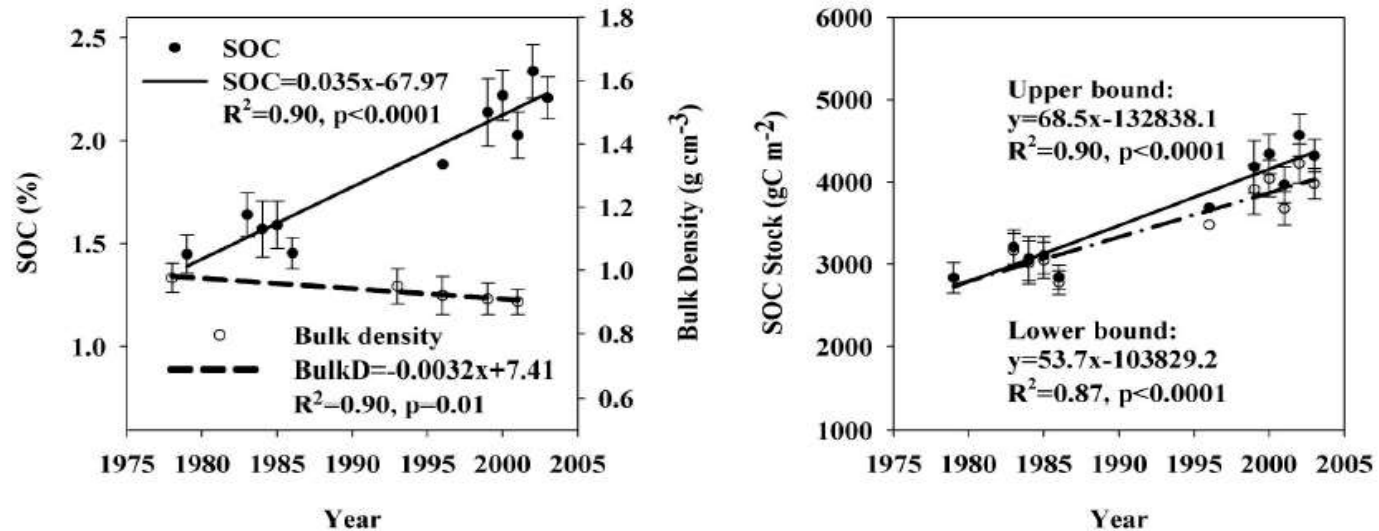
### 3 成熟生态系统土壤有机碳库能起到持续碳汇作用吗？



Pregitzer and Euskirchen (2004) 通过对120篇文献进行综合分析发现，寒带，温带，热带生物群落（包括落叶林、针叶林以及常绿树种）随着时间的推移，土壤有机碳库总体呈增加趋势。

土壤C储量下限 (1)  $SOC_{i+1}^L = SOC_0^L + \text{Thickness} \times (\text{Density}_{i+1} \times SOC_{i+1}^C - \text{Density}_0 \times SOC_0^C)$

土壤C储量上限 (2)  $SOC_{i+1}^U = SOC_0^U + \text{Thickness} \times \text{Density}_0 \times (SOC_{i+1}^C - SOC_0^C)$



**Fig. 1.** Temporal changes of (left) soil organic carbon concentration, bulk density, and (right) soil organic carbon stock in the top 20-cm soil layer in broadleaved old-growth forests in Dinghushan Nature Reserve. Upper and lower bounds contain the uncertainty introduced by the lack of monitoring of soil thickness during the study period. Error bars indicate standard deviation.

*Zhou et al (2006, Science); Zhou et al (2006, Sci. China);*

我们的研究发现地带性森林生态系统可以继续积累土壤有机碳



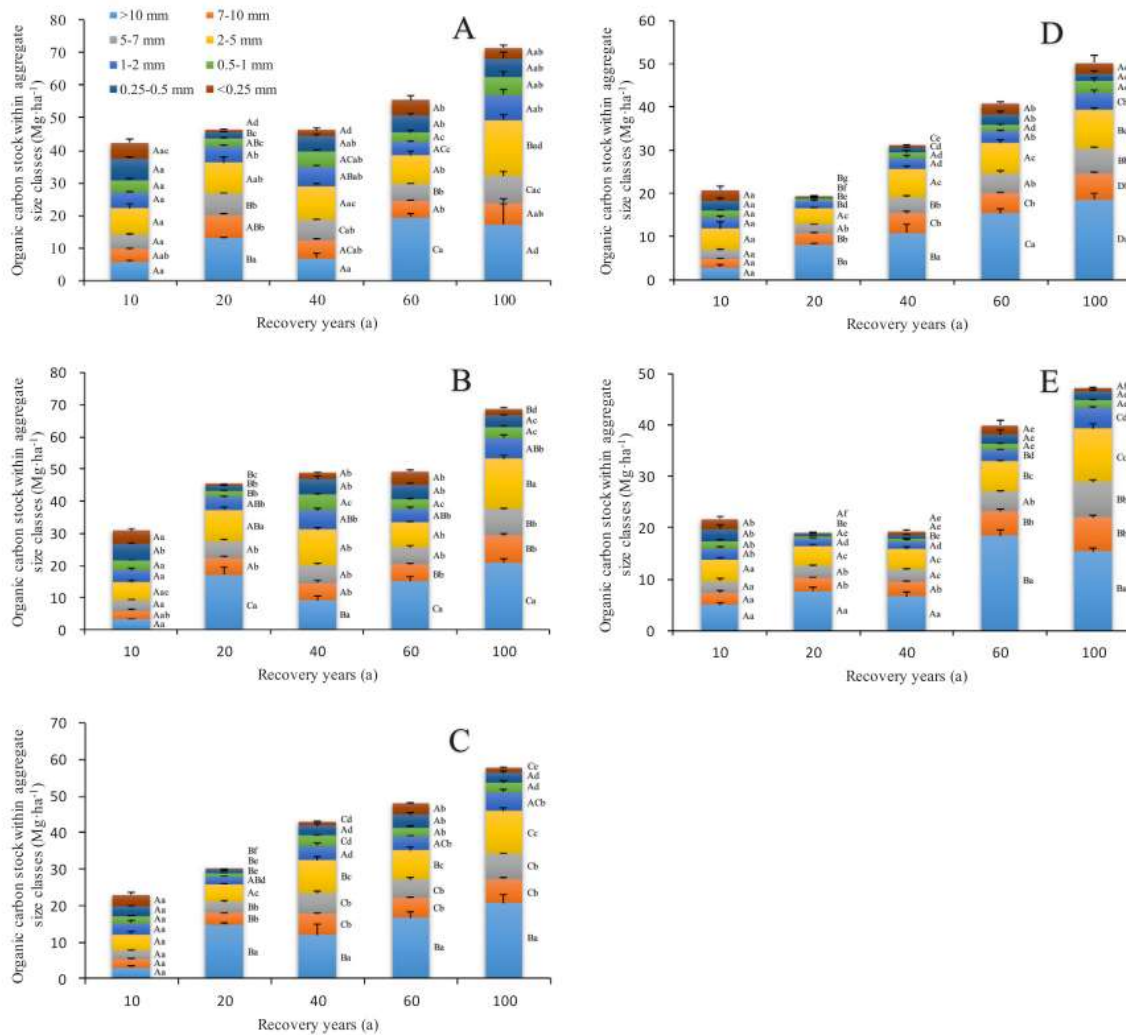
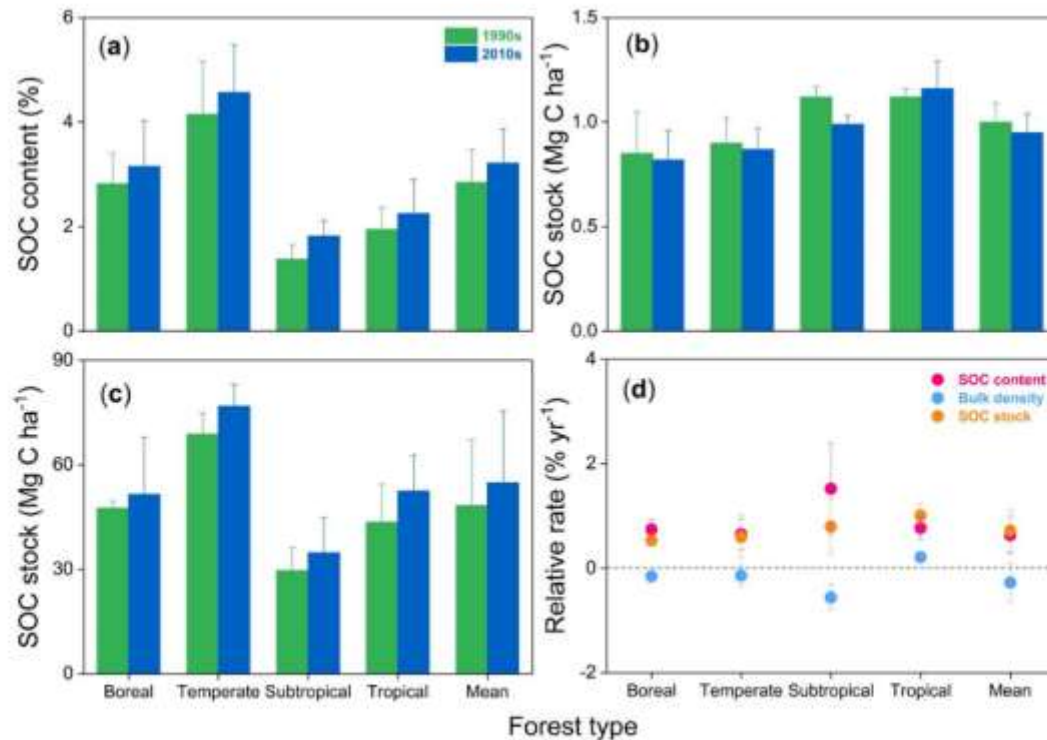


Fig. 3. Aggregate-associated SOC storage in different years after restoration. Capital letters indicate differences in the SOC in the aggregates of the same size in different recovery years ( $p < 0.05$ ). Lower-case letters indicate the differences in SOC in the aggregates with different sizes in the same recovery years ( $p < 0.05$ ). A indicates the 0–20 cm soil layer; B indicates the 20–40 cm soil layer; C indicates the 40–60 cm soil layer; D indicates the 60–80 cm soil layer; and E indicates the 80–100 cm soil layer.

Bai Y X,Zhou Y C,He H Z,2020.Effects of rehabilitation through afforestation on soil aggregate stability and aggregate-associated carbon after forest fires in subtropical China [J] .Geoderma,376:114548.doi:10.1016/j.geoderma.2020.114548.

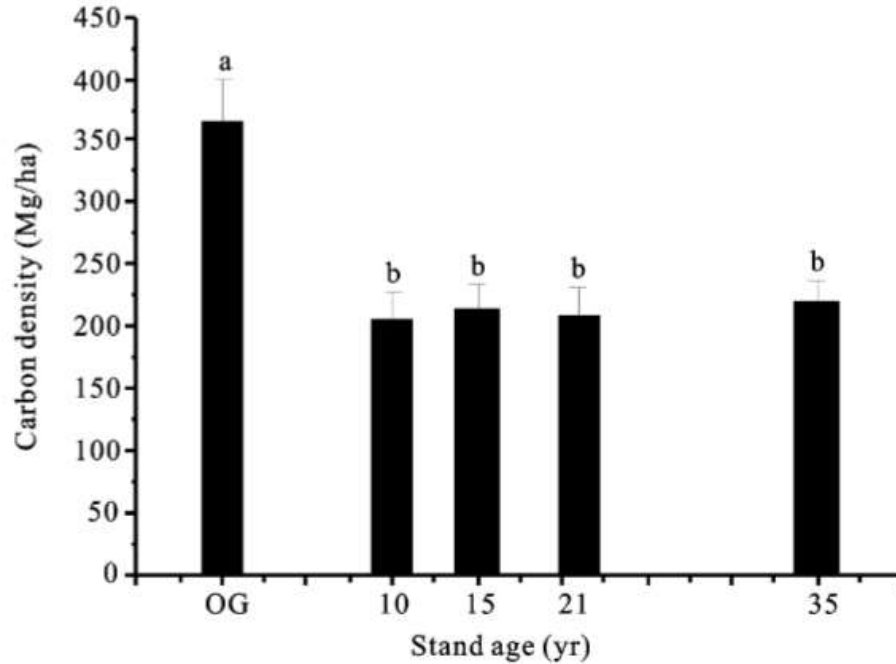
Bai et al. (2020) 通过对中国亚热带地区森林火灾后恢复 10、20、40、60 和 100a 的马尾松林土壤进行采样，评估林分年龄对造林过程中土壤有机碳的影响，结果表明，成熟和过成熟森林的土壤仍然具有较高的碳储存和封存率。



**Figure 2.** Mean soil organic carbon (SOC) content (a), bulk density (b), SOC stock (c), and their relative change rates (d) within 0–20 cm soil depth in the 1990s and the 2010s for the four forest sites in China. For more details, see Table S2 in the Supplement.

Zhu JX, Fang JY et al.,2020.Increasing soil carbon stocks in eight permanent forest plots in China [J] .Biogeosciences,17(3):715-726.doi:10.5194/bg-17-715-2020.

Zhu et al. (2020) 对中国8个永久性森林样地（北方（1998—2014年）、温带（1992—2012年）、亚热带（1987—2008年）和热带森林生物群落（1992—2012年））中土壤有机碳储量的20a变化进行分析发现，表层20cm土壤中的有机碳储量从1990s到2010s平均增加了0.13~0.91 Mg C ha<sup>-1</sup>year<sup>-1</sup>。



Qi et al. (2016) 对东北地区10、15、21、35a林龄的4个日本落叶松人工林（这些人工林是在砍伐原始红松-落叶阔叶林后建立的）和300a林龄的原始红松落叶林碳储量动态调查发现，21a和35a生落叶松人工林土壤有机碳含量均显著低于原始林。

**Fig. 4** Total carbon stock (TCS) of old-growth forest and different-aged larch plantations. OG represents old-growth forest; a and b indicate significant differences of carbon densities between old-growth forest and larch plantations

Qi G, Chen H, Zhou L, et al., 2016. Carbon stock of larch plantations and its comparison with an old-growth forest in northeast China [ J ] . Chin Geogr Sci, 26(1):10-21. doi:10.1007/s11769-015-0772-z.

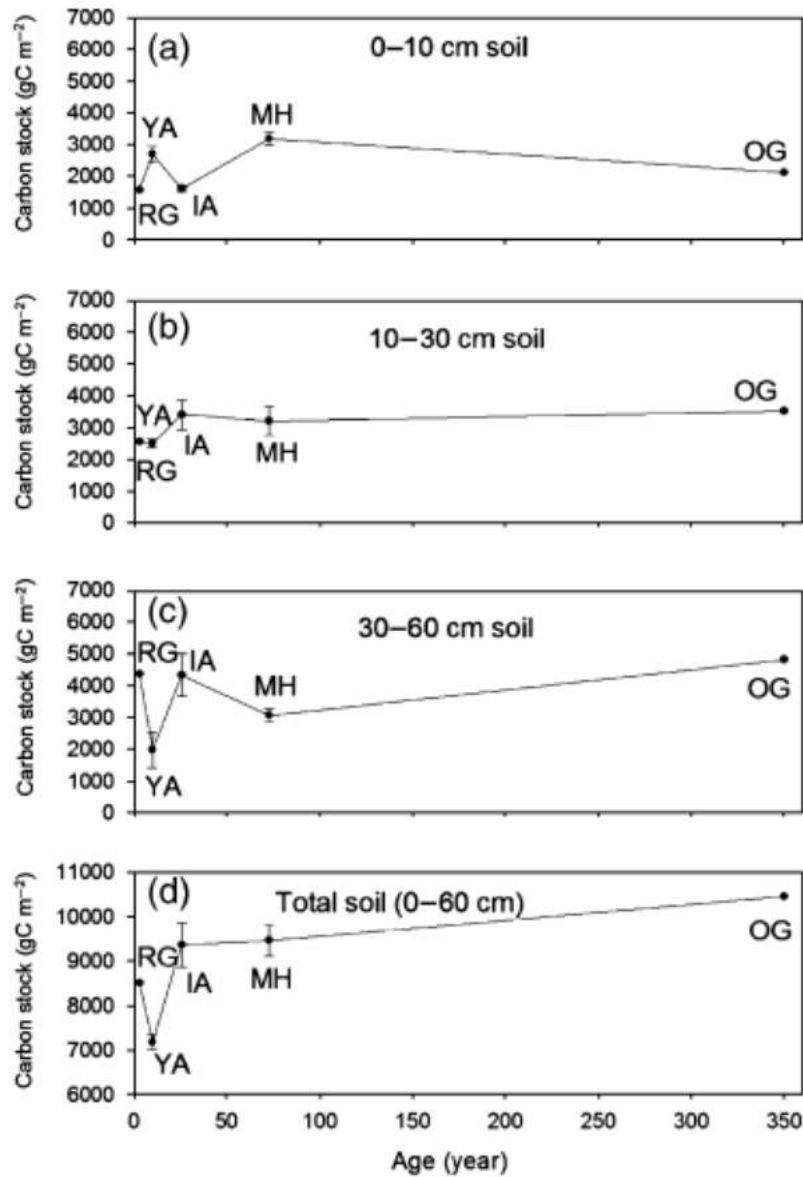


Fig. 4 Chronosequence of soil carbon stocks at 0–10 cm (a), 10–30 cm (b), 30–60 cm (c), and 0–60 cm (d) of soils. Error bars indicate standard deviations among replicated stands.

Tang et al. (2009) 对威斯康星州和密歇根州落叶林演替序列中的土壤碳储量研究发现, 0~60 cm处土壤碳从再生林阶段到幼龄林阶段减少, 在中龄林阶段开始恢复, 从成熟林到老龄林以平均 $0.036 \text{ Mg C ha}^{-1}\text{a}^{-1}$ 的速度不断增加。

Tang J W, Bolstad P V, Martin J G, 2009. Soil carbon fluxes and stocks in a Great Lakes forest chronosequence [J]. *Glob Change Biol*, 15(1):145-155. doi:10.1111/j.1365-2486.2008.01741.x.

Tefs and Gleixner (2012) 于2000、2004年对生长在Hainich国家公园的古老山毛榉林土壤进行成对取样分析发现，整个土壤剖面在4a内累积了6.57 Mg C ha<sup>-1</sup>，相当于每年1.64 Mg C ha<sup>-1</sup>的累积率。

**Table 1**

SOC stocks in 2000 and 2004, stock changes, *p*-values of stock changes and bulk density of soil samples at the Hainich NP. Bulk density is provided by M. Schrumpf (pers. comm.).

Soil depth [cm]	<i>N</i>	Soil organic carbon stocks [g m <sup>-2</sup> ]							Bulk density [kg m <sup>-2</sup> ]	
		2000		2004		Δ				
		$\bar{X}$	se	$\bar{X}$	se	$\bar{X}$	se	<i>p</i>	$\bar{X}$	sd
0-10	76	5039	134	4617	130	-422	128	0.002	44	7
10-20	78	3557	108	3481	102	-76	109	0.490	116	14
20-30	68	2244	83	2618	110	373	112	0.001	125	16
30-40	71	1623	59	1895	73	272	72	0.000	123	20
40-50	68	1469	73	1716	74	248	88	0.007	115	28
50-60	37	1255	77	1516	105	261	104	0.017	112	31
0-60	398	15,185	226	15,843	247	657	254	0.177		

Note: *N* = number of samples;  $\bar{X}$  = mean values; se = standard error; Δ = changes of mean values between 2000 and 2004; *p* = *p*-value; sd = standard deviation.

Tefs C, Gleixner G, 2012. Importance of root derived carbon for soil organic matter storage in a temperate old-growth beech forest: evidence from C, N and 14C content [J]. For Ecol Manag, 263:131-137. doi:10.1016/j.foreco.2011.09.010.

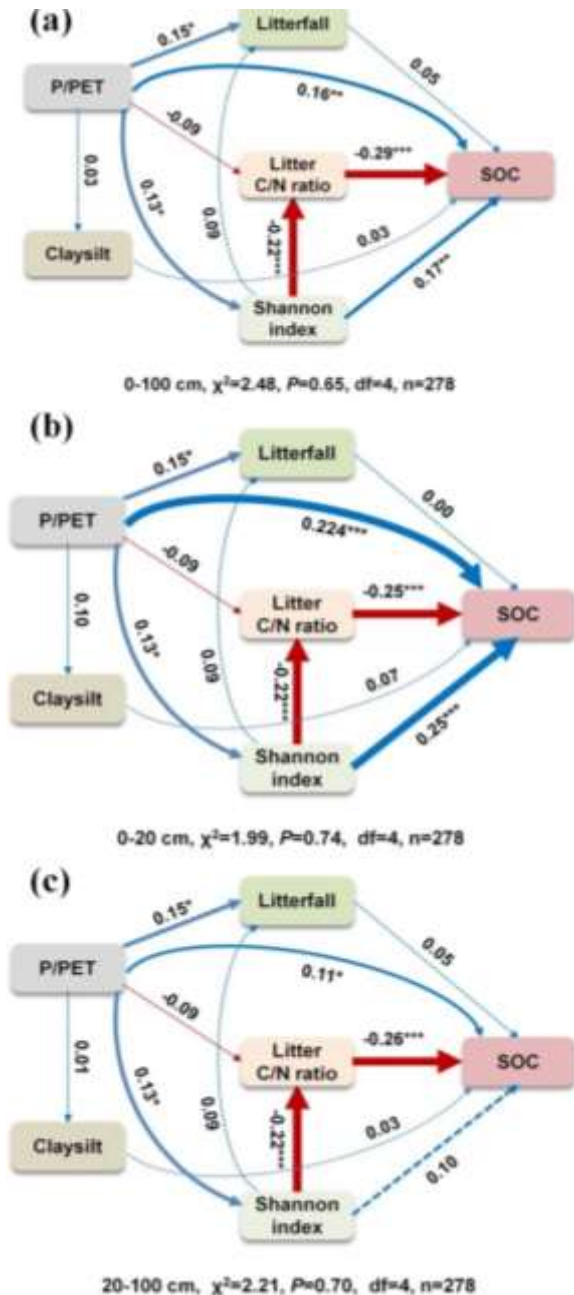
因此，成熟森林生态系统SOC即使不能一直固碳下去，也至少在相当长的时期内还可以高速固碳，至少在时间上是长于生物量固碳的。

那么，与生物量固碳同样的问题又来了——成熟森林生态系统SOC增加对缓解气候变化有意义吗？也就是说，前面所说的SOC在森林成熟后仍然积累的原因是否也是由气温和CO<sub>2</sub>上升所导致呢？

## 4 成熟森林土壤有机碳积累的内源和外源驱动机制

我们这里之所以要分清楚驱动成熟森林土壤有机碳积累的内源机制和外源机制是因为目的是试图探索一条实现“碳中和”战略的途径。如果成熟森林土壤有机碳积累的动因是外部环境（气温上升、大气降水格局改变、大气CO<sub>2</sub>浓度升高、N沉降上升）改变所引起的话，则这个SOC增加对“碳中和”目标并没有实际意义。因此，我们在将成熟森林土壤有机碳可以继续积累的全球研究结果当做是一条实现“碳中和”战略的途径之前，必须先阐明它的机制是什么。

任何由生态系统自身演替所引起的相关驱动因子改变从而导致土壤有机碳变化的，称为**内源机制驱动**；而任何由外部环境改变（如：气候变化，N沉降，酸沉降等）所引起的相关驱动因子改变从而导致土壤有机碳变化的，称为**外源机制驱动**。



- 土壤有机碳(SOC)决定于植物残体质(litter C/N)而不是量(litterfall), SOC与Litter C/N呈负相关; 只有低C/N比的前提下, 增加litterfall才促进SOC积累;
- SOC受湿润指数(P/PET)影响, 呈正相关;
- SOC和土壤质地(claysilt)没有关系;
- 物种多样性(Shannon index)主要影响植物残体的质来影响SOC, 对SOC直接影响只在土壤表层显现。



# 内源机制驱动-SOC来源随森林演替上升——在外部环境没有改变、森林生物量不增加的情况下也成立

季风常绿阔叶林3个不同演替阶段水热环境、物种数、凋落物质量及分解产物比例 摘自Huang and Zhou *et al* (2011, *Forest Ecology and Management*)

森林类型	土壤水分(%)	物种数	C/N比	木质素(%)	CO <sub>2</sub> 占比(%)	可溶性有机碳(%)	碎屑有机碳(%)	中间产物(%)
松林	17.2	15	50.8	31.2	46.5	10.8	42.7	53.5
混交林	21.4	46	46.8	26.2	34.4	20.5	45.1	65.6
季风林	24.3	85	35.4	23.4	23.8	19.7	56.6	76.2

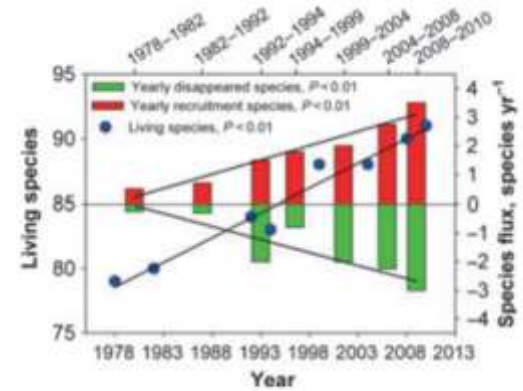
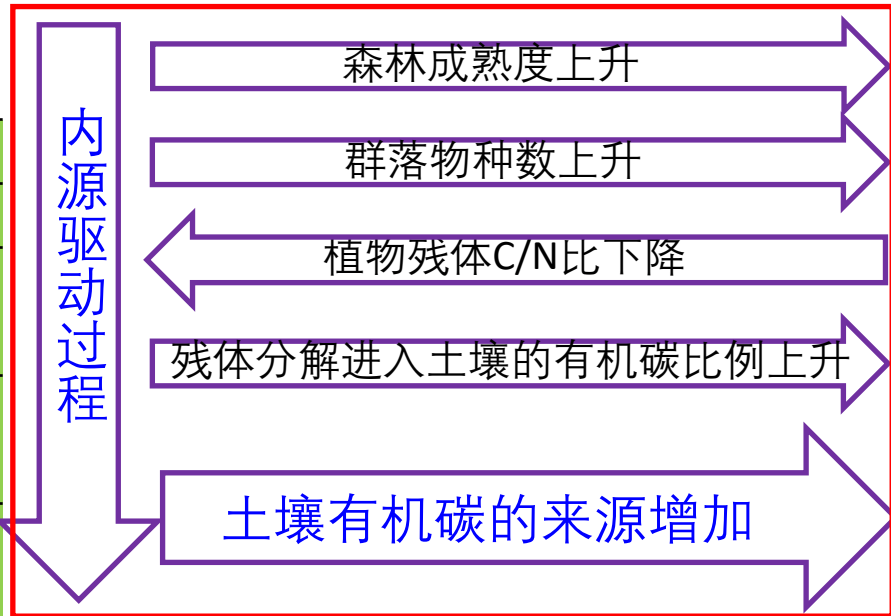


Fig. 7 Changes in the number of living, recruited, and disappeared species from 1978 to 2010. Zhou *et al.*, 2013, GCB

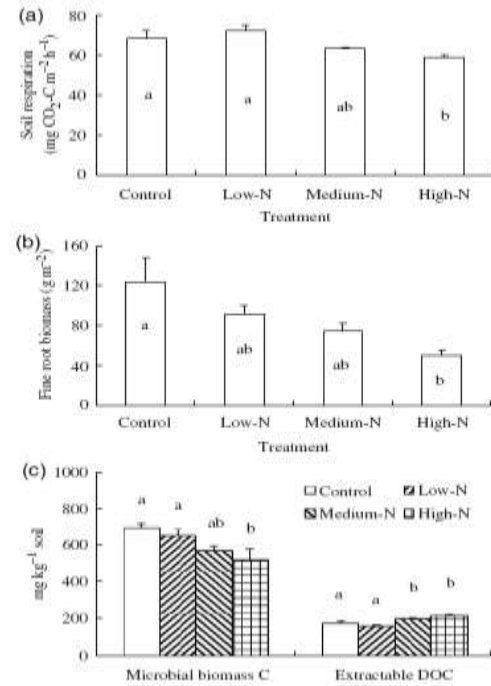
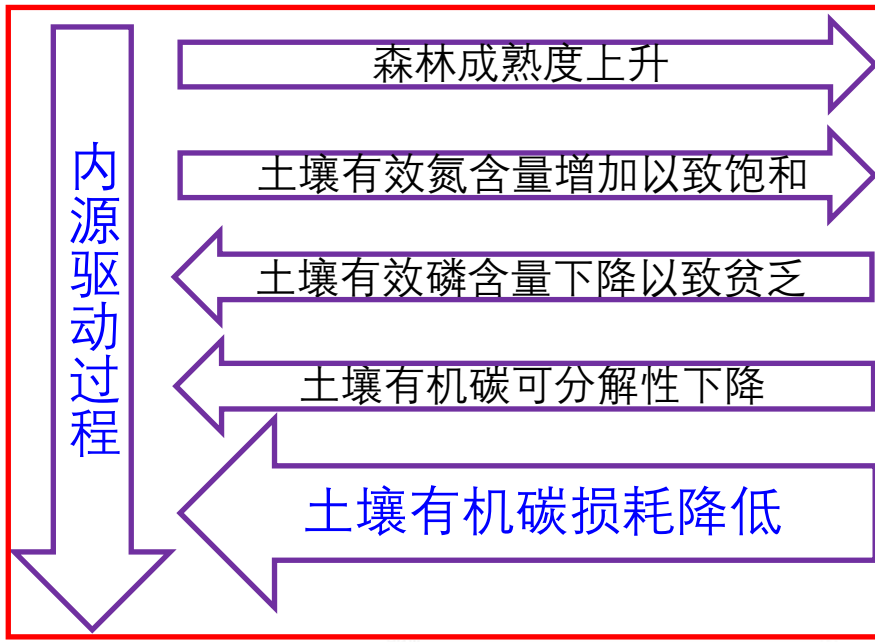
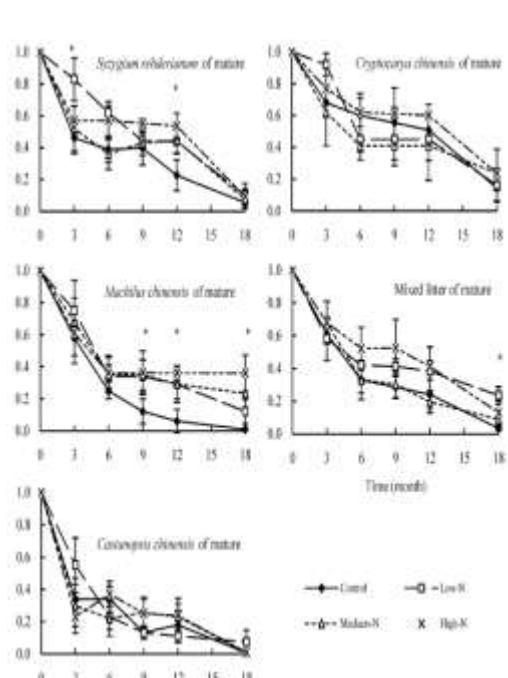
松林、季风常绿阔叶林凋落物数量、质量、土壤有机碳年输入量和净积累对比 摘自Xiong and Zhou *et al* (2020, *Journal of Applied Ecology*)

森林类型		松林	季风林
年凋落物量 (g C m <sup>-2</sup> yr <sup>-1</sup> )		389	397
C/N比	地上凋落物	36.7	27.6
	地下凋落物	74.1	66.2
输入土壤有机碳量 (g C m <sup>-2</sup> yr <sup>-1</sup> )	0-20 cm	88.2	115.0
	20-40 cm	11.5	33.7
SOC净积累量 (g C m <sup>-2</sup> yr <sup>-1</sup> )	0-20 cm	29.9	74.7
	20-40 cm	6.2	27.0



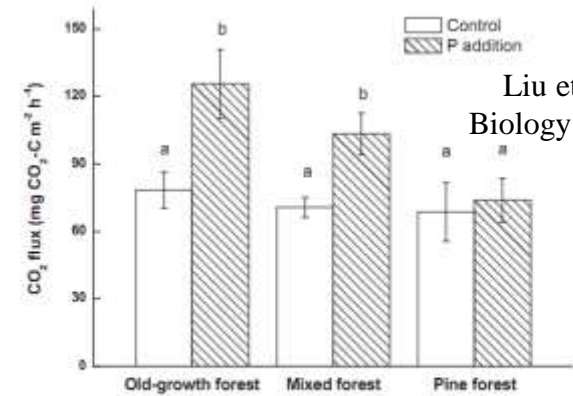
Yan and Zhou *et al* (2006, *Global Change Biology*); Huang and Zhou *et al* (2016, *Funct. Ecol.*); Zhou *et al* (2008, *Plant Soil*); Wang and Zhou *et al* (2017, *SBB*); Liu and Zhou *et al* (2019, *Biogeochemistry*), .....

# 内源机制驱动-SOC分解随森林演替而下降——在外部环境没有改变、森林生物量不增加的情况下也成立



Mo et al., 2008, Global Change Biology

Huang and Zhou et al., 2012, Plant Soil



Liu et al., 2012, Soil Biology and biochemistry

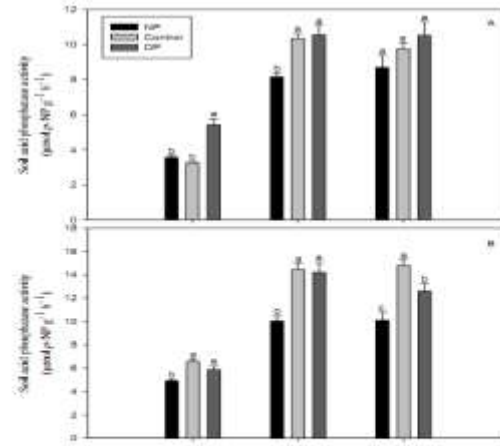
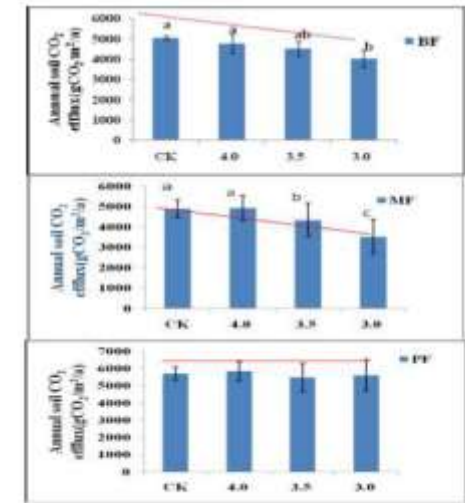
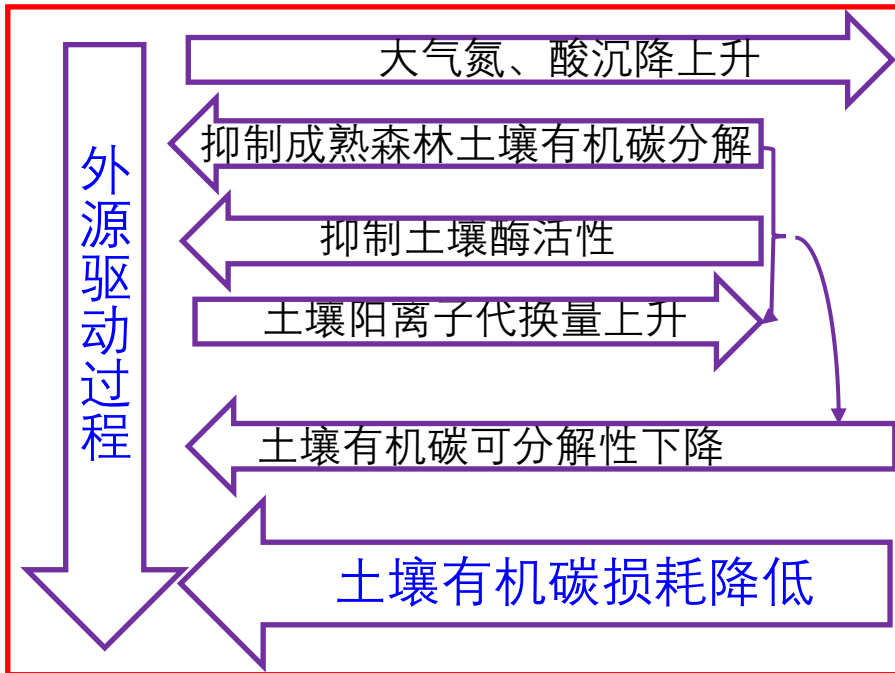


Fig. 2. Soil acid phosphatase activity in the dry (A) and wet (B) seasons under different precipitation treatments in 0–20 cm mineral soils of three forests at Dinghushan Biosphere Reserve. Error bars represent standard errors. Different lowercase letters denote significant differences between treatments at  $P < 0.05$  in the same forest. MPF, Maoson pine forest; MF, coniferous and broad-leaved mixed forest; MEBF, monsoon evergreen broad-leaved forest. NP, no precipitation; Control, natural precipitation; DP, double precipitation.

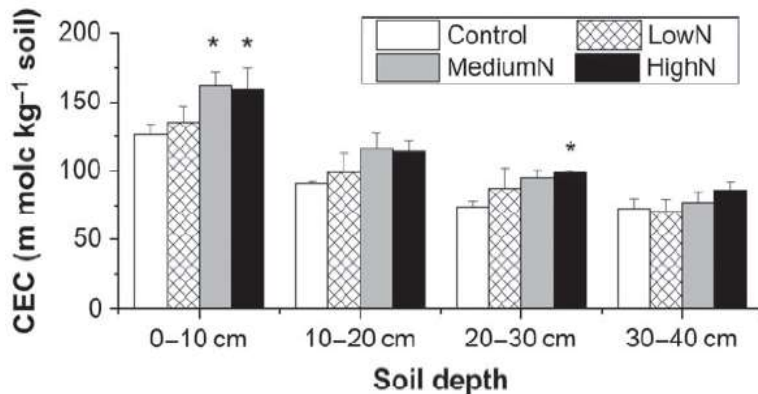
Huang and Zhou *et al* (2016, *Funct. Ecol.*);

Fig. 6. Soil respiration response to P addition in the three forest types. Values are means for three months. [Data from July–Sep.2009]. P addition = phosphorus addition since 2007. Significant differences ( $p < 0.05$ ) among treatments are indicated by different letters. Error bars show SE ( $n = 5$ ).

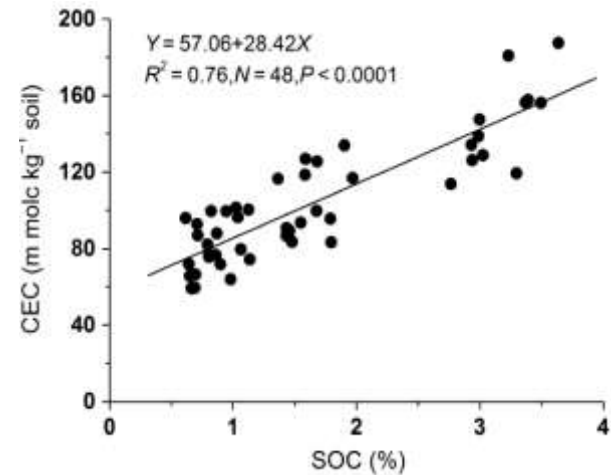


鼎湖山三种主要森林类型土壤 pH 值对模拟酸雨影响的响应  
Liang and Zhou et al., 2013

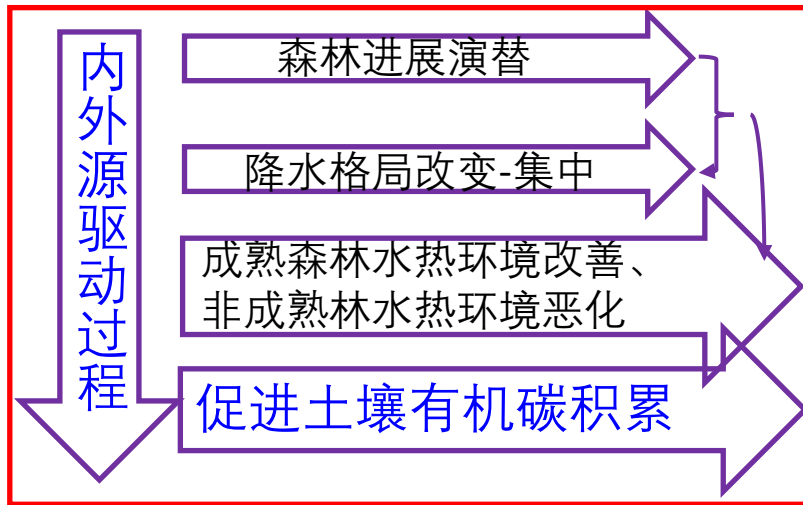
Zhou et al., 2008, *Plant & Soil*



Lu et al., 2014, *Global Change Biology*



# 内外源机制联合驱动-森林演替和降水集中导致成熟森林湿润指数上升, 促进SOC积累

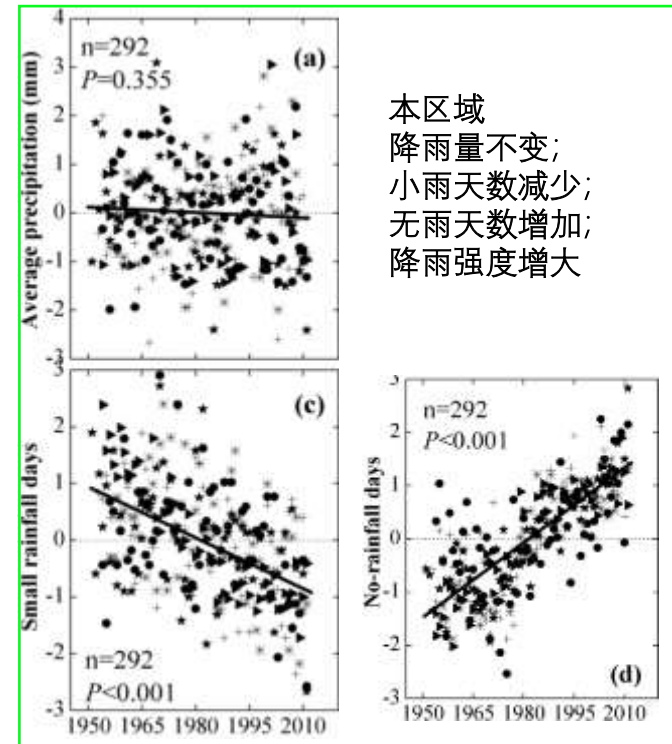


Wang and Zhou et al., 2019, Soil Biology and Biochemistry

Table 2. Mean and standard deviation ( $\delta$ ) of soil water content for two monitoring periods in three sub-catchments at Dinghushan.

	1983-1985		2001-2002	
	Average	$\delta$	Average	$\delta$
PF	3.11	1.11	1.89	0.45
PBF	3.73	1.02	2.09	0.27
MBF	4.12	1.01	2.2	0.35

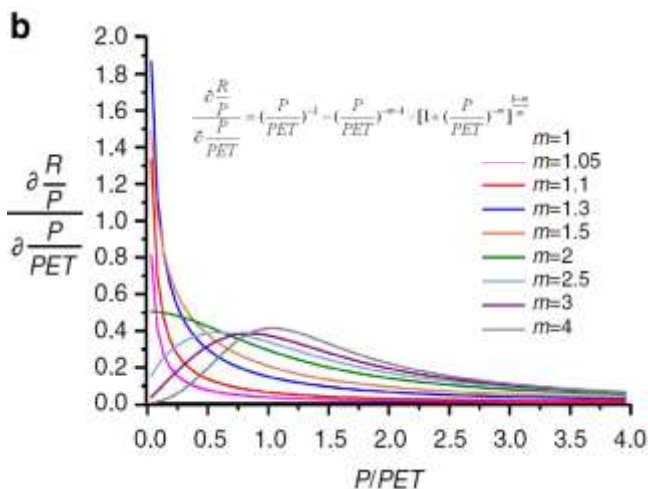
Zhou et al., 2004, Eurasian J. For. Res



Zhou et al., 2011, Global Change Biology  
Zhou et al., 2013, Global Change Biology

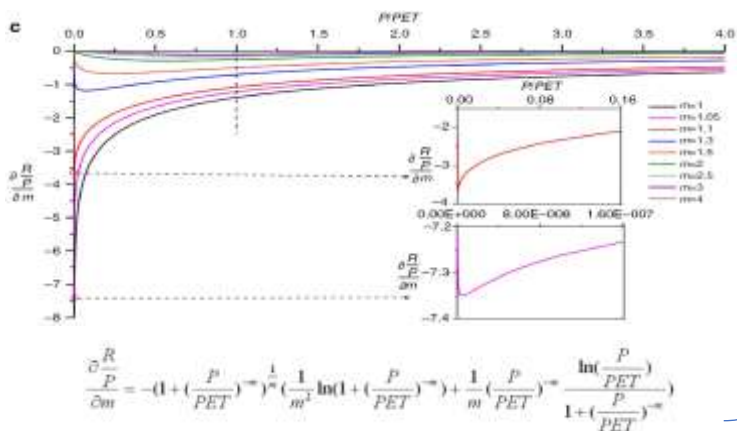
# 5 地球上哪些地方森林增加不导致径流减少的几率会大些呢？

Zhou et al (2015)阐明了不同气候区域(湿润度)、不同地貌条件(保水/不保水)、不同天气下(当天降水量/热量比值)下，径流率对森林增加的敏感性差异，为这个问题找到了理论途径。



将两个敏感性函数和两个临界值结合分析，解释了全球不同观测结果。

产水率对于气候指数的敏感性变化规律



产水率对于下垫面指数的敏感性变化规律

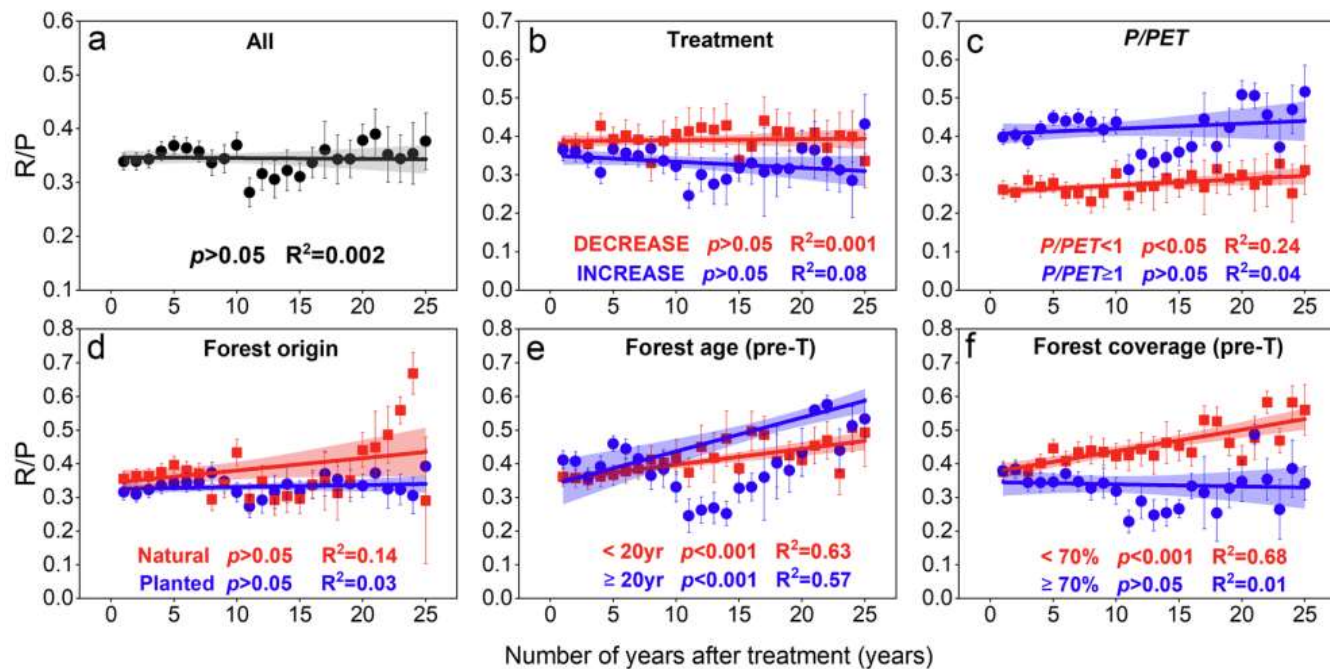
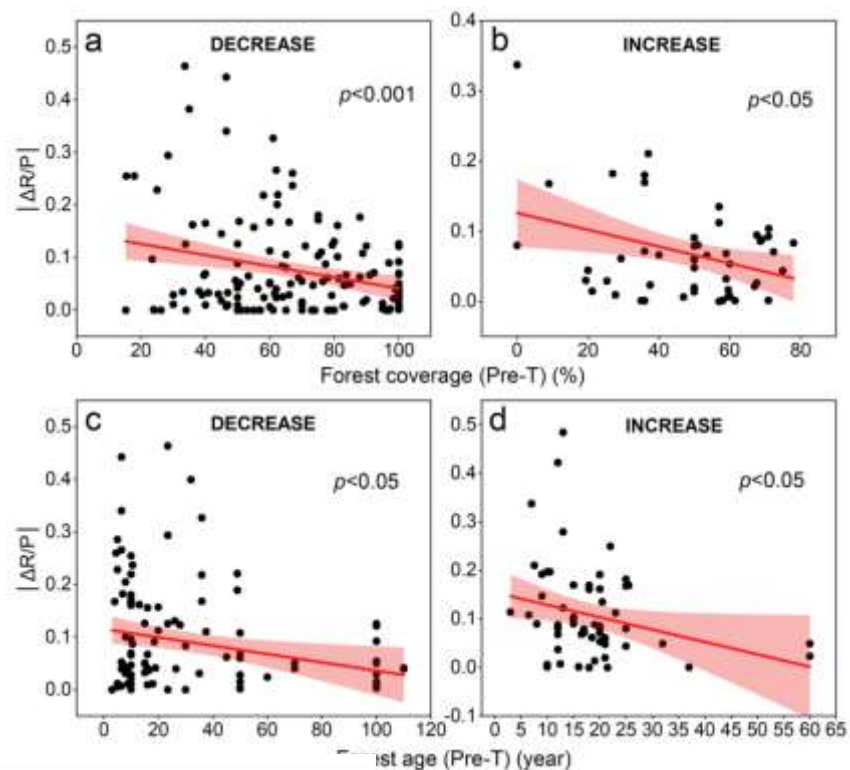
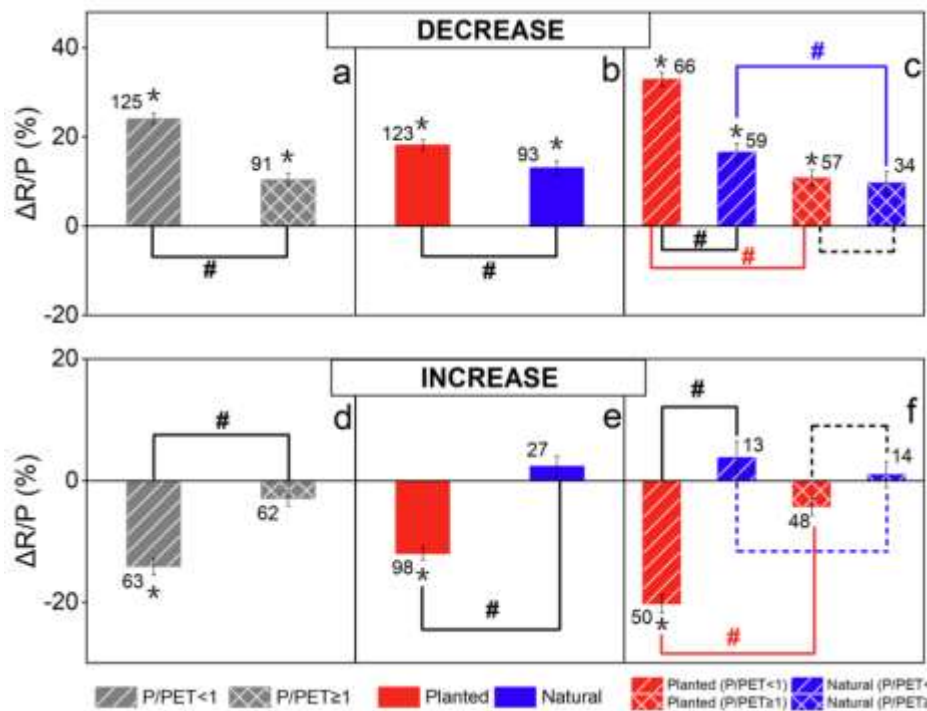
$P/PET=1$   
 $m=2$

Table 1 | Changes of the two sensitivity functions with wetness index and watershed characteristics.

Sensitivity functions	Variables	Change in trends with variables	Variable ranges for the trends	IP	Second derivatives
$(\partial R/\partial m)$	$m$	↑	$m(1, \infty)$ and $P/PET(0, \infty)$	No IP	$RM < 0$
	$P/PET$	From ↓ to ↑	$m(1, \infty)$ and $P/PET(0, 1)$	For each $m(1, \infty)$ , an IP exists in $P/PET(0, 1)$	From $MP < 0$ to $MP > 0$
		~	$P/PET=1$ and $m \rightarrow \infty$	~	$MP \rightarrow 0$
		↑	$m(1, \infty)$ and $P/PET(1, \infty)$	No IP	$MP > 0$
$(\partial R/\partial P)$	$m$	From ↑ to ↓	$m(1, \infty)$ and $P/PET(0, 1)$	For each $P/PET(0, 1)$ , an IP exists in $m(1, \infty)$	From $PM > 0$ to $PM < 0$
		~	$P/PET=1$ and $m \rightarrow \infty$	~	$PM \rightarrow 0$
		↑	$m(1, \infty)$ and $P/PET(1, \infty)$	No IP	$PM > 0$
	$P/PET$	↓	$m(1, 2)$ and $P/PET(0, \infty)$	No IP	$PP < 0$
		~	$m=2$ and $P/PET \rightarrow 0$	~	$PP \rightarrow 0$
		From ↑ to ↓	$m(2, \infty)$ and $P/PET(0, \infty)$	For each $m(2, \infty)$ , an IP exists in $P/PET(0, \infty)$	From $PP > 0$ to $PP < 0$

IP: inflection points; m: watershed characteristics; P/PET: wetness index; ↑: upward; ↓: downward; ~: non-trends.  
 $RM = \frac{\partial^2 R}{\partial m^2} < 0$ ,  $MP = \frac{\partial^2 R}{\partial P \partial m} < 0$ ,  $PM = \frac{\partial^2 R}{\partial m \partial P} > 0$ ,  $PP = \frac{\partial^2 R}{\partial P^2} < 0$

- $m < 2$  (排水性好的流域) 森林增加对产水率的负作用明显
- $m > 2$  (排水性差的流域) 森林增加对产水率的负作用不明显，甚至增加产水率
- $P/PET > 1.0$  (湿润地区) 森林增加不会减少产水率，在  $m > 2$  的地方会增加产水率
- $0.25 < P/PET < 1$  &  $m > 2$  (半湿润半干旱地区及  $m > 2$  下垫面) 可以进行森林恢复，在  $m > 2$  地方，产水率不会显著减少
- $0.25 < P/PET < 1$  &  $m < 2$  (半湿润半干旱地区及  $m < 2$  下垫面) 谨慎森林恢复，需承担产水率显著减少、以及干旱与洪涝风险
- $P/PET < 0.25$  (干旱地区) 严格限制植被改造，即使在  $m > 2$  地方，产水率也将显著减少
- 气候变化下，  $P/PET < 1$  的非湿润地区比  $P/PET > 1$  的湿润地区更容易发生洪灾



Yu and Zhou et al., 2022,  
communications earth & environment

### III 兼顾水资源的森林生态系统固碳之路

- 1 生态水文学：不损害水资源的绿量增加之路  
地形复杂的地区:(低山丘陵区——片孤城万仞山的地方); 小地形: 山洼(千万不要在山顶、山腰陡坡地); 千万不要在排水好的地方种森林!

湿润地区

最好是自然恢复

- 2 森林生态学：研究如何持久高速地促进生物量和土壤固碳。

- 3 加强森林经营管理的技术、经济方面的研究, 将过去以木材生产为目的转变为以固碳为目的的林业经营管理。

- 4 促进土壤固碳是兼顾水资源的森林生态系统固碳之路

$m < 2$  (排水性好的流域) 森林增加对产水率的负作用明显

$m > 2$  (排水性差的流域) 森林增加对产水率的负作用不明显, 甚至增加产水率

$P/PET > 1.0$  (湿润地区) 森林增加不会减少产水率, 在  $m > 2$  的地方会增加产水率

$0.25 < P/PET < 1$  &  $m > 2$  (半湿润半干旱地区及  $m > 2$  下垫面) 可以进行森林恢复, 在  $m > 2$  地方, 产水率不会显著减少

$0.25 < P/PET < 1$  &  $m < 2$  (半湿润半干旱地区及  $m < 2$  下垫面) 谨慎森林恢复, 需承担产水率显著减少、以及干旱与洪涝风险

$P/PET < 0.25$  (干旱地区) 严格限制植被改造, 即使在  $m > 2$  地方, 产水率也将显著减少

气候变化下,  $P/PET < 1$  的非湿润地区比  $P/PET > 1$  的湿润地区更容易发生洪灾

**敬请批评指正！**



虽然全球大江大河观测表明过去几十年来径流量非但没减少还在增加，大多都认为是CO<sub>2</sub>上升和气候改变所致(eg, Gedney et al., 2006, nature; Betts et al., 2007, nature; Piao et al., 2007, PNAS), 少量认为是森林增加的结果(eg, Zhou et al., 2010,WRR; Wang and Fu, 2011)。