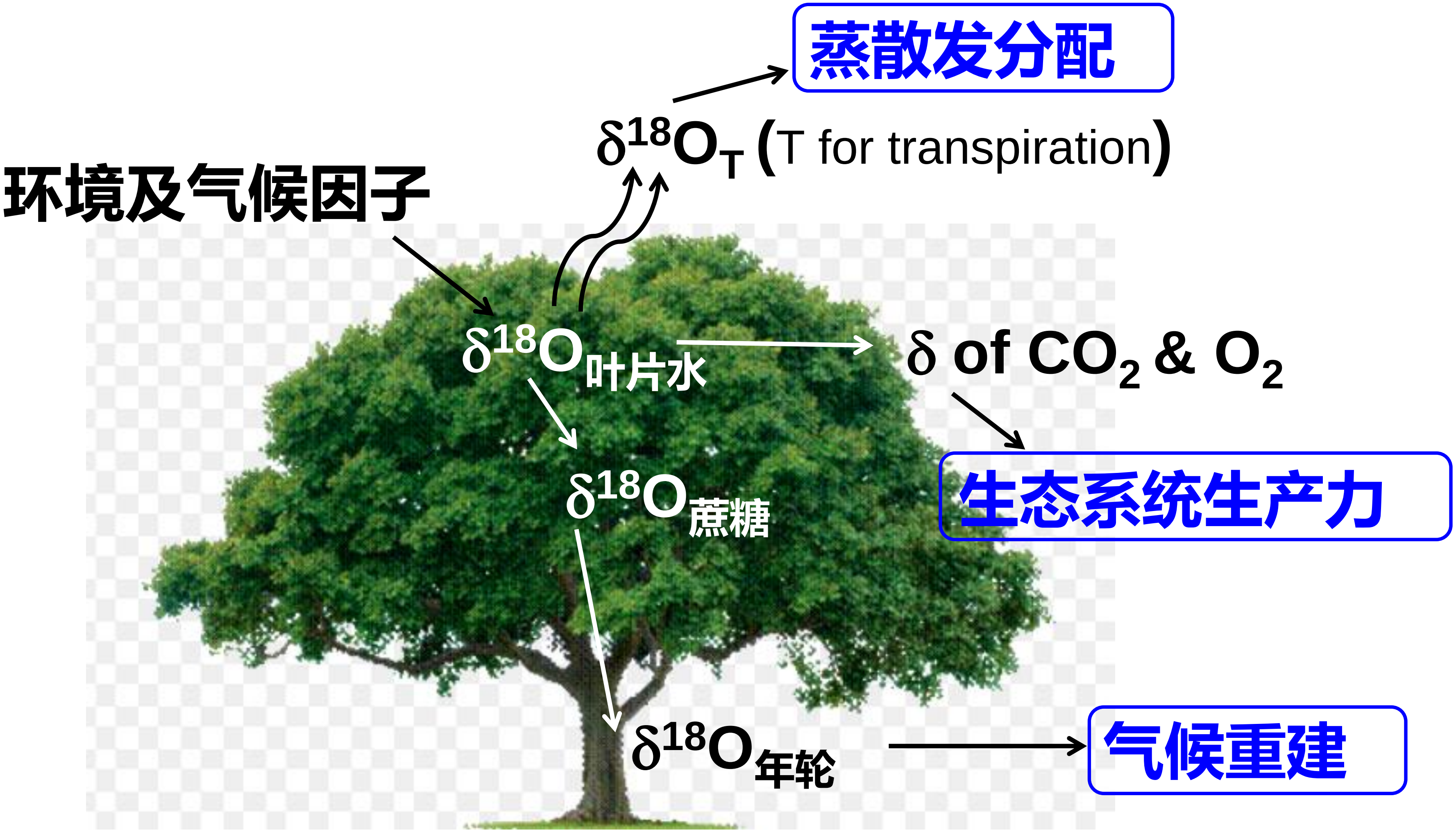
基于激光同位素测量的叶片水氧同位素富集机理研究

深圳大学 宋欣

$\delta^{18}O_{\text{叶片水}}$是多个生态学应用的基础



环境及气候因子

$\delta^{18}O_{\text{叶片水}}$

$\delta^{18}O_T$ (T for transpiration)

蒸散发分配

δ of CO_2 & O_2

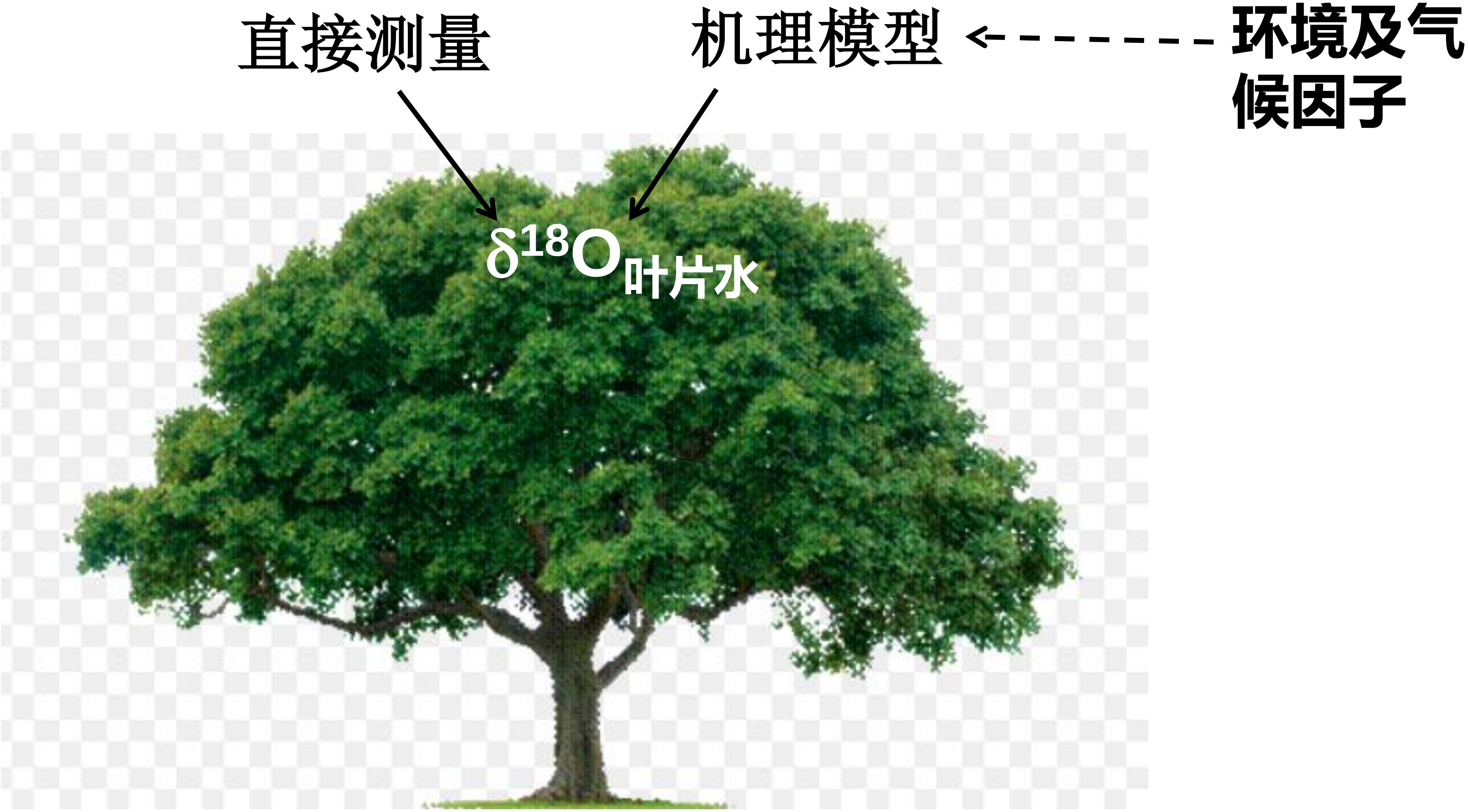
生态系统生产力

$\delta^{18}O_{\text{蔗糖}}$

$\delta^{18}O_{\text{年轮}}$

气候重建

怎样确定$\delta^{18}\mathrm{O}_{\text{叶片水}}$的值？

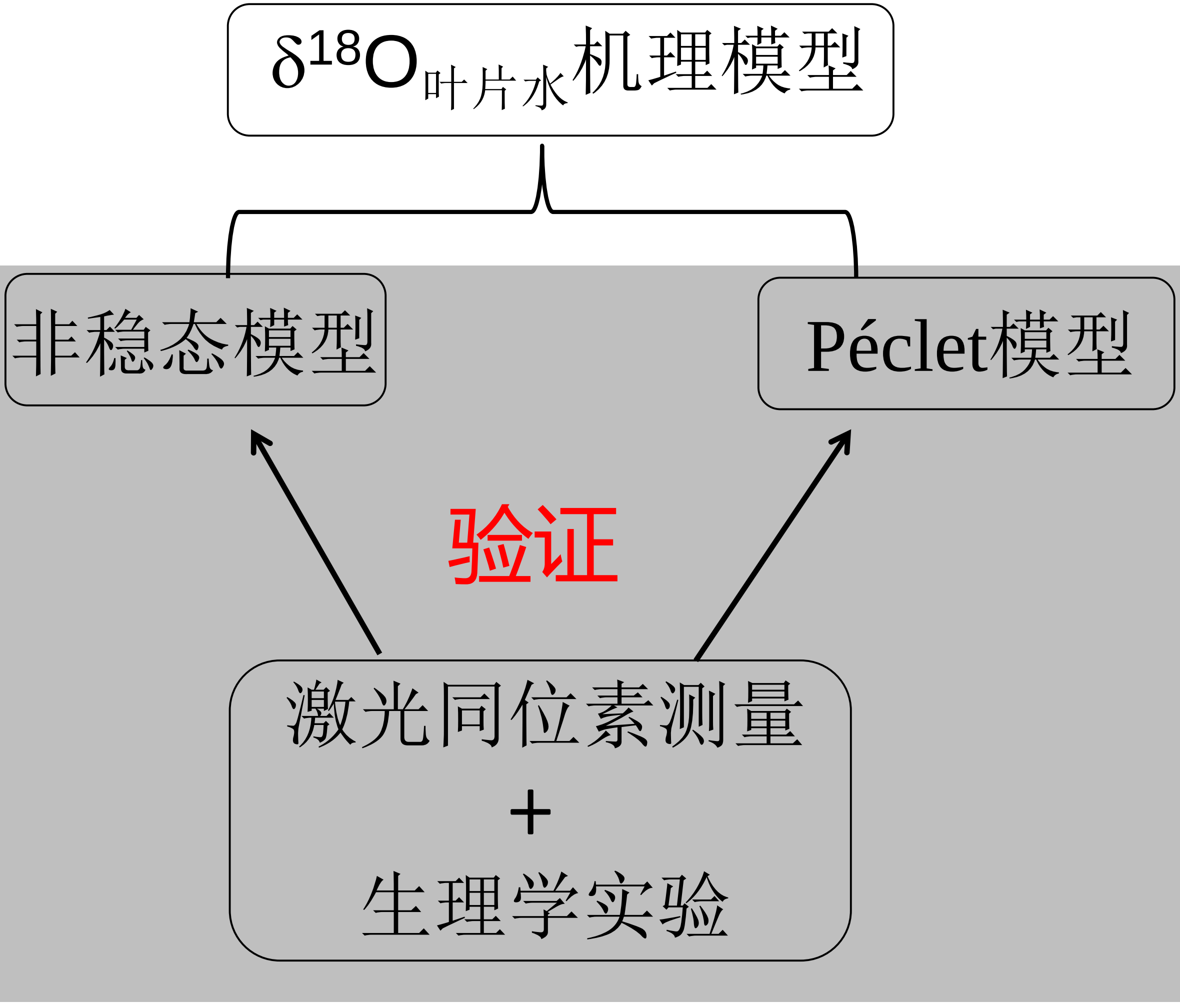


直接测量

机理模型 ← - - - - - - - - 环境及气候因子

$\delta^{18}\mathrm{O}_{\text{叶片水}}$

研究内容



$\delta^{18}O_{叶片水}$机理模型

非稳态模型

Péclet模型

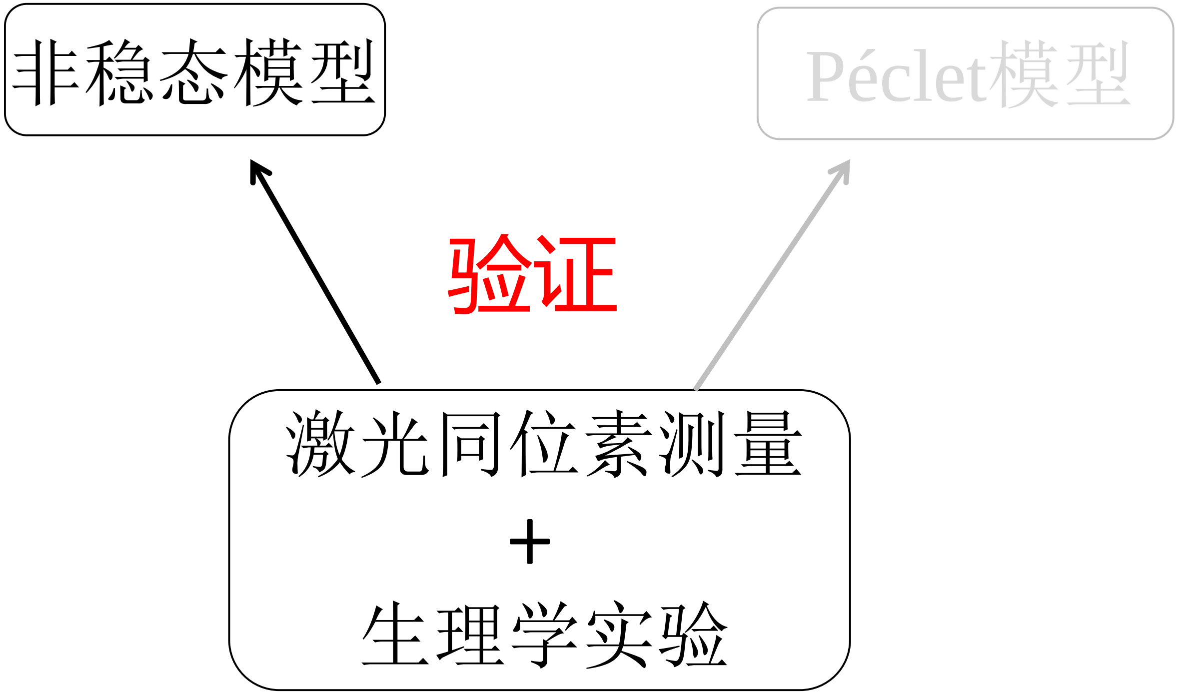
验证

激光同位素测量

+

生理学实验

研究内容



非稳态模型

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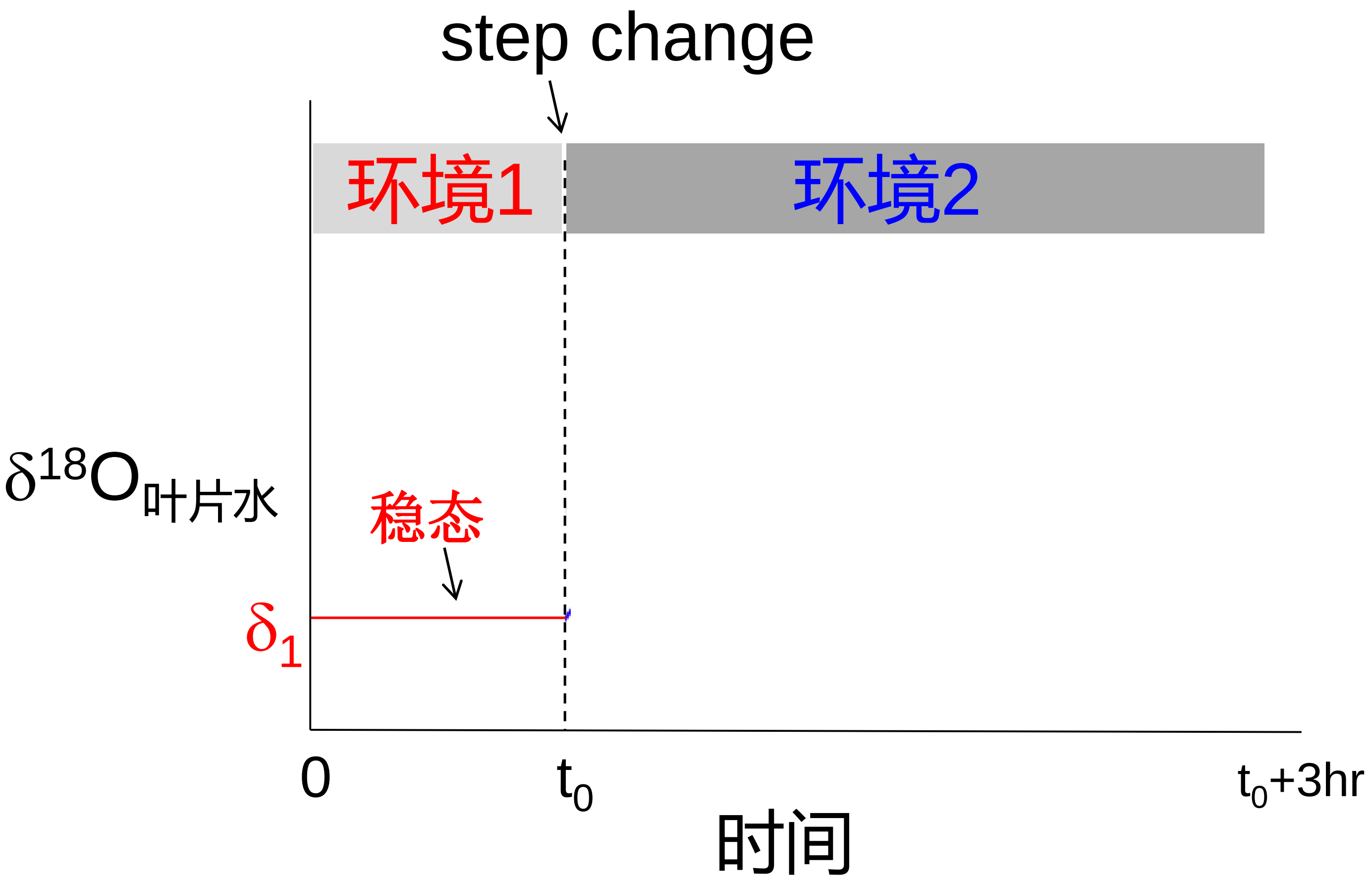
验证

激光同位素测量
+
生理学实验

同位素非稳态



自然情形下，环境因子很难长时间保持恒定不变，因而，**同位素非稳态是常态。**

同位素非稳态

同位素非稳态方程 (Dongmann 1974; Farquhar & Cernusak 2005)

$$\Delta^{18}O_{\text{叶片水}, \text{ t}} = \Delta^{18}O_{\text{叶片水}, \text{ ss}} + (\Delta^{18}O_{\text{叶片水}, \text{ t=0}} - \Delta^{18}O_{\text{叶片水}, \text{ ss}}) \exp(-t/\tau)$$

$\Delta^{18}O_{\text{叶片水}}$在时间点t的值

稳态 $\Delta^{18}O_{\text{叶片水}}$值

$\Delta^{18}O_{\text{叶片水}}$的起始值

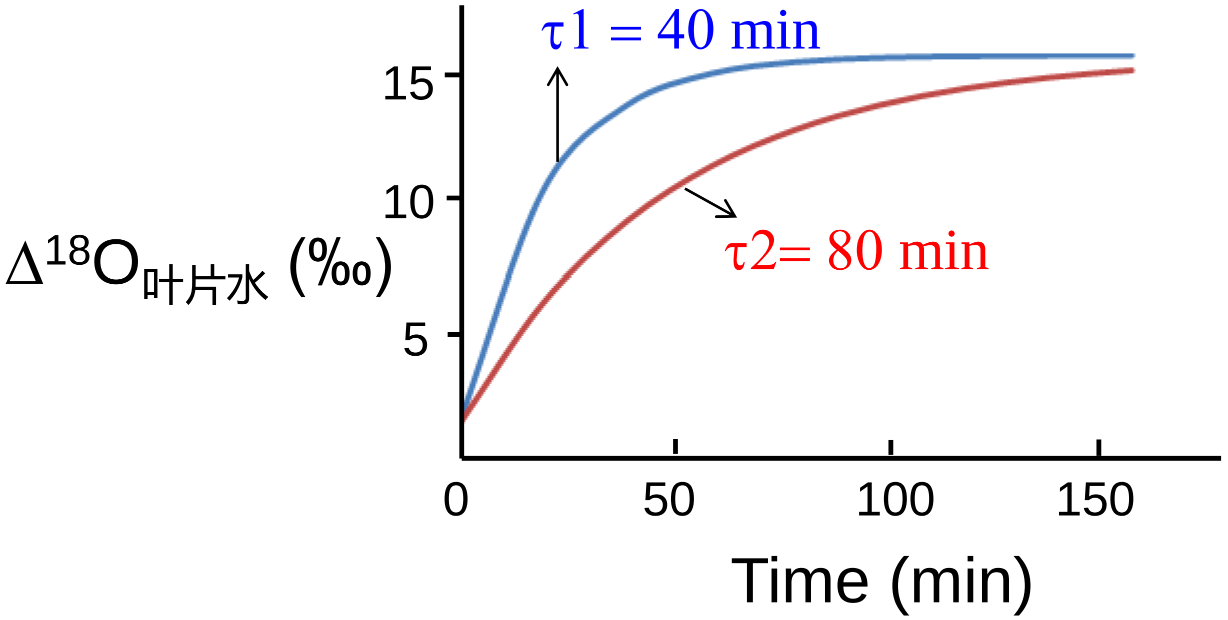
time constant

1. 非稳态方程可以用来预测非稳态过程中任一时间点t的叶片水同位素信号
2. τ 是时间常数，是非稳态方程的决定性参数

τ 的特性

1. τ 决定了非稳态过程$\Delta^{18}\mathrm{O}_{\text{叶片水}}$随时间变化的轨迹/形状

2. τ 越大， 叶片水抵达同位素稳态所需要的时间越长



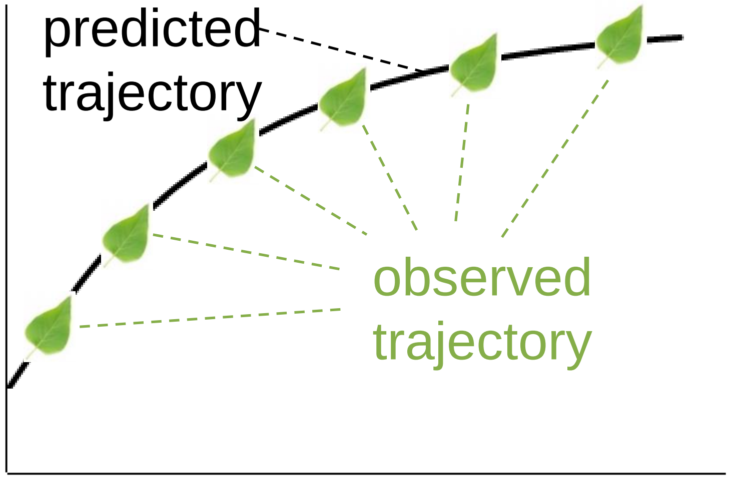
3. τ 与叶片水分周转速率相关

$$\tau = (1-f)\cdot\frac{W}{E}\cdot\alpha^{+}\left[\alpha_{\mathrm{k}}\left(\frac{w_{\mathrm{i}}-w_{\mathrm{a}}}{w_{\mathrm{i}}}\right)+\left(\frac{w_{\mathrm{a}}-w_{\mathrm{in}}}{w_{\mathrm{i}}}\right)\left(\frac{1}{1-w_{\mathrm{in}}}\right)\right]$$

怎样验证非稳态方程？

验证非稳态方程的关键在于验证 τ 的表达式是否正确

理论上，验证τ 可以通过检验同一叶片$\Delta^{18}O_{叶片水}$随时间变化的轨迹和τ表达式预测的轨迹是否一致来实现。



实际操作中，此路不通 -- 无法构建同一叶片$\Delta^{18}O_{叶片水}$的时间变化轨迹（现有的测定叶片水同位素的方法要求对叶片进行破坏性取样）。

怎样验证非稳态方程？

叶片水的同位素非稳态方程

$$\Delta^{18}O_{叶片水\ t} = \Delta^{18}O_{叶片水,\ SS} + (\Delta^{18}O_{叶片水,\ t=0} - \Delta^{18}O_{叶片水,\ SS})\ \exp(-t/\tau)$$

蒸发点水的同位素非稳态方程

$$\Delta^{18}O_{e,\ t} = \Delta^{18}O_{e,\ SS} + (\Delta^{18}O_{e,\ t=0} - \Delta^{18}O_{e,\ SS})\ \exp(-t/\tau)$$

蒸发点水与蒸腾水汽的同位素关系

$$\Delta^{18}O_{T,\ t} = (\Delta^{18}O_{e,\ t} - \Delta^{18}O_{e,\ SS})/K$$

蒸腾水汽 ($\Delta^{18}O_T$)的同位素非稳态方程

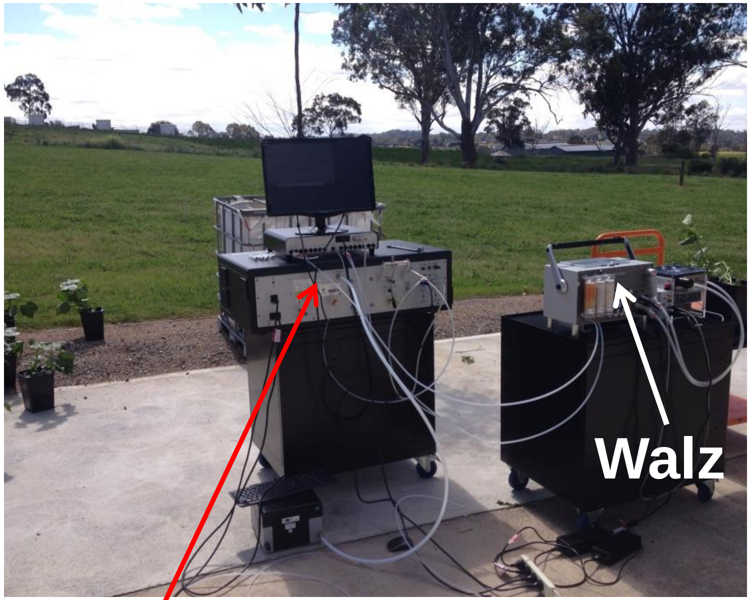
$$\Delta^{18}O_{T,\ t} = \Delta^{18}O_{T,\ t=0}\ \exp(-t/\tau)$$

$\Delta^{18}O_T$和$\Delta^{18}O_{leaf}$的非稳态时间变化轨迹是一致的

新方法：通过检验蒸腾水汽同位素信号随时间变化的轨迹验证τ 表达式是否正确。

测量方法

激光同位素仪与气体交换系统耦联
--- 可实现对同一叶片的$\Delta^{18}O_T$进行连续测量

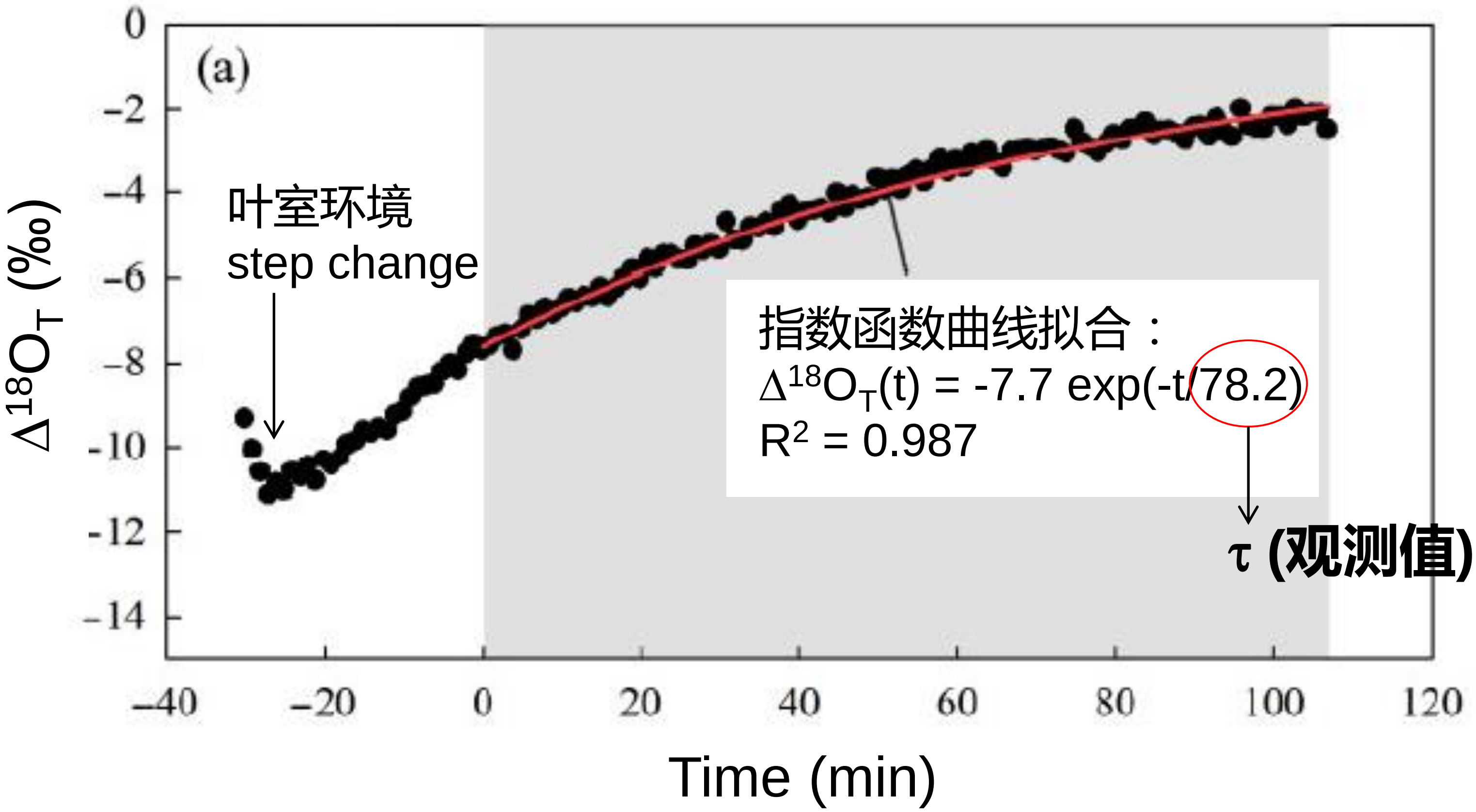


LGR激光同位素仪
（在线实时测量置于叶室内的叶片$\Delta^{18}O_T$信号）

Walz大叶叶室
（环境因子可控）

测量结果

棉花叶片的$\Delta^{18}O_T$非稳态过程示例



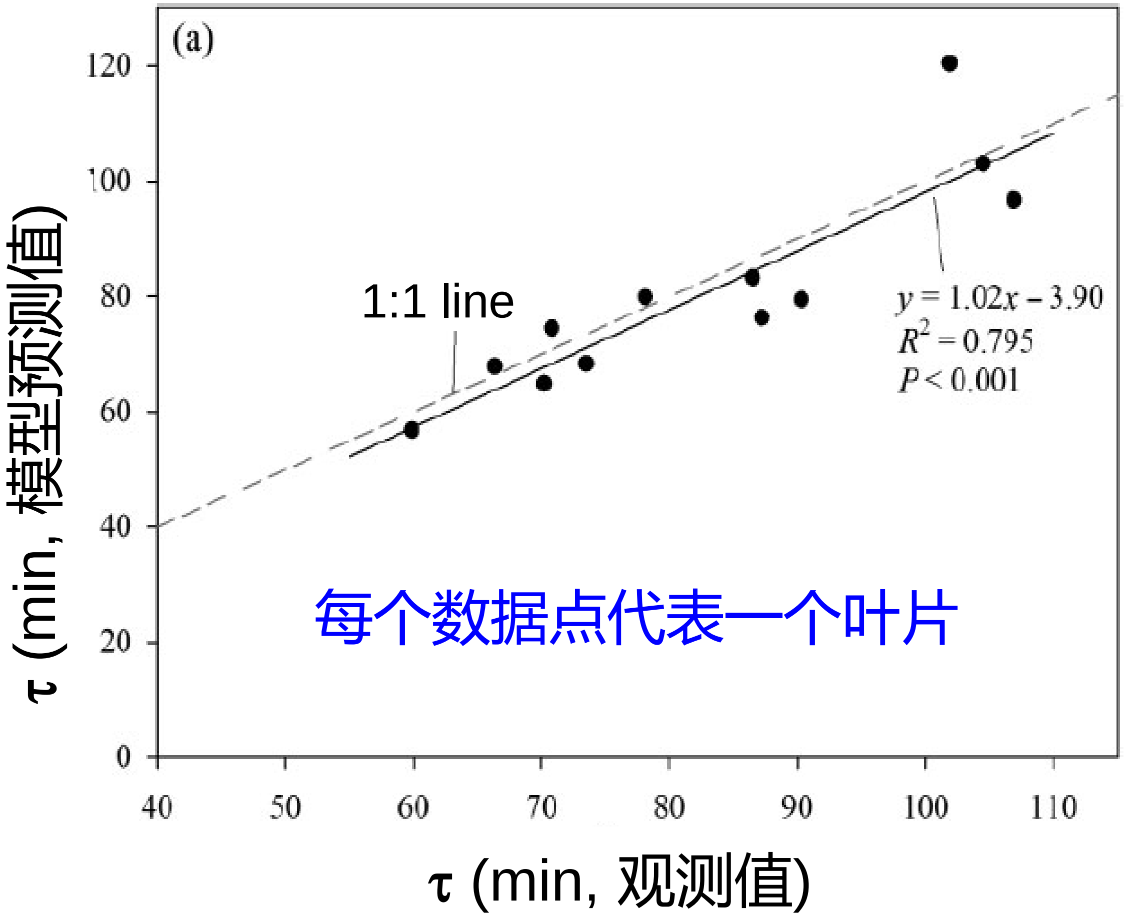
叶室环境
step change

指数函数曲线拟合：
$\Delta^{18}O_T(t) = -7.7 \exp(-t/78.2)$
$R^2 = 0.987$

τ (观测值)

测量结果

观测值和模型预测值比较



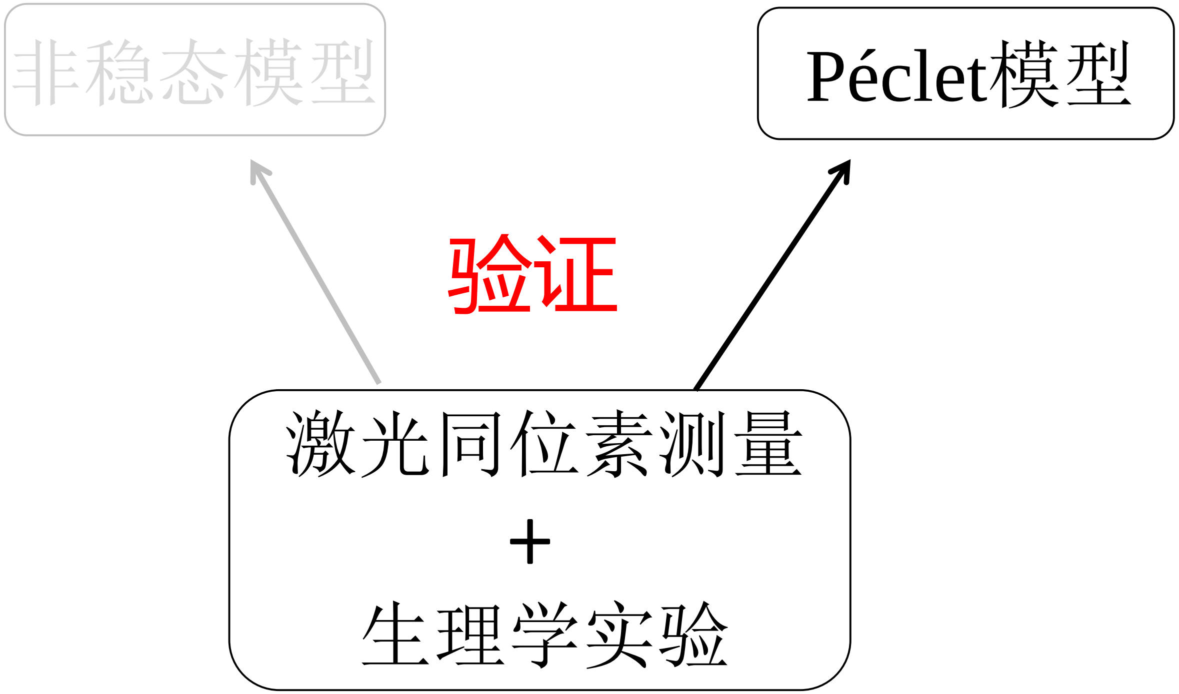
每个数据点代表一个叶片

1. τ 的观测值与基于非稳态方程的预测值吻合完好。

2. 首次从实验角度验证非稳态方程的正确性。

Song X, Simonin KA, Loucos KE, Barbour MM. (2015) Modeling non-steady state isotope enrichment of leaf water in a gas-exchange cuvette environment. *Plant Cell and Environment* 38:2618-2628.

研究内容



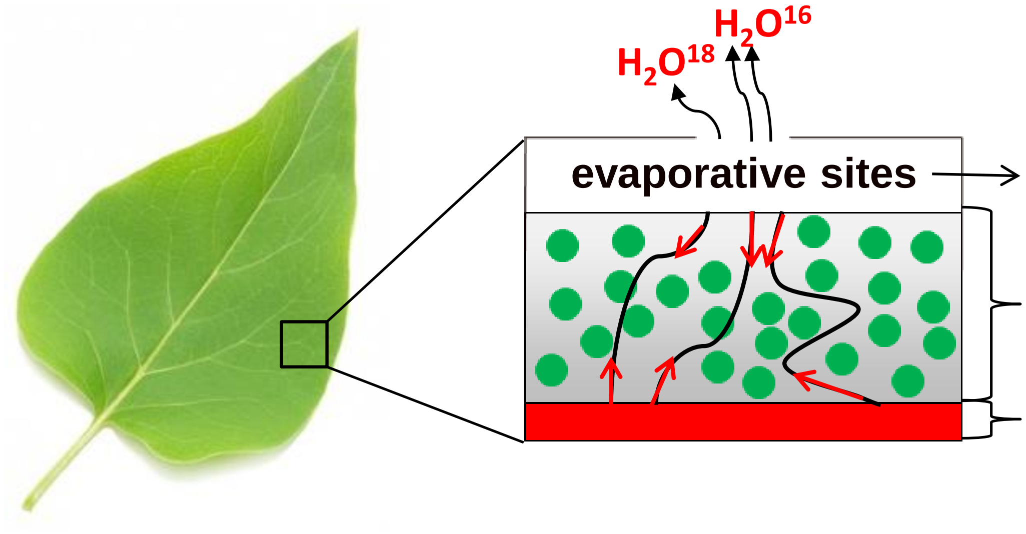
非稳态模型

Péclet模型

验证

激光同位素测量
+
生理学实验

Péclet模型



气孔蒸发点水分 ($\delta^{18}O_e$)

叶片内部水分 ($\delta^{18}O_{lamina}$)

叶脉水 ($\delta^{18}O_{sw}$)

叶片蒸腾运输与气孔蒸发点附近水的反向扩散是两个相互拮抗的过程，这两个过程在叶片内部达到平衡，该平衡可用**Péclet效应**描述。

Péclet模型

$$\Delta^{18}O_{lamina} = (\text{Péclet correction})^{*}\Delta^{18}O_e$$

$$\text{Péclet correction} = \frac{1-\exp(-P)}{P}$$

$$P = \frac{L^{*}E}{C^{*}D}$$

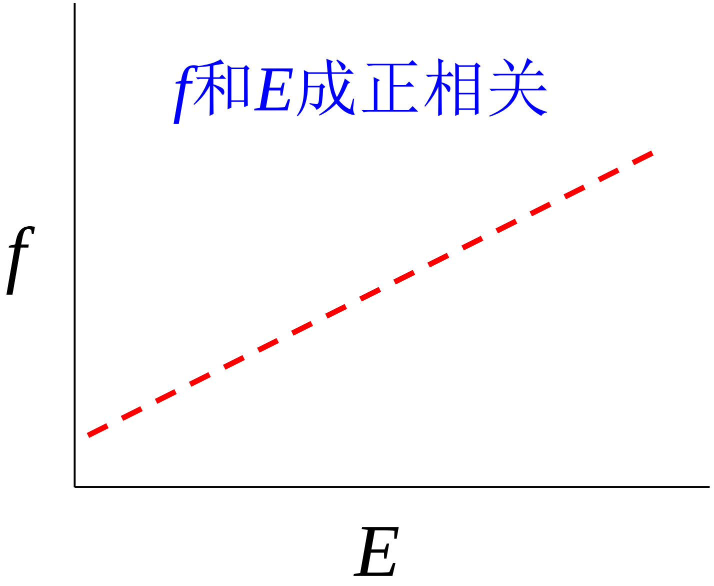
Craig & Gordon 1965; Farquhar & Lloyd, 1993

怎样验证Péclet模型？

如果Péclet模型正确，则 f 和蒸腾速率 E 成正相关

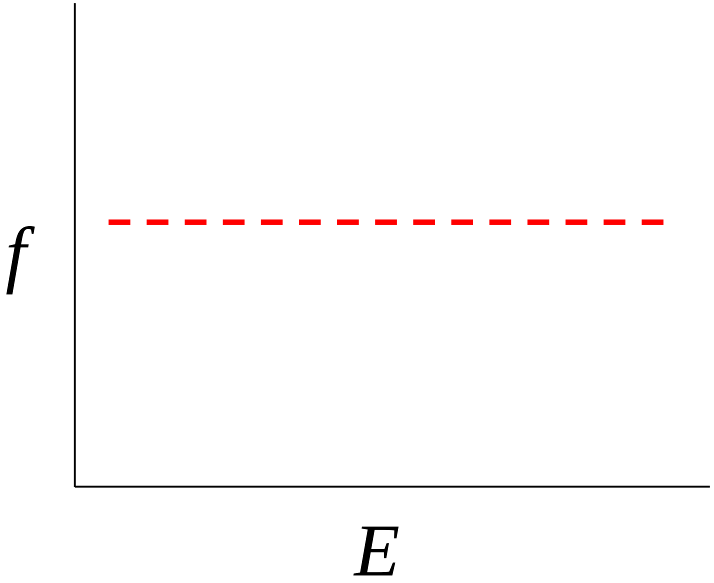
f 是叶片水和气孔蒸发点水同位素信号的比例差分

$$f = 1 - \frac{\Delta^{18}O_{\text{叶片水}}}{\Delta^{18}O_e}$$



怎样验证Péclet模型？

如果*f* 和*E*没有相关性



Péclet 模型 ✗

Two-pool 模型 ✓

$$\Delta^{18}O_{lamina} = (\cancel{\text{Péclet correction}})*\Delta^{18}O_e$$

怎样验证Péclet模型？

$$f = 1 - \frac{\Delta^{18}O_{\text{叶片水}}}{\Delta^{18}O_e}$$

无法直接测量
（计算$\Delta^{18}O_e$需要知道$\delta^{18}O_T$）

前激光时代，f估算可能存在较大误差
因为$\delta^{18}O_T$无法实时测量

怎样验证Péclet模型？

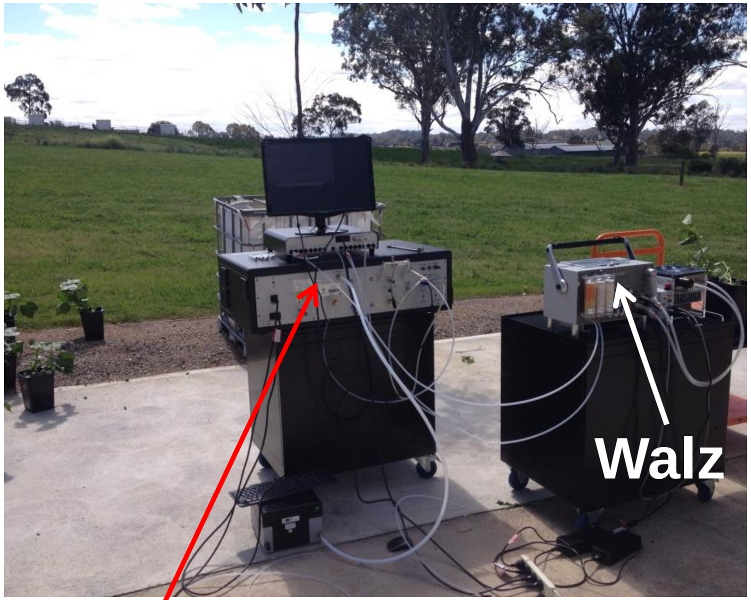
$$f = 1 - \frac{\Delta^{18}O_{叶片水}}{\Delta^{18}O_e}$$

无法直接测量

（计算$\Delta^{18}O_e$需要知道$\delta^{18}O_T$）

实验方法

激光同位素仪与气体交换系统偶联
--- 可实现对*f*-*E*关系的准确检验

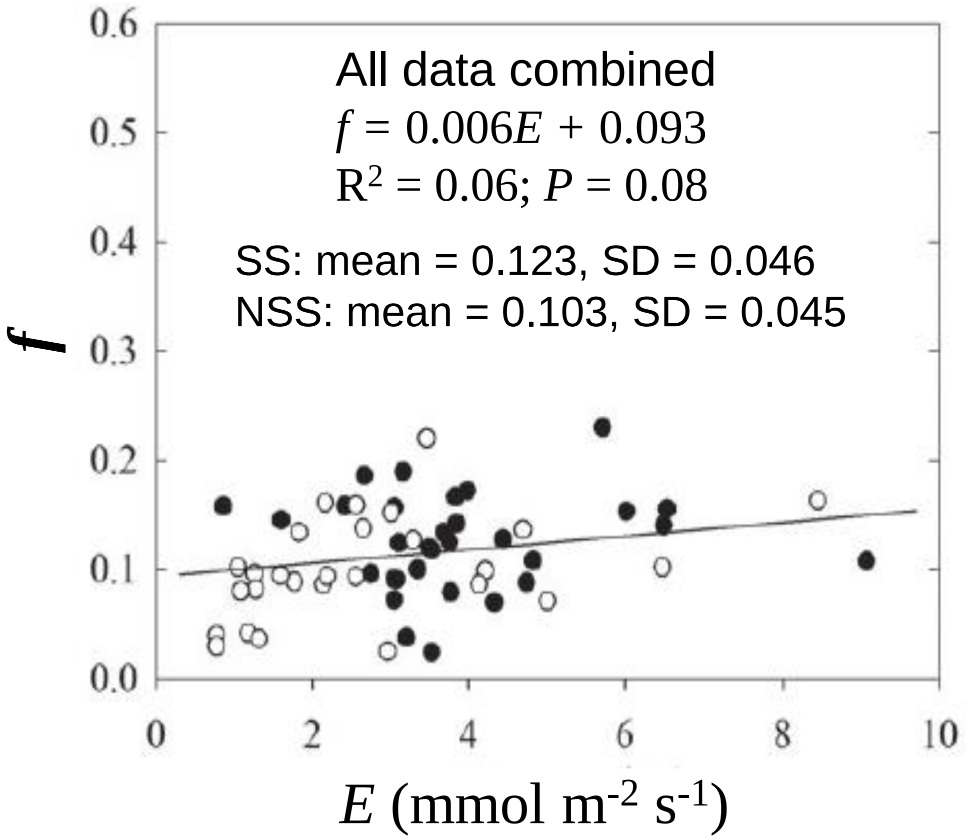


LGR激光同位素仪
（在线实时测量置于叶室内的叶片$\Delta^{18}O_T$信号）

Walz大叶叶室
（环境因子可控）

实验结果

棉花叶片实验揭示：*f* 与 *E*不具显著相关性



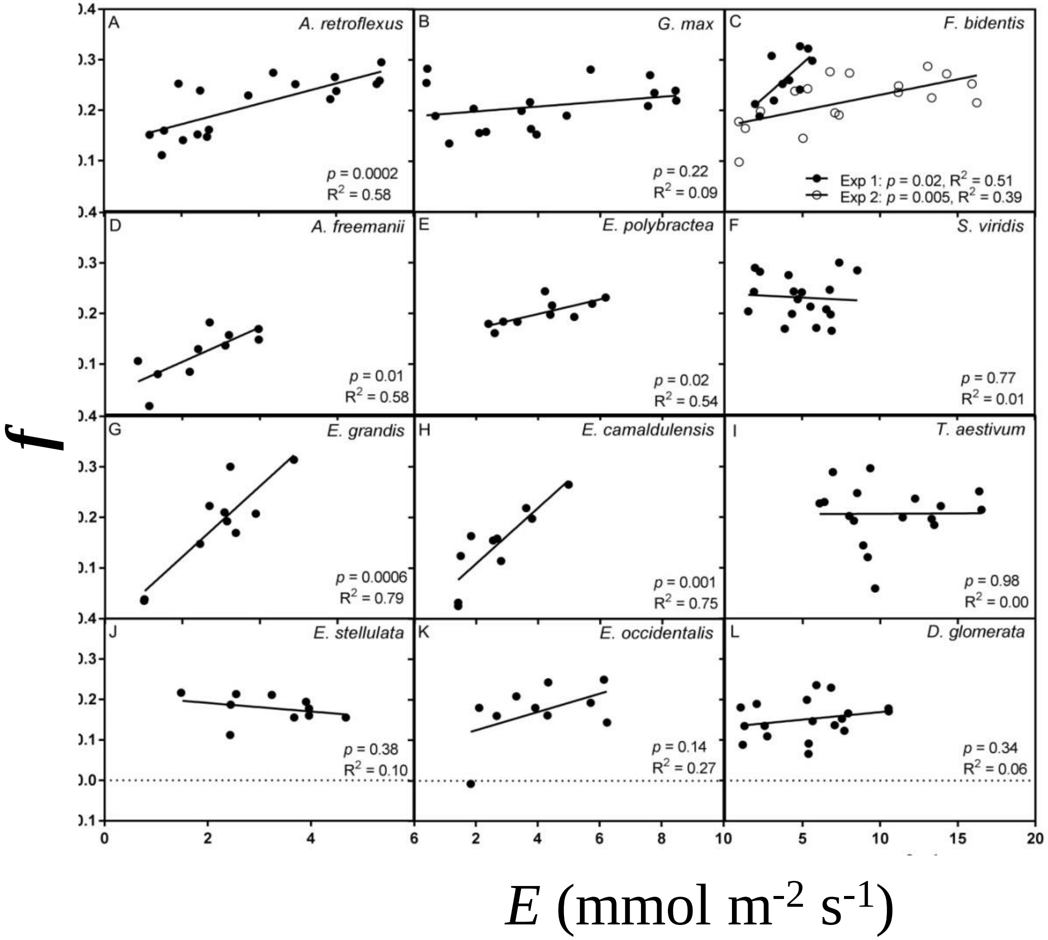
Lack of experimental support for the **Péclet** theory in cotton.

The simpler, **two-pool** model seems adequate for predicting cotton leaf water enrichment.

Song X, Loucos KE, Simonin KA, Farquhar GD, Barbour MM. (2015) Measurements of transpiration isotopologues and leaf water to assess enrichment models in cotton. *New Phytologist* 206: 637-646.

Péclet模型可能并非普适性的正确理论

更多测量结果（12种植物）



Evidence for the validity of the Péclet theory was found only in **5** out of the **12** species examined.

Leaf **hydraulic** design may be a determinant of patterns of leaf water isotope enrichment.

Loucos KE, Lockhart EL, **Song X**, Simonin KA, Barbour MM, Farquhar GD. Hydraulic design determines patterns of leaf water isotope enrichment. *To be submitted to Plant Physiology*

模型选择

到目前为止，Péclet的谜题尚未完全解决

To Péclet or not to Péclet? That’s the question.

模型选择

Global Change Biology

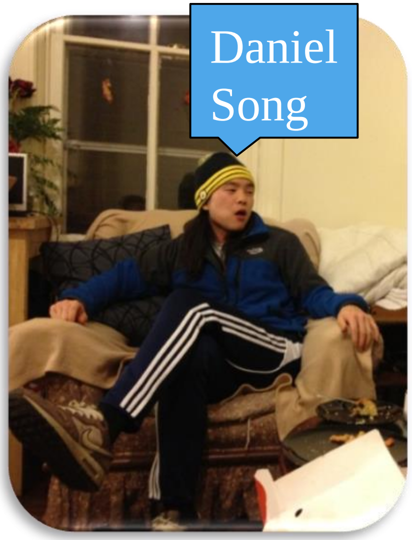
Global Change Biology (2012) **18**, 1769–1780, doi: 10.1111/j.1365-2486.2012.02648.x

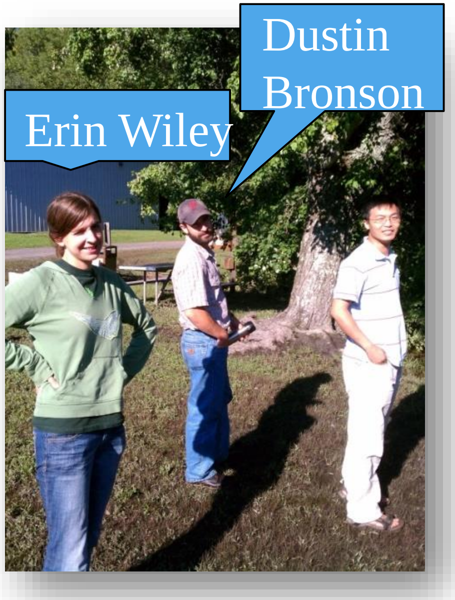
Modeling biophysical controls on canopy foliage water ^{18}O enrichment in wheat and corn

WEI XIAO*, XUHUI LEE†, XUEFA WEN‡, XIAOMIN SUN‡ and SHICHUN ZHANG§

冠层尺度： Péclet效应不是必须考虑的要素

特别致谢





USDA United States Department of Agriculture
Forest Service

Silas Little Experimental Forest

NSF

Australian Government

Australian Research Council

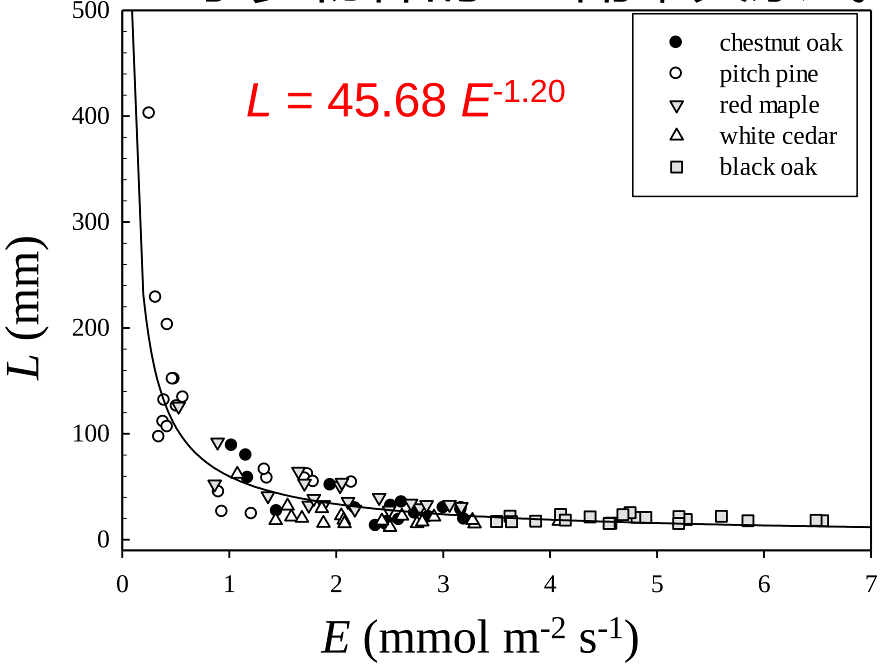
Thank you!

模型选择

到目前为止，Péclet的谜题尚未完全解决

如果必须使用Péclet模型

基于多物种的*L*-*E*副幂关系式



Two-pool模型

$$\Delta^{18}O_{lamina} = \cancel{(\text{Péclet correction})}*\Delta^{18}O_{e}$$

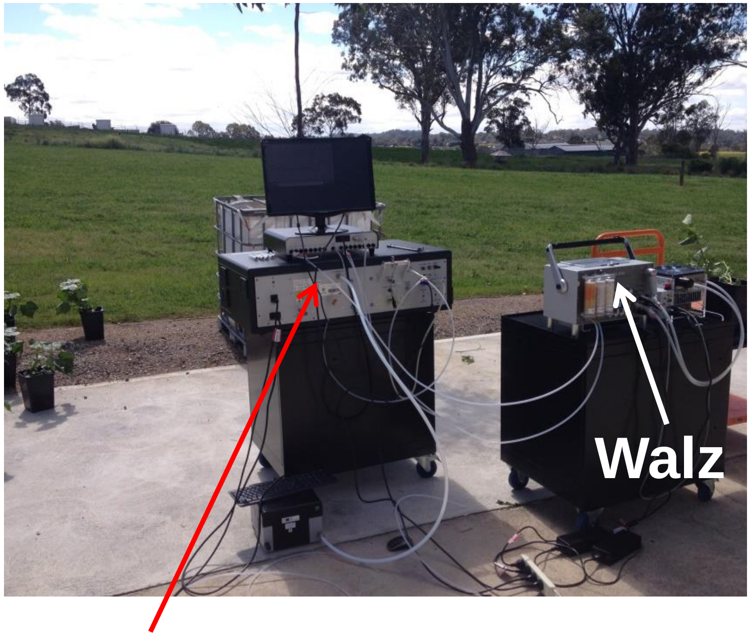
或

$$\Delta^{18}O_{lamina} = \Delta^{18}O_{e}$$

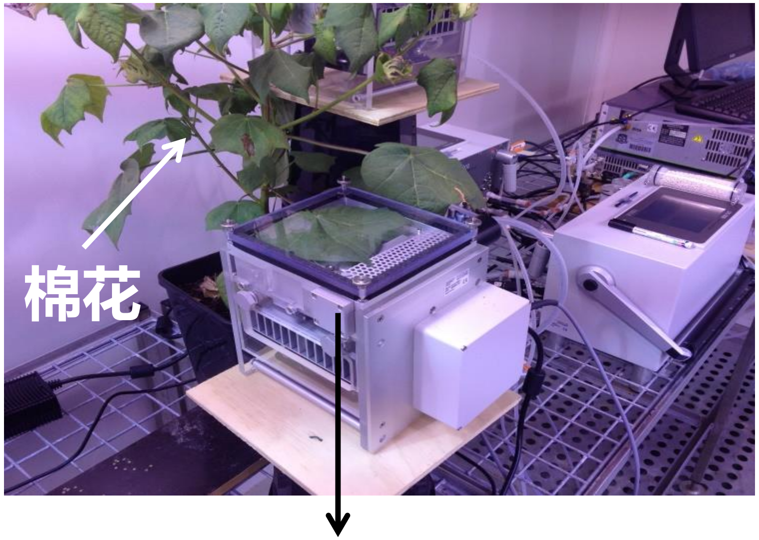
测量方法

激光同位素仪与气体交换系统偶联

--- 可实现对同一叶片的$\Delta^{18}O_T$进行连续测量



LGR激光同位素仪
（在线实时测量置于叶室内的叶片$\Delta^{18}O_T$信号）



Walz大叶叶室
（环境因子可控）

非稳态模型

非稳态叶片水氧同位素富集模型

$$\Delta^{18}O_{lw}(t) = \frac{\Delta^{18}O_{lw\_ss}\cdot K + [(K+\frac{dW}{dt})\cdot\Delta^{18}O_{lw}(t-1) - K\cdot\Delta^{18}O_{lw\_ss}]\cdot e^{\frac{-(K+\frac{dW}{dt})\cdot t}{W(t-1)+\frac{dW}{dt}\cdot t}}}{K+\frac{dW}{dt}}$$

leaf water enrichment

leaf water content

where $K = \frac{\frac{E\cdot L}{C\cdot D}}{1-e^{-\frac{E\cdot L}{C\cdot D}}}\cdot\frac{g\cdot w_i}{\alpha^{+}\cdot\alpha^{K}}$

stomata conductance

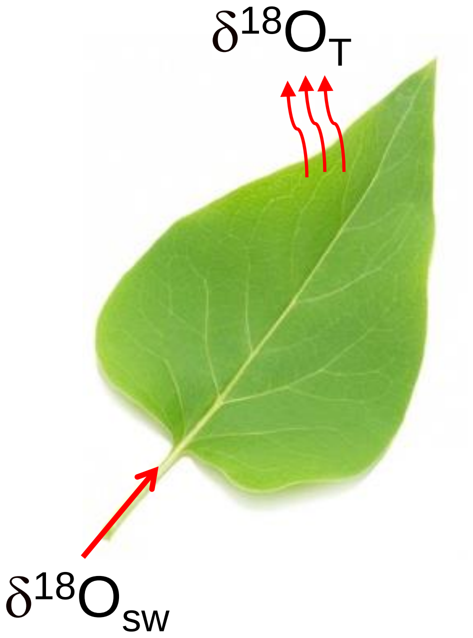
kinetic & equilibrium fractionation factors

water vapor isotope enrichment

$$\Delta^{18}O_{leaf\_ss} = \epsilon^{+} + \epsilon^{K} + (\epsilon^{K} - \Delta^{18}O_{v})\mathrm{RH}$$

Farquhar & Cernusak 2005

同位素稳态



环境因子保持恒定的情况下，
叶片水最终会达到同位素稳态，
此时，

$$\delta^{18}O_T = \delta^{18}O_{sw}$$

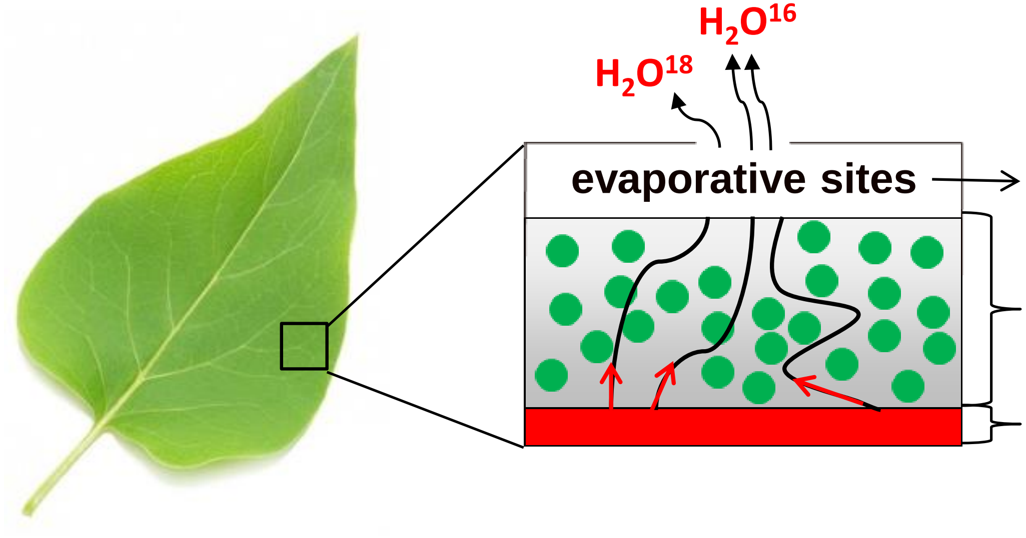
（蒸腾水汽同位素信号等于水源水信号）

同位素稳态

$\delta^{18}O_T = \delta^{18}O_{sw}$ } $\delta^{18}O_e$ (and $\delta^{18}O_{leaf}$)

Craig-Gordon方程

叶片水的蒸腾富集



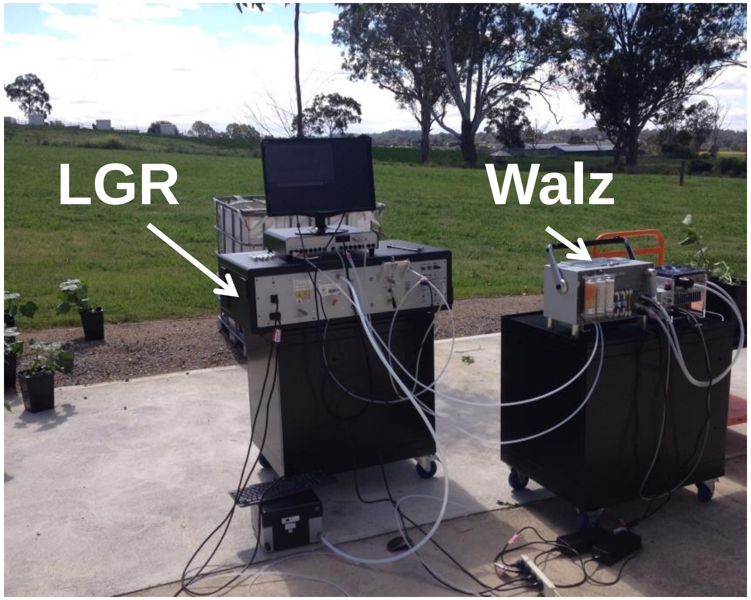
气孔蒸发点水分 ($\delta^{18}O_e$)

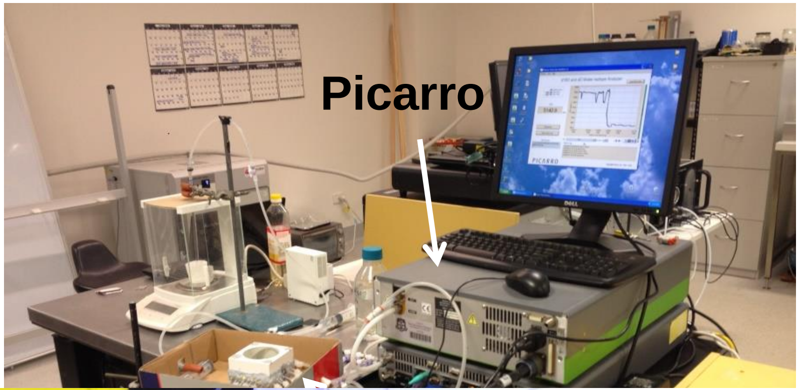
叶片内部水分 ($\delta^{18}O_{lamina}$)

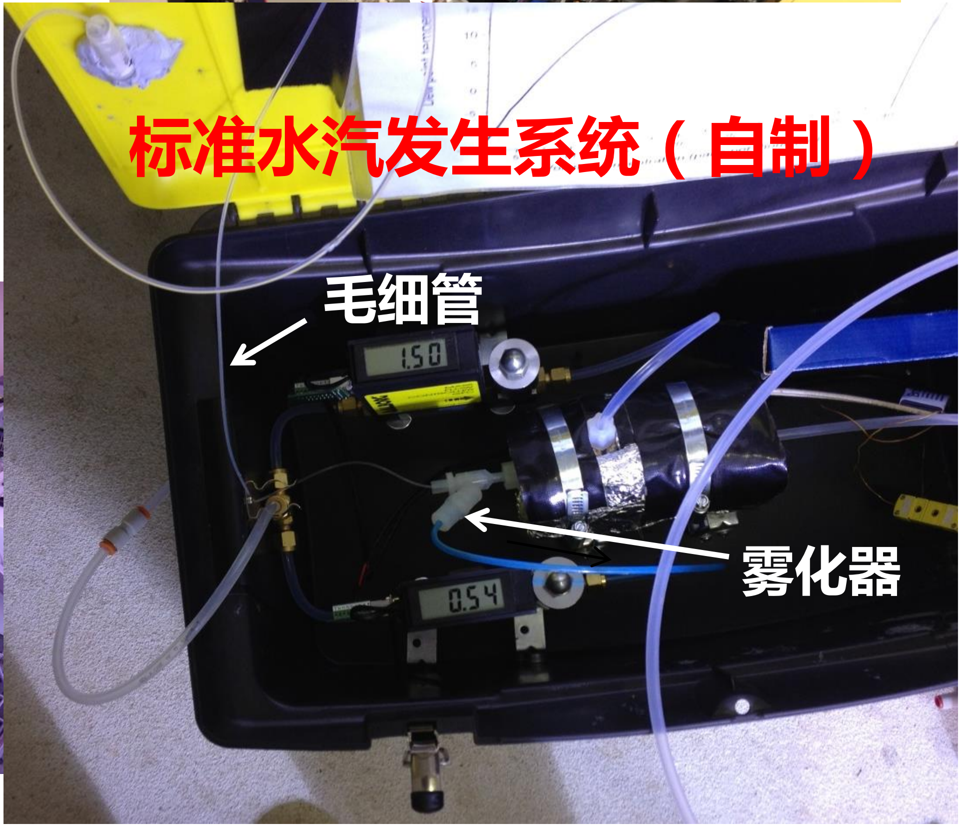
叶脉水 ($\delta^{18}O_{sw}$)

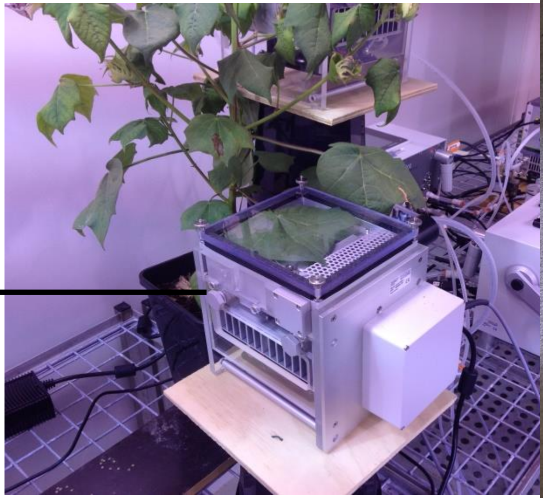
蒸腾作用导致叶片水的氧同位素发生富集，
i.e., $\delta^{18}O_{leaf} > \delta^{18}O_{sw}$

激光同位素仪与气体交换系统联用测量$\delta^{18}O_T$和E









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