

基于FLUXNET的CLM模型生态系统呼吸模拟验证*

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摘要 准确估算陆地生态系统呼吸 (Ecosystem respiration, RE) 对全球陆地生态系统碳收支研究具有重要意义. 模型模拟是估算陆地RE变化的一种常用手段. 然而目前陆地生态系统过程模型的RE模拟尚未得到充分验证. 基于耦合模式比较计划第五阶段 (Coupled Model Intercomparison Project Phase 5, CMIP5) 的通用陆面模型 (Community land model, CLM) RE模拟结果和全球通量网 (FLUXNET) 66个站点的涡度相关通量观测数据 (277条站点年数据) 评估CLM模型对RE的模拟效果. 结果表明: (1) 在空间尺度上, CLM低估了高纬度站点RE, 高估了低纬度站点RE, 但高纬度低估量更大导致空间格局整体低估 (相对误差为-3.56%). (2) 在时间尺度上, CLM模型基本捕捉了RE的年际和季节变化, 相关系数分别为0.60 ($P < 0.001$) 和0.63 ($P < 0.001$); CLM低估年尺度和月尺度的RE (以C计), 绝对误差分别是-182.21 g m⁻² a⁻¹、-120.16 g m⁻² mon⁻¹, 相对误差分别是-17.84%、-10.60%. (3) CLM模型对不同植被功能型的RE模拟效果不同, 由优及差依次为混交林、常绿针叶林、草地、农田、落叶阔叶林、常绿阔叶林. 本研究在时空尺度上量化了CLM模型的生态系统呼吸模拟误差, 并分析了土壤呼吸 Q_{10} 和 MR_{base} 参数以及土壤碳库模拟等因素的影响, 可为CLM模型的生态系统呼吸模块参数优化提供依据, 进而提升其模拟精度. (图4 表3 参80 附图2 附表2)

关键词 生态系统呼吸; 通用陆面模型 (CLM); 全球通量网 (FLUXNET); 模拟效果

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Benchmarking the ecosystem respiration simulated by CLM based on FLUXNET*

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Abstract Accurate estimation of terrestrial ecosystem respiration (RE) is of great significance to the study of the global terrestrial ecosystem's carbon budget. Model simulation is a common method to simulate terrestrial RE changes. However, the RE simulation of the current terrestrial ecosystem's process models has not been fully verified yet. In this study, we evaluated the RE simulated by the Community Land Model (CLM) using eddy covariance flux observations of 66 stations from FLUXNET (277 site-years). The results showed that: (1) CLM underestimated RE at high latitude sites while overestimated it at low latitude stations. The magnitude of the former was larger than that of the latter, thus leading to the overall underestimation of RE (the relative error was -3.56%). (2) At the temporal scale, CLM roughly captured the interannual and seasonal variation

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of RE. The correlation coefficients were 0.60 ($P < 0.001$) and 0.63 ($P < 0.001$), respectively. CLM underestimated the annual and monthly RE, with the absolute error of $182.21 \text{ g C m}^{-2} \text{ a}^{-1}$ and $120.16 \text{ g C m}^{-2} \text{ mon}^{-1}$, respectively. The relative errors were 17.84% and 10.60%, respectively. (3) The simulation results of the different plant functional types from the best to worst were ranked as mixed forest, evergreen coniferous forest, grassland, farmland, deciduous broadleaved forest, and evergreen broadleaved forest. This study quantified the error of CLM-RE simulation at the spatial-temporal scale and analyzed its influence factors, such as soil respiration Q_{10} , MR_{base} parameters, and soil carbon reservoir simulation. The results can help in optimizing CLM-RE and improving the accuracy of RE simulations.

Keywords ecosystem respiration; Community Land Model (CLM); FLUXNET; simulated performance

陆地生态系统呼吸 (Ecosystem respiration, RE) 和总初级生产力 (Gross primary productivity, GPP) 共同决定陆地生态系统净碳交换量 (Net ecosystem exchange of CO_2 , NEE) 的大小。因此, 准确量化RE和GPP的动态趋势对理解陆地生态系统碳汇变化至关重要^[1]。然而, RE受复杂的物理、化学和生物相互作用过程的调控, 具有很强的时空异质性, 在全球尺度上尚未被准确估算^[2], 从而给全球陆地生态系统碳收支评估带来较大不确定性。Ballantyne等研究表明在气候变化背景下, 增温减缓导致的RE降低成为陆地生态系统碳汇增加的主要原因^[3]。因此准确估算陆地RE对全球陆地生态系统碳收支研究具有重要意义。

近年来, RE模拟验证多集中于森林^[4-6]、草地^[7-8]和农田^[9]等单一生态系统, 对不同生态系统类型综合验证分析相对较少。同时, RE模拟验证研究范围多侧重于某一地区或大洲, 例如北美^[10]、欧洲^[11]和东亚^[12]等区域, 而全球尺度上的验证研究相对欠缺。RE的估算主要包括遥感模型^[2, 13]和过程模型^[14-16], 其中遥感模型结构相对简单, 难以表达较完整的RE机理过程^[17], 所以RE模拟不确定性仍较大。过程模型其相对完善的参数化结构可较精确地模拟RE变化过程^[18]。通用陆面模型 (Community Land Model, CLM) 包含植被、凋落物、土壤碳氮和植被物候等模块, 是模拟大气-植被-土壤连续生物地球物理和生物地球化学过程的主流模型^[19]。同时, CLM可较精确地模拟不同尺度不同植被型的GPP、蒸散 (Evapotranspiration, ET)^[20-23]和叶面积指数 (Leaf Area Index, LAI)^[24-25]等变量, 但在全球尺度上的RE模拟结果尚未验证。

涡度相关技术的通量观测是直接测定陆地生态系统与大气间碳水通量的重要方法, 为全球陆地生态系统碳循环过程及其控制机理、时空格局等方面的研究提供了重要信息^[26]。目前全球FLUXNET通量长期监测网络经27年发展为准确估算碳通量变化提供了良好的平台^[27]。本研究利用FLUXNET-66个站点 (覆盖全球21个国家) 的RE观测数据对CLM-RE模拟结果进行验证, 包括常绿阔叶林 (EBF)、落叶阔叶林 (DBF)、常绿针叶林 (ENF)、混交林 (MF)、草地 (GRA)、农田 (CRO) 6种不同植被功能型 (按国际地圈生物圈计划 (International Geosphere Biosphere Programme, IGBP) 分类), 从空间格局、年际和季节变化对CLM-RE模拟结果进行验证分析, 旨在评估此模型对不同生态系统的适用性及

预测精度, 并探究模拟的主要误差和不确定性来源, 为后续CLM呼吸模块参数改进提供依据, 进而提高CLM-RE模拟精度, 为全球陆地生态系统碳收支研究提供支撑。

1 数据与方法

1.1 FLUXNET-RE观测数据

FLUXNET作为全球涡度相关通量观测网络, 是目前最大的 CO_2 、 H_2O 和能量通量的合成数据集 (<http://fluxnet.fluxdata.org/>), 其共享的通量数据经过统一质量控制、插补和拆分处理^[28-29], 将NEE拆分出RE和GPP供科学工作者研究应用。本文将拆分的RE数据作为观测数据用以CLM-RE模拟结果的验证分析, 并在原有数据处理的基础上进一步作了异常值识别和剔除, 最终选取的66个站点 (277站点年数据) 分布于热带、温带和寒带。FLUXNET-RE观测数据时间范围从1999-2005年不等, 1-3年共28个站点, 4-6年共25个站点, 7年以上共13个站点, 欧洲和亚洲通量站点数据累计较多。66个站点共包含混交林、草地、常绿阔叶林、常绿针叶林、落叶阔叶林和农田6种植被功能型, 详细站点信息参见附表1。

1.2 CLM_RE模拟数据

CMIP5是世界气候研究计划 (World Climate Research Programme, WCRP) 耦合模型工作组 (Working Group on Coupled Modelling, WGCM) 和国际地圈-生物圈计划 (International Geosphere Biosphere Programme, IGBP) 共同推出协调气候的模型试验计划^[30], 超过20个气候模式组的50多个模式对历史和未来全球气候进行了数值模拟试验。CESM1是模拟地球气候系统的耦合气候模式, 是CMIP5众多模式之一, 可模拟地球大气层、海洋、陆地、陆地冰和海冰等不同过程, 其中CLM是CESM1的陆面部分。CLM是NCAR (National Center of Atmospheric research) 发展推广的陆面过程模型, 它在综合BATS (Biosphere-Atmosphere Transfer Scheme, BATS)、IAP94 (Land surface model which was established at the Institute of Atmosphere Physics, Chinses Academy of Sciences in 1994, IAP94)、LSM (Land Surface Model, LSM) 等陆面模型优点的基础上, 改进了一些物理过程参数化方案, 并且加入水文、动态植被等过程^[19], 是目前世界上发展较为完善且具发展潜力的陆面过程模型之一。本文的RE模拟数据来源于CLM模型的历史模拟数据 (<https://esgf-node.lnl.gov/search/cmip5/>), 时间覆盖范围为1850-2005

年. 此外, 本文在原有下载数据的基础上进行了投影转换, 并利用66个FLUXNET站点的经纬度在 $0.9^\circ \times 1.25^\circ$ 的空间尺度上提取了对应的RE模拟数据且作了异常值筛选, 同时也按照IGBP分类对CLM-RE模拟数据进行了划分, 其数据年份选择和时间尺度划分处理方法与观测数据相同.

1.3 CLM-RE模拟结构

CLM模型模拟生态系统呼吸可分为自养呼吸 (Autotrophic respiration, RA) 和异养呼吸 (Heterotrophic respiration, RH), 其中自养呼吸包括用于新组织合成的生长呼吸 (Growth respiration, RG) 和已合成的活组织 (叶、细根、活粗根、活枝干) 在维持功能状态过程中的维持呼吸 (Maintenance respiration, RM), 而异养呼吸主要是土壤呼吸中的微生物呼吸. 自养呼吸是氮含量、基础维持呼吸速率和温度的函数, 异养呼吸是土壤碳含量、碳库周转速率、温度和湿度的函数^[19], 其表达式如下:

$$RG = 0.3 \times CF_{\text{alloc}} \quad (1)$$

$$RM = NS \times MR_{\text{base}} \times Q_{10RA}^{(T-T_{\text{ref}})/10} \quad (2)$$

$$RH = C \times K \times T_{\text{scalor}} \times W_{\text{scalor}} \quad (3)$$

$$T_{\text{scalor}} = Q_{10RH}^{(T-T_{\text{ref}})/10} \quad (4)$$

$$W_{\text{scalor}} = \sum_{j=1}^5 \begin{cases} 0 & \varphi_j < \varphi_{\min} \\ \frac{\log(\phi_{\min}/\phi_j)}{\log(\phi_{\min}/\phi_{\max})} r_j & \varphi_{\min} \leq \varphi_j \leq \varphi_{\max} \\ 1 & \varphi_j \geq \varphi_{\max} \end{cases} \quad (5)$$

$$RE = RG + RM + RH \quad (6)$$

式中, CF_{alloc} 是用于植被生长光合产物, NS 为植物体活组织的氮含量 ($\text{N}, \text{g m}^{-2}$), C 为土壤碳含量 ($\text{C}, \text{g m}^{-2}$), $MR_{\text{base}} = 2.525\text{e}^{-6}$ 为每单位氮的基础维持呼吸速率 ($\text{C/N}, \text{gg}^{-1} \text{s}^{-1}$), K 为土壤碳库周转速率 (d^{-1}), T_{scalor} 和 W_{scalor} 分别是温度和湿度对异养呼吸的影响. Q_{10RA} 和 Q_{10RH} 分别是自养呼吸和异养呼吸的温度敏感系数 ($Q_{10RA} = Q_{10RH} = 1.5$), T 为一定条件下的空气温度和土壤温度 ($^\circ\text{C}$), T_{ref} 和 T_{ref}^* 分别是自养呼吸和异养呼吸的参考温度 ($T_{\text{ref}} = 20^\circ\text{C}$, $T_{\text{ref}}^* = 25^\circ\text{C}$). CLM模型土壤呼吸模块为单层土壤有机质结构, 模型只考虑前五层土壤组分 (29 cm), r_j 为第 j 层土壤中根分布的比例, φ_j 、 $\varphi_{\min}$ 、 $\varphi_{\max}$ 分别为第 j 层土壤水势, 最低土壤水势和饱和土壤水势 (通过土壤质地确定).

1.4 统计方法

本研究从时空尺度对CLM-RE模拟能力进行了验证分析, 模拟结果度量指标主要包括皮尔逊相关系数 (R) 和均方根误差 (RMSE). 另外, 季节变化除了 R 和 RMSE, 还选取标准差 (SD) 和归一化后的中心均方根误差 (RMSD) 对模拟效果进行综合排名^[10]. 具体计算步骤如下: (1) 分别对66个站点/6个植被型4项度量指标由优及差进行排序 (RMSE、RMSD、SD升序; R 降序), 并对排名结果按顺序赋值; (2) 计算66个站点/6个植被型4项度量指标排序结果的平均值和标准差, 并对平均值从小到大排序, 排序越小代表其模拟效果越好.

$$R = \frac{\sum_{n=1}^N (m_n - \bar{m})(o_n - \bar{o})}{\sqrt{\sum_{n=1}^N (m_n - \bar{m})^2 \sum_{n=1}^N (o_n - \bar{o})^2}} \quad (7)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{n=1}^N (m_n - o_n)^2} \quad (8)$$

$$\text{SD} = \sqrt{\frac{1}{N} \sum_{n=1}^N (m_n - \bar{m})^2} \quad (9)$$

$$\text{RMSD} = \sqrt{\frac{1}{N} \sum_{n=1}^N [(m_n - \bar{m})(o_n - \bar{o})]^2} \quad (10)$$

式中, R 为相关系数, RMSE为均方根误差, SD为标准差, RMSD为中心均方根误差, m_n 为第 n 个模拟值, o_n 为第 n 个观测值, N 为总样本数.

2 结果分析

2.1 RE空间格局模拟效果

CLM捕捉RE空间格局模拟效果相对较好 ($R = 0.64$, $P < 0.001$) (图1a), 与FLUXNET观测的66个站点RE年总量 ($\text{C}, 1082.46 \text{ g m}^{-2} \text{ a}^{-1}$) 相比, CLM模拟RE的绝对误差为 $-38.43 \text{ g m}^{-2} \text{ a}^{-1}$, 相对误差为 -3.56% . 各植被型RE模拟效果有所差异 (图1a), 常绿阔叶林除AU-Tum站点模拟RE低估外, 其余站点模拟RE均高估, 使得常绿阔叶林整体RE高估量占比观测值 31.54% ; 农田、草地和落叶阔叶林低估站点较多, 其模拟RE相对误差为 -12.51% 至 -21.75% ; 常绿针叶林和混交林高估站点占各自总站点数约 40% , 其模拟RE相对误差分别是 11.64% 和 4.09% . 不同纬度带下RE模拟效果差异相对较大 (图1b), 纬度高于 50° 的17个站点其RE被低估, 平均低估量为 $374.97 \text{ g m}^{-2} \text{ a}^{-1}$, 占比观测值 -36.26% ; 低纬度地区RE被高估, 特别是常绿针叶林的MY-PSO、CN-Qin和常绿阔叶林的CN-Din较明显, 高估量大于 $1200 \text{ g m}^{-2} \text{ a}^{-1}$; 而中纬度地区RE存在不同程度的高估和低估, 模拟偏差为 $-955.80 - 358.29 \text{ g m}^{-2} \text{ a}^{-1}$.

2.2 RE年际变化模拟效果

CLM模拟RE年际变化相关性总体相对较高 (图2), R 值为 0.60 ($P < 0.01$). 落叶阔叶林、常绿针叶林和农田模拟效果相对较差, R 值均小于 0.3 . 混交林、草地和常绿阔叶林模拟效果相对较好, R 值分别是 0.62 ($P < 0.01$)、 0.47 ($P < 0.01$) 和 0.47 , 因此CLM-RE模拟值与观测值年际变化相关性总体较高.

除常绿阔叶林模拟RE年际变化整体高估以外, 其余5种植被型模拟RE年际变化均存在不同程度的低估, 使得CLM模拟RE年际变化总体低估, 其相对误差为 -10.60% (表1). 落叶阔叶林、混交林和农田模拟RE偏差相对较小 (RMSE介于 $234.60 - 350.82 \text{ g m}^{-2} \text{ a}^{-1}$), 而常绿阔叶林、常绿针叶林和草地模拟RE偏差相对较大 (RMSE介于 $405.09 - 1024.24 \text{ g m}^{-2} \text{ a}^{-1}$), 使得模型模拟RE偏差总体相对较大 (RMSE = $590.94 \text{ g m}^{-2} \text{ a}^{-1}$). 整体来看混交林相关性较高的相关性 & 较低的模拟偏差使得模型在年际变化捕捉过程中效果相比其他植被型较好.

2.3 RE季节变化模拟效果

除常绿阔叶林观测RE为“双峰”型变化之外, 其余植被型季节特征相似, 大都表现出“单峰”型变化 (图3). 另外, 除常绿阔叶林季节变化整体高估 (平均高估 $52.62 \text{ g m}^{-2} \text{ mon}^{-1}$, 相对误差为 37.95%) 之外, 其余植被型逐月均存在不同程度的高估/低估. 农田、常绿针叶林和草地冬季 (12-次年

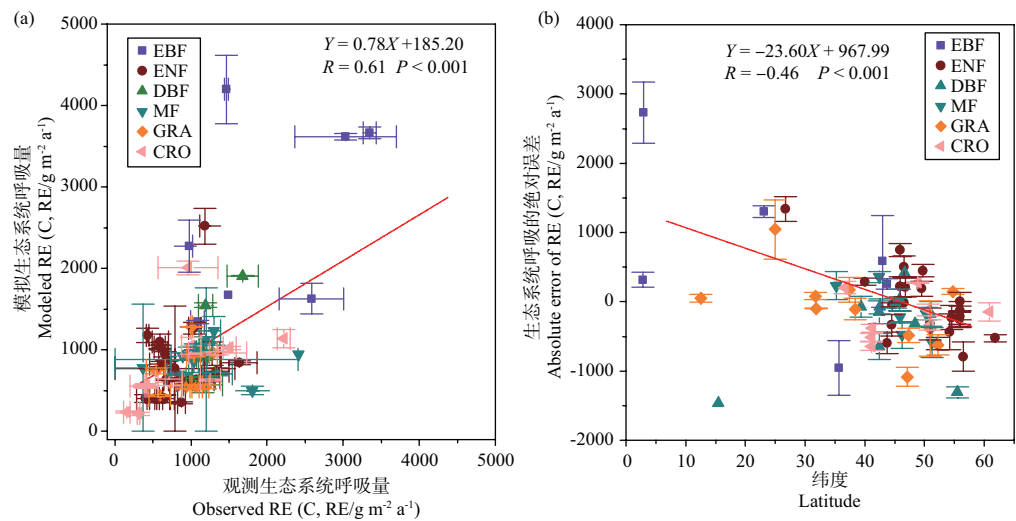


图1 各植被型RE模拟与观测空间格局对比 (a) 及RE绝对误差随纬度变化规律 (b). MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.

Fig. 1 Comparison of the spatial pattern of RE in different plant functional types between simulation and observation (a) and the variation of absolute error of RE with latitude (b). MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

2月) RE高估14.73 $\text{g m}^{-2} \text{ mon}^{-1}$, 占比观测值61.03%; 落叶阔叶林和混交林冬季模拟RE与观测值相对吻合, 相对误差仅为7.79%. 落叶阔叶林、常绿针叶林、草地、混交林和农田生长季(4-9月)低估相对较大, 平均低估47.20 $\text{g m}^{-2} \text{ mon}^{-1}$, 占比观测值35.48%; 尤其农田生态系统生长旺季低估较明显, 其低估量高达118.35 $\text{g m}^{-2} \text{ mon}^{-1}$, 占比观测值62.37%. 此外, CLM模型没有捕捉到常绿阔叶林RE的“双峰”型变化, 且RE模拟值相比观测值逐月存在较大正偏差 ($\text{RMSE} = 54.14 \text{ g m}^{-2} \text{ mon}^{-1}$). 各站点季节变化趋势图参见附图1.

CLM模拟RE季节变化相关性较高 ($R = 0.63, P < 0.001$), 且各植被型模拟相关性均在0.5以上 (图4). 混交林模拟结果相比观测值大多位于1:1线附近, 且相关系数可达0.80 ($P < 0.001$), 表明混交林RE模拟效果相比其余植被型较好. 为了进一步评估各植被型及各站点综合模拟效果, 本研究根据各度量指标 (R 、 RMSE 、 RMSD 、 SD) 对其模拟效果进行综合排名, 各植被型模拟效果由优及差依次为混交林、常绿针叶林、草地、农田、落叶阔叶林、常绿阔叶林, 详

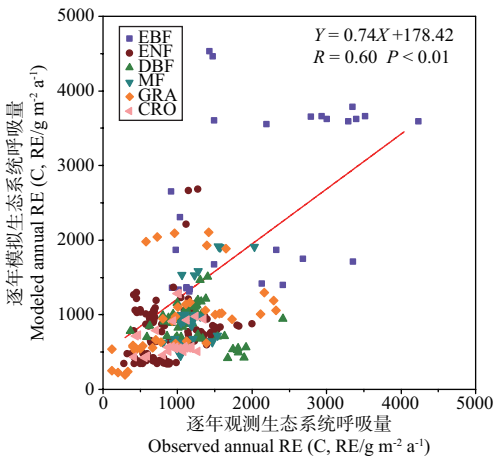


图2 各植被型RE的年内变化模拟与观测对比. MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.

Fig. 2 Comparison of the interannual variability of RE in different plant functional types between simulation and observation. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

表1 各植被型RE的年内变异模拟与观测评估

Table 1 Evaluation of the interannual variability of RE in different plant functional types between simulation and observation

植被功能型 Plant functional type	样本数 Sample	模拟值年均量 Annual average of simulated RE ($\text{RE/g m}^{-2} \text{ a}^{-1}$)	观测值年均量 Annual average of observed RE ($\text{RE/g m}^{-2} \text{ a}^{-1}$)	绝对误差 Absolute error ($\text{AE/g m}^{-2} \text{ a}^{-1}$)	相对误差 Relative error ($P/\%$)	相关系 数(R)	均方根误差 ($\text{RMSE/g m}^{-2} \text{ a}^{-1}$)
EBF	27	2593.87	2110.39	483.48	22.91	0.47	1024.24
ENF	102	775.00	896.69	-121.69	-13.57	0.20	405.09
DBF	32	887.16	1225.10	-337.93	-27.58	0.26	244.03
MF	50	1008.78	1216.79	-208.01	-17.10	0.62*	350.82
GRA	28	958.54	1019.53	-60.99	-5.98	0.47*	486.19
CRO	38	662.10	949.79	-287.70	-30.29	0.22	234.60
ALL	277	1013.31	1133.47	-120.16	-10.60	0.60*	590.94

*表示相关关系显著 ($P < 0.01$). MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.

* means significant correlation ($P < 0.01$). MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland.

细站点排名参见表2.

3 讨论

本研究利用FLUXNET站点RE观测数据评估的CLM时空尺度模拟RE大小以及变化捕捉情况与已有模型研究结果较为接近. 基于CASA模型估算的全球多数站点RE存在低估^[31], CLM模型利用站点观测数据作为模型驱动的模拟RE

(千烟洲和鼎湖山站点)存在高估^[32], 这与本文RE空间格局的整体低估和低纬站点RE高估相一致. 另外, 多数陆地生物圈模型低估了北美地区RE的年际变化^[10], 遥感模型和过程模型对不同植被型RE的年际和季节模拟效果均存在差异^[13-14], ORCHIDEE模型高估了常绿阔叶林RE的季节变异(以法国Pue站点为例)^[11]. CLM模型对长时间序列观测的哈佛森林站点(US-Ha1)的模拟效果与Urbanski等^[33]的研究结

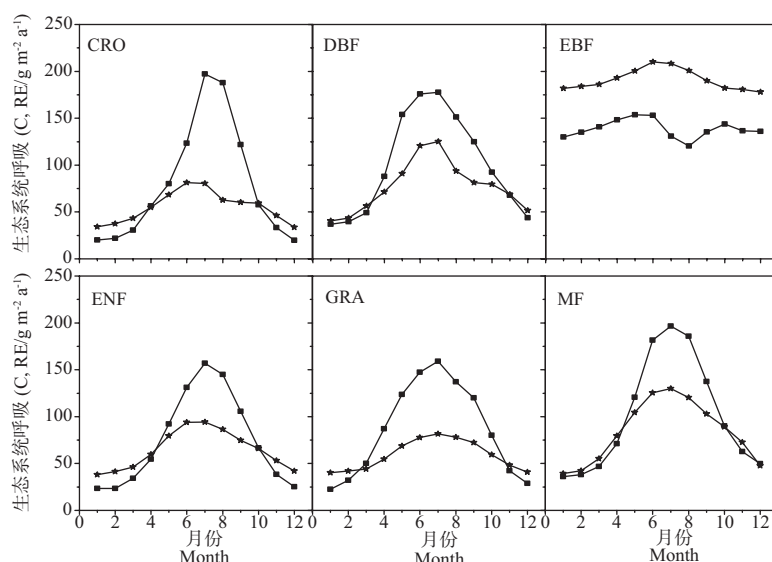


图3 各植被型RE模拟值(★)与观测值(■)的多年平均季节变化. MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.

Fig. 3 Mean annual seasonal variations of simulated (★) and observed (■) RE for all plant functional types. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

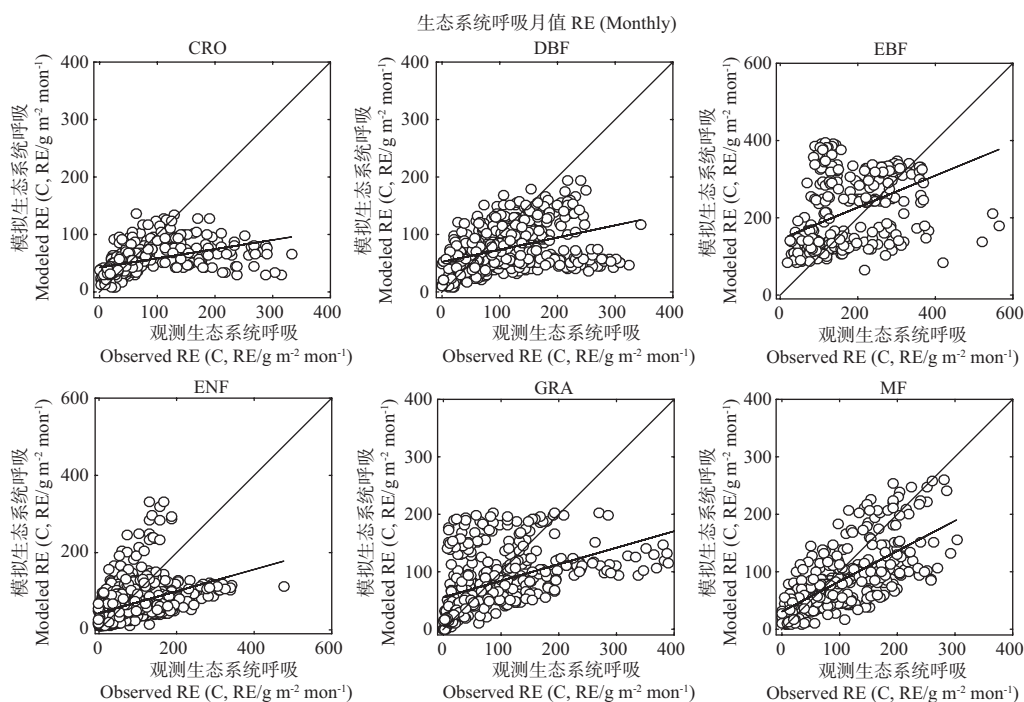


图4 各植被型月尺度RE模拟与观测值散点图. MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.

Fig. 4 The scatter plots of the monthly simulated and observed RE of different plant functional types. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland

果也基本一致。此外,本研究将CLM-RE全球模拟结果与区域性RE模拟结果进行比较,发现模型全球尺度RE模拟效果相比区域性RE模拟效果差异较大(表3)。其中北美和欧洲地区各植被型RE季节变化模拟相关性与全球模拟结果较为接近, R 值相差0.1左右,而东亚地区各植被型RE季节变化模拟相关性相比全球较高,草地 R 值相差0.48,这可能是模型驱动数据及空间分辨率不同所致。欧洲地区各植被型整体RE季节变化模拟偏差相比全球、北美和东亚地区较高, RMSE介于63.90-93.00 $\text{g m}^{-2} \text{mon}^{-1}$,这主要是由于模型没有考虑到欧洲地中海地区夏季土壤水限制等因素^[35]。混交林在北美、欧洲、东亚乃至全球尺度上其模拟效果相比其他植被型均较好。

FLUXNET-RE与CLM-RE的空间分辨率不匹配对模型模拟评估会造成一定的影响。CLM-RE模拟数据的空间尺度为 $0.9^\circ \times 1.25^\circ$,而涡度相关通量数据空间尺度一般在1-10 km,所以数据集空间尺度的差异会影响CLM-RE空间格局的模拟效果。同时,观测条件的限制导致NEE测定结果与其他方法的估计结果相差80%-200%^[35],且部分异常数据判断标准和缺失数据插补方法的选择会造成通量数据存在差异,因此通量数据本身也存在一定的不确定性,这种不确定性会影响CLM-RE的空间、年际和季节捕捉效果。

RE对温度的敏感性- Q_{10} 是CLM模拟生态系统呼吸的关键因子,一直以来它的大小是关注的热点^[36]。以长白山温带混交林为例的敏感性分析结果表明,对RE影响较大的生态系统呼吸参数为土壤呼吸敏感性参数 Q_{10} -RS和土壤碳库周转速率 K (附表2)。这两个参数变化10%将分别引起RS变化88%和63%,并分别使RE变化82%和60%。可见,土壤呼吸敏感性参数 Q_{10} -RS是影响生态系统呼吸的重要参数。CLM模拟全球尺度RE的 Q_{10} 仅区分自养呼吸($Q_{10} = 1.5$)和异养呼吸($Q_{10} = 1.5$),并无植被型和区域的划分。而Zhou等利用模型反演算法得出全球平均土壤呼吸 Q_{10} (Q_{10} -soil respiration, Q_{10} -RS)为1.72,且各植被型 Q_{10} -RS差异较大,同时全球平均 Q_{10} -RS相比区分植被型的 Q_{10} -RS,其模拟RE约低估25%^[31]。说明本研究较低的 Q_{10} -RS以及无植被型区分可能是模拟RE空间尺度整体低估的部分原因。Xu等研究表明模型高纬相比低纬较高的 Q_{10} -RS可降低高纬站点RS的模拟误差,进一步表明高纬站点的 Q_{10} -RS较小可能是导致其模拟RE低估的原因之一^[37]。另外,Curiel等研究发现生长季相比非生长季较高的 Q_{10} -RS可促进模型更好地捕捉季节变异,这也可能是本研究RE模拟值在生长旺季相比观测值低估74.16%的部分原因^[38]。Peng等研究发现土壤深度为0-10 cm时, Q_{10} -RS随土壤深度增加而增大,而CLM模拟全球RE未考虑多层土壤有机质结构,所以对RE模拟结果也会产生影响^[39]。

此外,包括CLM在内的多数模型模拟不同区域RE的 MR_{base} 为统一值,这对RE时空格局模拟效果也有一定影响^[40-41]。Yuan等研究表明利用站点 MR_{base} 相比全球统一值,其全球RE模拟与观测相关性从0.5提升至0.71,且美国东南部亚热带森林站点的 MR_{base} 相比较^[42]。这说明利用站点 MR_{base} 可提升RE的模拟精度,同时也可能是US-MMS站点RE模拟低

表2 各植被型及各站点RE模拟效果综合排名

Table 2 Comprehensive ranking of the simulated performance of RE for all plant functional types and different sites

植被功能型/站点 名称 PFT Site	综合排名 Rank	植被功能型/站点 名称 PFT Site	综合排名 Rank
MF	29.21 (13.77)	DE-Gri	32.00 (20.02)
CN-Cha	24.50 (23.46)	NL-Hor	31.25 (17.48)
BE-Vie	21.00 (7.25)	CN-HaM	29.75 (19.06)
US-PFa	26.50 (13.57)	AU-How	33.50 (15.82)
US-Syv	31.00 (12.75)	US-Wkg	35.25 (20.18)
JP-SMF	32.50 (16.16)	ZA-Kru	48.75 (12.80)
BE-Bra	39.75 (9.44)	US-Ton	40.75 (23.21)
ENF	31.16 (14.36)	CRO	32.44 (12.46)
FI-Hyy	24.00 (19.66)	FI-Jok	22.75 (7.53)
US-NR1	17.50 (21.20)	US-ARM	20.25 (17.84)
RU-fyo	28.75 (20.35)	DE-Kli	28.25 (11.71)
CA-Qfo	25.75 (21.18)	BE-Lon	27.50 (7.40)
NL-Loo	27.50 (18.12)	FR-Gri	31.25 (4.82)
IT-Lav	30.25 (20.22)	US-Ne1	44.00 (19.26)
CN-Qia	41.00 (21.12)	US-Ne3	42.50 (13.65)
IT-Ren	30.50 (13.01)	US-Ne2	43.00 (17.51)
CA-SF1	29.75 (5.58)	DBF	32.55 (18.43)
CA-NS3	25.75 (7.50)	ZM-Mon	16.50 (26.27)
CA-NS5	29.50 (3.20)	US-Wi3	35.25 (30.77)
CZ-BK1	25.25 (7.46)	US-Ha1	20.00 (19.22)
CA-SF2	37.50 (11.52)	US-WCr	25.00 (14.04)
CA-NS1	27.25 (9.86)	DK-Sor	37.00 (24.30)
US-Wi4	31.00 (16.93)	US-MMS	31.50 (11.15)
DE-Tha	36.75 (6.61)	DE-Hai	34.00 (10.42)
CA-NS4	28.00 (14.92)	IT-PT1	38.50 (6.18)
IT-La2	34.50 (4.72)	FR-Fon	39.50 (13.68)
CA-NS2	31.50 (14.04)	IT-Ro2	36.75 (22.52)
US-Me2	38.25 (22.11)	IT-Ro1	44.00 (24.16)
US-Wi0	39.25 (12.30)	EBF	50.54 (10.53)
IT-SRo	43.50 (12.22)	FR-Pue	30.00 (10.32)
US-Me1	33.75 (25.46)	CN-Din	58.50 (9.01)
GRA	31.61 (18.45)	AU-Tum	47.50 (18.57)
RU-Ha1	14.75 (18.05)	AU-Wac	42.00 (13.47)
CH-Oel	27.25 (16.78)	BR-Sa1	54.75 (12.58)
AT-Neu	33.75 (22.53)	BR-Sa3	56.00 (9.03)
US-ARM	20.75 (17.01)	MY-PSO	65.00 (0.71)

MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田; Rank代表各植被型及各站点模拟效果排名, 括号内表示排名结果的标准差。

PFT: Plant functional type; Sites: Site name. MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland. Rank represented the simulated performance of each plant function type and station, the standard deviation of the ranking results was in the parentheses

估的部分原因。

土壤碳库为RE提供了底物,所以碳库模拟的大小也是RE模拟是否准确的原因之一。然而,CLM整体低估全球土壤碳库^[43],并且北美、中美以及高纬度地区土壤碳库低估相比较大^[44-45],所以CLM土壤碳库的低估可能会导致全球RE低估以及高纬度RE低估相对较大。同时较高的土壤碳库模拟和 Q_{10} -RS也可降低RE模拟的整体低估^[32, 46]。另外,CLM低估了低纬度站点(中国长白山和千烟洲)的根际碳周转时间,进而引起RS和RE的高估^[45]。CLM模拟农田生态系统的误差相比其他植被型较大,其原因可能归咎于模型未考虑人类活动因素的影响^[47]。

为了进一步改进CLM模型生态系统呼吸的模拟精度,

表3 CLM-RE全球模拟与区域模拟结果比较
Table 3 Comparison of CLM-RE between global and regional simulation results

区域 Area	驱动数据 Driving data	空间分辨率 Spatial resolution	植被型 PFT	R	均方根误差 (RMSE/g m ⁻² mon ⁻¹)	参考文献 Reference
北美 North America	CRUNCEP	2.8° × 2.8°	ENF	0.64	25.30	[10]
	CRUNCEP		DBF	0.76	39.60	[10]
	CRUNCEP		CRO	0.55	58.90	[10]
	CRUNCEP		GRA	0.38	63.70	[10]
东亚 East Asia	CRU TS3.1	0.5° × 0.5°	ENF	0.93	12.60	[11]
	CRU TS3.1		DBF	0.94	10.20	[11]
	CRU TS3.1		CRO	0.9	21.90	[11]
	CRU TS3.1		GRA	0.98	8.40	[11]
	CRU TS3.1		EBF	0.45	27.90	[11]
	CRU TS3.1		MF	0.96	16.20	[11]
欧洲 Europe	ERA-I	0.8° × 0.8°	ENF	0.66	75.30	[12]
	ERA-I		DBF	0.46	93.00	[12]
	ERA-I		CRO	0.63	69.30	[12]
	ERA-I		GRA	0.6	73.50	[12]
	ERA-I		EBF	0.63	63.90	[12]
全球 Global scale	rlilpl	0.9° × 1.25°	ENF	0.73	53.53	本研究 This study
	rlilpl		DBF	0.52	47.88	本研究 This study
	rlilpl		CRO	0.75	58.96	本研究 This study
	rlilpl		GRA	0.53	57.16	本研究 This study
	rlilpl		EBF	0.63	99.70	本研究 This study
	rlilpl		MF	0.8	52.22	本研究 This study

MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田。
PFT: Plant functional type; MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland.

本研究收集了文献资料^[5, 48-80], 对不同植被型的 Q_{10} -RS进行了整合分析(图S2)。结果表明各植被型 Q_{10} -RS相比差异较大, Q_{10} -RS最大值与最小值相差0.91。其中, 落叶阔叶林 Q_{10} -RS相比其他植被型较大(2.54), 常绿阔叶林 Q_{10} -RS相比其他站点较小(1.75); 落叶林 Q_{10} -RS(2.54)明显大于常绿林 Q_{10} -RS(1.85)。总体来看, 森林生态系统的 Q_{10} -RS(2.14)最大, 草地生态系统(1.86)其次, 农田生态系统(1.63)最小。后期模型优化过程中应对不同植被型赋予不同的 Q_{10} -RS, 从而降低CLM-RE的模拟误差, 提升各植被型RE的空间、年际和季节变化的模拟精度。同时也应将更多可能因素综合考虑到CLM-RE模拟的误差诊断中, 进而提高其全球时空格局的模拟精度。

4 结论

本研究利用FLUXNET-66个站点RE观测数据对CLM-RE模拟数据在时空尺度上进行验证分析。总体而言, CLM-RE的时空尺度模拟结果与已有研究较为接近。然而, 与FLUXNET-RE 站点观测数据相比, (1) CLM-RE在空间尺度上低估站点相对较多(占比总站点数60.61%), 且模型高估了低纬度站点RE, 低估了高纬度站点RE; (2) CLM模型基本捕捉了RE的年际和季节变化, 相关系数分别为0.60 ($P < 0.001$) 和0.63 ($P < 0.001$), 但年际和季节变化模拟均存在低估现象(相对误差分别为-17.84%、-10.60%)。在RE季节变化模拟过程中, 模型除常绿阔叶林整体高估以外, 其他植被型均在生长季低估, 相比观测值平均低估35.48%; (3) CLM对不同植被型模拟效果不同, 由优及差依次为混交林、常绿针叶

林、草地、农田、落叶阔叶林、常绿阔叶林。

参考文献 [References]

1 Li W, Ciais P, Wang YL, Yin Y, Peng SS, Zhu ZC, Bastos A, Yue C, Ballantyne AP, Broquet G, Canadell JG, Cescatti A, Chen C, Cooper L, Friedlingstein P, Le Quere C, Myneni RB, Piao SL. Recent changes in global photosynthesis and terrestrial ecosystem respiration constrained from multiple observations [J]. *Geophys Res Lett*, 2018, **45** (2): 1-11

2 Jagermeyr J, Gerten D, Lucht W, Hostert P, Migliavacca M, Nemani R. A high-resolution approach to estimating ecosystem respiration at continental scales using operational satellite data [J]. *Glob Change Biol*, 2014, **20** (4): 1191-1210

3 Ballantyne A, Smith W, Anderegg W, Kauppi P, Sarmiento J, Tans P, Shevliakova E, Pan YD, Poulter B, Anav A, Friedlingstein P, Houghton R, Running S. Accelerating net terrestrial carbon uptake during the warming hiatus due to reduced respiration [J]. *Nat Climate Change*, 2017, **7** (2): 148-155

4 Clark DA, Asao S, Fisher R, Reed S, Reich PB, Ryan MG, Wood TE, Yang XJ. Reviews and syntheses: field data to benchmark the carbon cycle models for tropical forests [J]. *Biogeosciences*, 2017, **14** (20): 1-44

5 于贵瑞, 温学发, 李庆康, 张雷明, 任传友, 刘允芬, 关德新. 中国亚热带和温带典型森林生态系统呼吸的季节模式及环境响应特征[J]. 中国科学(D辑:地球科学), 2004, **34** (S2): 84-94 [Yu GR, Wen XF, Li QK, Zhang LM, Ren CY, Liu YF, Guan JX. Seasonal patterns and environmental response characteristics of typical forest ecosystems in subtropical and temperate regions of China. *Sci China Ser D-Earth Sci*, 2004, **34** (S2): 84-94]

- 6 葛蓉, 何洪林, 任小丽, 张黎, 冯艾琳, 王辉民, 张军辉. 基于模型数据融合的中国温带和亚热带典型森林生态系统碳通量模拟[J]. 生态学报, 2017, **37** (5): 1409-1420 [Ge R, He HL, Ren XL, Zhang L, Feng AL, Wang HM, Zhang JH. Carbon flux simulation of typical temperate and subtropical forest ecosystems in China based on model-data fusion approach. *Acta Ecol Sin*, 2017, **37** (5): 1409-1420]
- 7 Ge R, He HL, Ren XL, Zhang L, Li P, Zeng N, Yu GR, Zhang LY, Yu SY, Zhang FW, Li HQ, Shi PL, Chen SP, Wang YF, Xin, XP, Ma YM, Ma MG, Zhang Y, Du MY. A satellite-based model for simulating ecosystem respiration in the Tibetan and Inner Mongolian Grasslands [J]. *Remote Sens*, 2018, **10** (1): 149-169
- 8 张继平, 刘春兰, 郝海广, 孙莉, 乔青, 王辉, 宁杨翠. 基于MODIS GPP/NPP数据的三江源地区草地生态系统碳储量及碳汇量时空变化研究[J]. 生态环境学报, 2015, **24** (1): 8-13 [Zhang JP, Liu CL, He GH, Sun L, Qiao Q, Wang H, Ning YC. Spatial-temporal change of carbon storage and carbon sink of grassland ecosystem in the three-river headwaters region based on MODIS GPP/NPP Data [J]. *Ecol Environ Sin*, 2015, **24** (1): 8-13]
- 9 陈国鹏, 赵文智, 吉喜斌. 河西走廊绿洲玉米农田生态系统呼吸特征及温度响应[J]. 自然资源学报, 2015, **30** (10): 1617-1627 [Chen GP, Zhao WZ, Ji XB. Ecosystem respiration of maize agroecosystem and its response to temperature in the Hexi Corridor China [J]. *J Nat Resour*, 2015, **30** (10): 1617-1627]
- 10 Raczka BM, Davis KJ, Huntzinger D, Neilson RP, Poulter B, Richardson AD, Xiao JF, Baker I, Ciais P, Keenan TF, Law B, Post WM, Ricciuto D, Schaefer K, Tian HQ, Tomelleri E, Verbeeck H, Viovy N. Evaluation of continental carbon cycle simulations with North American flux tower observations [J]. *Ecol Monogr*, 2013, **83** (4): 531-556
- 11 Balzarolo M, Boussetta S, Balsamo G, Beljaars A, Maignan F, Calvet JC, Lafont S, Barbu A, Poulter B, Chevallier F, Szczypta C, Papale D. Evaluating the potential of large scale simulations to predict carbon fluxes of terrestrial ecosystems over a European Eddy Covariance network [J]. *Biogeosciences*, 2014, **11** (10): 11857-11897
- 12 Ichii K, Kondo M, Lee YH, Wang SQ, Kim J, Ueyama M, Lim HJ, Shi H, Suzuki T, Ito A, Kwon H, Ju WM, Huang M, Sasai T, Asanuma J, Han SJ, Hirano T, Hirata R, Kato T, Li SG, Li YN, Maeda T, Miyata A, Matsuura Y, Murayama S, Nakai Y, Ohta T, Saitoh TM, Saigusa N, Takagi K, Tang YH, Wang HM, Yu GR, Zhang YP, Zhao FH. Site-level model data synthesis of terrestrial carbon fluxes in the Carbon East Asia eddy-covariance observation network: toward future modeling efforts [J]. *J For Res*, 2013, **18** (1): 13-20
- 13 Ai JL, Jia GS, Epstein HE, Wang HS, Zhang AZ, Hu YH. MODIS - based estimates of global terrestrial ecosystem respiration [J]. *J Geophys Res Biogeosci*, 2018, **123** (3): 326-352
- 14 Site S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, Venevsky S. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model [J]. *Glob Change Biol*, 2010, **9** (2): 161-185
- 15 Marconi S, Chiti T, Nole A, Valentini R, Collalti A. The role of respiration in estimation of net carbon cycle: coupling soil carbon dynamics and canopy turnover in a novel version of 3D-CMCC forest ecosystem model [J]. *Forests*, 2017, **8** (220): 1-25
- 16 Zeng N, Mariotti A, Wetzel P. Terrestrial mechanisms of interannual CO₂ variability [J]. *Glob Biogeochem Cycle*, 2005, **19** (1): 1-15
- 17 Wu CY, Gaumont-Guay D, Black TA, Jassal RS, Xu SG, Chen JM, Gonsamo A. Soil respiration mapped by exclusively use of MODIS data for forest landscapes of Saskatchewan, Canada [J]. *ISPRS-J Photogramm Remote Sens*, 2014, **94** (8): 80-90
- 18 Krinner G, Viovy N, Noblet-Ducoudré N D, Ogée J. A dynamic global vegetation model for studies of the coupled atmosphere - biosphere system [J]. *Glob Biogeochem Cycle*, 2005, **19** (1): 1-33
- 19 Oleson KW, Lawrence DM, Bonan GB, Drewniak B, Huang M, Koven CD, Levis S, Li F, Riley WJ, Subin ZM, Swenson SC, Thornton PE, Bozbiyik A, Fisher R, Kluzek E, Lamarque JF, Lawrence PJ, Leung LR, Lipscomb W, Muszala S, Ricciuto DM, Sacks W, Sun Y, Tang J, Yang ZL. Technical Description of Version 4.5 of the Community Land Model (CLM) [M]. Boulder: National Center for Atmospheric Research, 2013
- 20 Bonan GB, Lawrence PJ, Oleson K, Swenson SC. Improving canopy processes in the Community Land Model version 4 (CLM) using global flux fields empirically inferred from FLUXNET data [J]. *J Geophys Res Biogeosci*, 2011, **116** (G2): 96-101
- 21 Mao JF, Fu WT, Shi XY, Ricciuto DM, Fisher JB, Dickinson RE, Wei YX, Shem W, Piao SL, Wang KC, Schwalm, CR, Tian HQ, Mu MQ, Arain A, Ciais P, Cook R, Dai YJ, Hayes D, Hoffman FM, Huang MY, Huang S, Huntzinger DN, Ito A, Jain A, King AW, Lei HM, Lu CQ, Michalak AM, Parazoo N, Peng CH, Peng SS, Poulter B, Schaefer K, Afarov E, Thornton PE, Wang WL, Zeng N, Zeng ZZ, Zhao F, Zhu QA, Zhu ZC. Disentangling climatic and anthropogenic controls on global terrestrial evapotranspiration trends [J]. *Environ Res Lett*, 2015, **10** (9): 1-13
- 22 Shi XY, Mao JF, Thornton PE, Huang MY. Spatiotemporal patterns of evapotranspiration in response to multiple environmental factors simulated by the Community Land Model [J]. *Environ Res Lett*, 2013, **8** (2): 199-201
- 23 王媛媛, 谢正辉, 贾炳浩, 于燕. 基于陆面过程模式CLM4的中国区域植被总初级生产力模拟与评估[J]. 气候与环境研究, 2015, **20** (1): 97-110 [Wang YY, Xie ZH, Jia BH, Yu Y. Simulation and evaluation of gross primary productivity in China by using land surface model CLM4 [J]. *Climat Environ Res*, 2015, **20** (1): 97-110]
- 24 Kim Y, Wang G.L. Modeling seasonal vegetation variation and its validation against moderate resolution imaging spectroradiometer (MODIS) observations over North America [J]. *J Geophys Res*, 2005, **110**: 1-13
- 25 Lawrence PJ, Chase TN. Representing a new MODIS consistent land surface in the Community Land Model (CLM 3.0) [J]. *J Geophys Res Biogeosci*, 2015, **112** (G1): 252-257
- 26 于贵瑞, 孙晓敏. 陆地生态系统通量观测的原理与方法[M]. 北京: 高等教育出版社, 2006 [Yu GR, Sun XM. Principles of Flux Measurement in Terrestrial Ecosystems [M]. Beijing: Higher Education Press, 2006]
- 27 Baldocchi D, Chu HS, Reichstein M. Inter-annual variability of net and gross ecosystem carbon fluxes: a review [J]. *Agric For Meteorol*, 2018,

- 249: 520-533
- 28 Falge E, Baldocchi D, Olson R, Anthoni P, Aubinet M, Bernhofer C, Burba G, Ceulemans R, Clement R, Dolman H, Granier A, Gross P, Grunwald T, Hollinger D, Jensen NO, Katul G, Keronen P, Kowalski A, Lai CT, Law BE, Meyers T, Moncrieff H, Moors E, Munger JW, Pilegaard K, Rannik U, Rebmann C, Suyker A, Tenhunen J, Tu K, Verma S, Vesala T, Wilson K, Wofsy S. Gap filling strategies for defensible annual sums of net ecosystem exchange [J]. *Agric For Meteorol*, 2001, **107** (1): 43-69
 - 29 Reichstein M, Falge E, Baldocchi D, Papale D, Aubinet M, Berbigier P, Bernhofer C, Buchmann N, Gilmanov T, Granier A, Grunwald T, Havrankova K, Ilvesniemi H, Janous D, Knohl A, Laurila T, Lohila A, Loustau D, Matteucci G, Meyers T, Miglietta F, Ourcival JM, Pumpanen J, Rambal S, Rotenberg E, Sanz M, Tenhunen J, Seufert G, Vaccari F, Vesala T, Yakir D, Valentini R. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm [J]. *Glob Change Biol*, 2005, **11** (9): 1424-1439
 - 30 Taylor KE, Stouffer RJ, Meehl GA. An overview of CMIP5 and the experiment design [J]. *Bull Amer Meteorol Soc*, 2012, **93** (4): 485-498
 - 31 Zhou T, Shi PJ, Hui DF, Luo YQ. Global pattern of temperature sensitivity of soil heterotrophic respiration (Q10) and its implications for carbon-climate feedback [J]. *J Geophys Res Biogeosci*, 2009, **114** (G2): 271-274
 - 32 Zhang L, Mao JF, Shi XY, Ricciuto D, He HL, Thornton P, Yu GR, Li P, Liu M, Ren XL, Han SJ, Li YN, Yan JH, Hao YB, Wang HM. Evaluation of the Community Land Model simulated carbon and water fluxes against observations over ChinaFLUX sites [J]. *Agric For Meteorol*, 2016, **226**: 174-185
 - 33 Urbanski S, Barford C, Wofsy S, Kucharik C, Pyle E, Budney J, McKain K, Fitzjarrald D, Czirkowsky M, Munger JW. Factors controlling CO2 exchange on timescales from hourly to decadal at Harvard Forest [J]. *J Geophys Res Biogeosci*, 2015, **112** (G2): 225-236
 - 34 Migliavacca M, Reichstein M, Richardson AD, Colombo R, Sutton MA, Lasslop G, Tomelleri E, Wohlfahrt G, Carvalhais N, Cescatti A, Mahecha MD, Montagnani L, Papale D, Zaehle S, Arain A, Arneth A, Black TA, Carrara A, Dore S, Gianelle D, Helfter C, Hollinger D, Kutsch WL, Lafleur PM, Nouvellon Y, Rebmann C, Da Rocha HR, Rodeghiero M, Rouspard O, Sebastia MT, Seufert G, Soussana JF, Van Der Molen MK. Semiempirical modeling of abiotic and biotic factors controlling ecosystem respiration across eddy covariance sites [J]. *Glob Change Biol*, 2011, **17**: 390-409
 - 35 Wilson K, Goldstein A, Falge E, Aubinet M, Baldocchi D, Berbigier P, Bernhofer C, Ceulemans R, Dolman H, Field C, Grelle A, Ibrom A, Law BE, Kowalski A, Meyers T, Moncrieff J, Monson R, Oechel W, Tenhunen J, Valentini R, Verma S. Energy balance closure at FLUXNET sites [J]. *Agric For Meteorol*, 2002, **113** (1): 223-243
 - 36 Davidson EA, Janssens IA. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change [J]. *Nature*, 2006, **440** (7081): 165-173
 - 37 Yang KJ, Yang YL, Xu ZF, Wu QG. Temperature sensitivity of soil respiration in China's forest ecosystems: patterns and controls [J]. *Appl Soil Ecol*, 2015, **93**: 105-110
 - 38 Yuste JC, Janssens IA, Carrara A, Ceulemans R. Annual Q10 of soil respiration reflects plant phenological patterns as well as temperature sensitivity [J]. *Global Change Biol*, 2004, **10** (2): 161-169
 - 39 Peng SS, Piao SL, Wang T, Sun JY, Shen ZH. Temperature sensitivity of soil respiration in different ecosystems in China [J]. *Soil Biol Biochem*, 2009, **41** (5): 1008-101
 - 40 Reichstein M, Rey A, Freibauer A, Tenhunen J, Valentini R, Banza J, Casals P, Cheng YF, Grunzweig JM, Irvine J, Joffre R, Law BE, Loustau D, Miglietta F, Oechel W, Ourcival JM, Pereira JS, Peressotti A, Ponti F, Qi Y, Rambal S, Rayment M, Romanya J, Rossi F, Tedeschi V, Tirone G, Xu M, Yakir D. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices [J]. *Glob Biogeochem Cycle*, 2003, **17** (4): 1-15
 - 41 Reichstein M, Ciais P, Papale D, Valentini R, Running S, Viovy N, Cramer W, Granier A, Ogee J, Allard V. Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis [J]. *Global Change Biol*, 2010, **13** (3): 634-651
 - 42 Yuan WP, Luo YQ, Li XL, Liu SG, Yu GR, Zhou T, Bahn M, Black A, Desai AR, Cescatti A, Marcolla B, Jacobs C, Chen JQ, Aurela M, Bernhofer C, Gielen B, Bohrer G, Cook DR, Dragoni D, Dunn AL, Gianelle D, Grunwald T, Ibrom A, Leclerc MY, Lindroth A, Liu HP, Marchesini LB, Montagnani L, Pita G, Rodeghiero M, Rodrigues A, Starr G, Stoy PC. Redefinition and global estimation of basal ecosystem respiration rate [J]. *Glob Biogeochem Cycle*, 2011, **25**: 1-14
 - 43 Wieder WR, Bonan GB, Allison SD. Global soil carbon projections are improved by modelling microbial processes [J]. *Nat Clim Chang*, 2013, **3** (10): 909-912
 - 44 Bonan GB, Hartman MD, Parton WJ, Wieder WR. Evaluating litter decomposition in earth system models with long-term litterbag experiments: an example using the Community Land Model version 4 (CLM) [J]. *Global Change Biol*, 2013, **19** (3): 957-974
 - 45 Todd-Brown KEO, Randerson JT, Post WM, Hoffman FM, Tarnocai C, Schuur EAG, Allison SD. Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations [J]. *Biogeosciences*, 2013, **10** (3): 1717-1736
 - 46 Karhu K, Auffret MD, Dungait JAJ, Hopkins DW, Prosser JI, Singh BK, Subke JA, Wookey PA, Agren GI, Sebastia MT, Gouriveau F, Bergkvist G, Meir P, Nottingham AT, Salinas N, Hartley IP. Temperature sensitivity of soil respiration rates enhanced by microbial community response [J]. *Nature*, 2014, **513** (7516): 81-95
 - 47 Eugster W, Moffat AM, Ceschia E, Aubinet M, Ammann C, Osborne B, Davis PA, Smith P, Jacobs C, Moors E, Le Dantec, Beziat P, Saunders M, Jans W, Grunwald T, Rebmann C, Kutsch WL, Czerny R, Janous D, Moureaux C, Dufranne D, Carrara A, Magliulo V, Di Tommasi P, Olesen JE, Schelde K, Olioso A, Bernhofer C, Cellier P, Larmanou E, Loubet B, Wattenbach M, Marloie O, Sanz MJ, Sogaard H, Buchmann N. Management effects on European cropland respiration [J]. *Agric Ecosyst Environ*, 2010, **139** (3): 346-362
 - 48 郑泽梅. 中国陆地生态系统土壤呼吸时空变异的影响因素及其定

- 量评价[D]. 北京: 中国科学院大学, 2009 [Zheng ZM. The controlling factors and evaluation of the spatio-temporal of variability of soil respiration of terrestrial [D]. Beijing: University of Chinese Academy of Sciences, 2009]
- 49 王森, 姬兰柱, 李秋荣, 刘延秋. 土壤温度和水分对长白山不同森林类型土壤呼吸的影响[J]. 应用生态学报, 2003, **14** (8):1234-1238 [Wang M, Ji LZ, Li QR, Liu YQ. Effects of soil temperature and moisture on soil respiration in different forest types in Changbai Mountain [J]. *Chin J Appl Ecol*, 2003, **14** (8): 1234-1238]
- 50 周存宇, 周国逸, 张德强, 王迎红, 刘世忠. 鼎湖山森林地表CO₂通量及其影响因子的研究[J]. 中国科学: 地球科学, 2004, **34** (S2): 175-182 [Zhou CY, Zhou GY, Zhang DQ, Wang YH, Liu SZ. Study on surface CO₂ flux and its influencing factors in Dinghu mountain forest [J]. *Sci China Ser D-Earth Sci*, 2004, **34** (s2): 175-182]
- 51 邓琦, 刘世忠, 刘菊秀, 孟泽, 张德强. 南亚热带森林凋落物对土壤呼吸的贡献及其影响因素[J]. 地球科学进展, 2007, **22** (9): 976-986 [Deng Q, Liu SZ, Liu JX, Meng Z, Zhang DQ. Contribution of litter fall to soil respiration and its affecting factors in southern subtropical Forest of china [J]. *Prog Geogr*, 2007, **22** (9): 976-986]
- 52 Yan JH, Wang YP, Zhou GY, Zhang DQ. Estimates of soil respiration and net primary production of three forests at different succession stages in South China [J]. *Glob Change Biol*, 2006, **12** (5): 810-821
- 53 陈全胜, 李凌浩, 韩兴国, 阎志丹, 王艳芬, 张焱, 熊小刚, 陈世苹, 张丽霞, 高英志, 唐芳, 杨晶, 董云社. 典型温带草原群落土壤呼吸温度敏感性与土壤水分的关系[J]. 生态学报, 2003, **24** (4):831-836 [Chen QS, Li LH, Han XG, Yan ZD, Wang YF, Zhang Y, Xiong XG, Chen SP, Zhang LX, Gao YZ, Tang F, Yang J, Dong YS. Temperature sensitivity of soil respiration in relation to soil moisture in communities of typical temperate steppe in Inner Mongolia. *Ecol Environ*, 2003, **24** (4): 831-836]
- 54 刘立新, 董云社, 齐玉春, 周凌晔. 内蒙古锡林河流域土壤呼吸的温度敏感性[J]. 中国环境科学, 2007, **27** (2): 226-230 [Liu LX, Dong YS, Qi YC, Zhou LX. Study on the temperature sensitivity of soil respiration in Xilin River of Inner Mongolia, China [J]. *China Environ Sci*, 2007, **27** (2): 226-230]
- 55 Chen SK, Edwards CA, Subler S. A microcosm approach for evaluating the effects of the fungicides benomyl and captan on soil ecological processes and plant growth [J]. *Appl Soil Ecol*, 2001, **18** (1): 1-82
- 56 Geng YB, Luo GQ. Influencing factors and partitioning of respiration in a leymus chinensis steppe in Xilin river basin, Inner Mongolia, China[J]. *J Geogr Sci*, 2011, **21** (1): 165-177
- 57 蒋高明, 黄银晓. 北京山区辽东栎林土壤释放CO₂的模拟实验研究[J]. 生态学报, 1995, **17** (5): 477-482 [Jiang GM, Huang YX. A study on the measurement of CO₂ emission from the soil of the simulated *Quercus liaotungensis* forest sampled from Beijing Mountain areas [J]. *Ecol Environ*, 1995, **17** (5): 477-482]
- 58 Jiang GM, Han XG, Zhou GS. Changes of atmosphere CO₂, photosynthesis of the grass layer and soil CO₂ evolution in a typical temperate deciduous forest stand on the mountainous areas of Beijing [J]. *Acta Bot Sin*, 1997, **39** (7): 653-660
- 59 张宪权. 东北地区落叶松人工林土壤呼吸的时空异质性研究[D]. 上海: 华东师范大学, 2005 [Zhang XQ, Spatial and temporal heterogeneity of soil respiration in *Larix olgensis* plantation in Northeast China [D]. Shanghai: East China Normal University, 2005]
- 60 Wang CK, Yang JY. Rhizosphere and heterotrophic components of soil respiration in six Chinese temperate forests [J]. *Glob Change Biol*, 2010, **13** (1): 123-131
- 61 贾淑霞. 落叶松和水曲柳人工林土壤呼吸比较研究[D]. 哈尔滨: 东北林业大学, 2006 [Jia SX. The study of soil respiration in Davurian larch and Manchurian ash plantations [D]. Harbin: Northeast Forestry University, 2006]
- 62 Kato T, Tang YH, Gu S, Hirota M, Cui XY, Du MY, Li YN, Zhao XQ, Oikawa T. Seasonal patterns of gross primary production and ecosystem respiration in an alpine meadow ecosystem on the Qinghai-Tibetan Plateau [J]. *J Geophys Res-Atmos*, 2004, **109** (12): 1-9
- 63 张东秋, 石培礼, 何永涛, 徐玲玲, 张宪洲, 钟志明. 西藏高原草原化小嵩草草甸生长季土壤微生物呼吸测定[J]. 自然资源学报, 2006, **21** (3): 458-464 [Zhang DQ, Shi PL, He YT, Xu LL, Zhang XZ, Zhong ZM. Quantification of soil heterotrophic respiration in the growth period of Alpine Steppe-Meadow on the Tibetan plateau [J]. *J Nat Resour*, 2006, **21** (3): 458-464]
- 64 Borken W, Xu YJ, Davidson EA, Beese A. Site and temporal variation of soil respiration in European beech, Norway spruce, and Scots pine forests [J]. *Glob Change Biol*, 2010, **8** (12): 1205-1216
- 65 Buchmann N. Biotic and abiotic factors controlling soil respiration rates in *Picea avies* stands [J]. *Soil Biol Biochem*, 2000, **32** (11): 1625-1635
- 66 Yuste JC, Janssens IA, Carrara A, Meiresonne, L, Ceulemans R. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest [J]. *Tree Physiol*, 2003, **23** (18): 1263-1270
- 67 Davidson EA, Belk E, Boone RD. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest [J]. *Glob Change Biol*, 2010, **4** (2): 217-227
- 68 Moren AS, Lindroth A. CO₂ exchange at the floor of a boreal forest [J]. *Agric For Meteorol*, 2000, **101** (1): 1-14
- 69 Meyer N, Welp G, Amelung W. The temperature sensitivity (Q_{10}) of soil respiration: controlling factors and spatial prediction at regional scale based on environmental soil classes [J]. *Glob Biogeochem Cycle*, 2018, **32**: 306-323
- 70 Gritsch C, Zimmermann M, Zechmeister-Boltenstern S. Interdependencies between temperature and moisture sensitivities of CO₂ emissions in European land ecosystems [J]. *Biogeosciences*, 2012, **12** (6): 4433-4464.
- 71 Andrews JA, Matamala R, Westover KM, Schlesinger WH. Temperature effects on the diversity of soil heterotrophs and the delta C-13 of soil-respired CO₂ [J]. *Soil Biol Biochem*, 2000, **32** (5): 699-706
- 72 Arevalo CBM, Chang SX, Bhatti JS, Sidders D. Mineralization potential and temperature sensitivity of soil organic carbon under different land uses in the parkland region of Alberta, Canada [J]. *Soil Sci Soc Am J*, 2012, **76** (1): 241-252
- 73 Bekku YS, Nakatsubo T, Kume A. Effect of warming on the temperature dependence of soil respiration rate in arctic, temperate and tropical soils [J]. *Appl Soil Ecol*, 2003, **22** (3): 1-210

- 74 Bradford MA, Watts BW, Davies CA. Thermal adaptation of heterotrophic soil respiration in laboratory microcosms [J]. *Glob Change Biol*, 2010, **16** (5): 1576-1588
- 75 Conant RT, Drijber RA, Haddix ML, Parton WJ, Paul EA, Plante AF, Six J, Steinweg JM. Sensitivity of organic matter decomposition to warming varies with its quality [J]. *Glob Change Biol*, 2010, **14** (4): 868-877
- 76 Cross A, Grace J. The effect of warming on the CO₂ emissions of fresh and old organic soil from under a Sitka spruce plantation [J]. *Geoderma*, 2010, **157** (3-4): 1-132
- 77 Wickland KP, Neff JC. Decomposition of soil organic matter from boreal black spruce forest: environmental and chemical controls [J]. *Biogeochemistry*, 2008, **87** (1): 29-47
- 78 Jenkins ME, Adams MA. Respiratory quotients and Q_{10} of soil respiration in sub-alpine Australia reflect influences of vegetation types[J]. *Soil Biol Biochem*, 2011, **43** (6): 1266-1274
- 79 Hamdi S, Chevallier T, Ben Aissa N, Ben Hammouda M, Gallali T, Chotte JL, Bernoux M. Short-term temperature dependence of heterotrophic soil respiration after one-month of pre-incubation at different temperatures [J]. *Soil Biol Biochem*, 2011, **43** (9): 1752-1758
- 80 Reichstein M, Subke JA, Angeli AC, Tenhunen JD. Does the temperature sensitivity of decomposition of soil organic matter depend upon water content, soil horizon, or incubation time? [J]. *Glob Change Biol*, 2010, **11** (10): 1754-1767

附表1 FLUXNET研究站点概况

Table S1 Information of FLUXNET sites

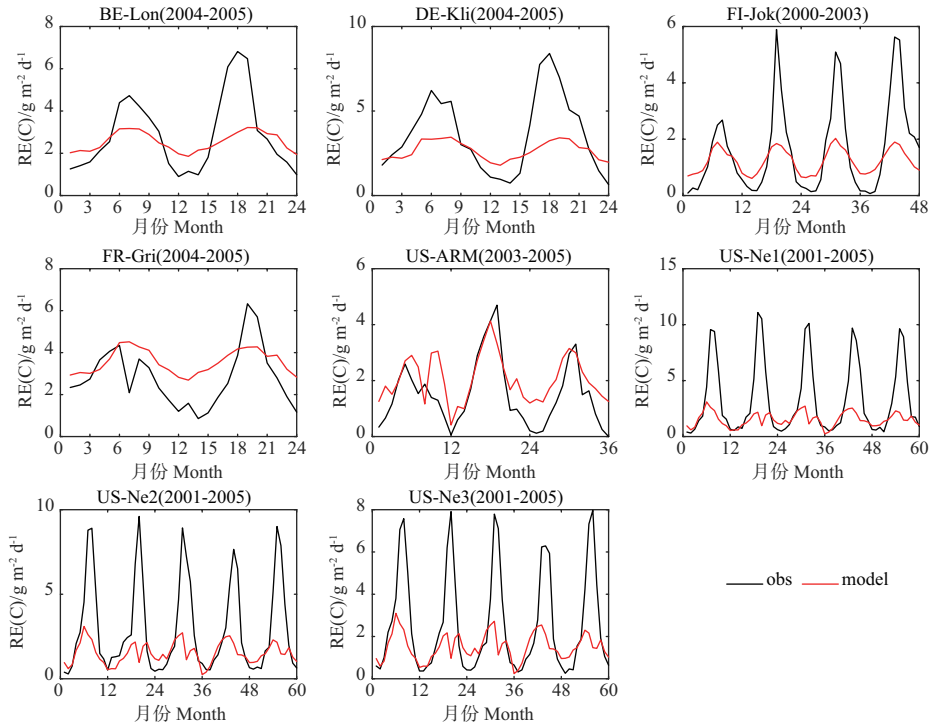
站点 Site	国家 Country	植被型 PFT	经度 Longitude ($\alpha/^{\circ}\text{E}$)	纬度 Latitude ($\beta/^{\circ}\text{N}$)	研究时段 Time	观测生态系统呼吸 Observed RE ($\text{RE/g m}^{-2} \text{a}^{-1}$)	年均温 MAT ($^{\circ}\text{C}$)	年降水量 MAP (h/mm)
BE-Bra	比利时	MF	4.5206	51.3092	1999-2005	1157.69	9.8	750
BE-Vie	比利时	MF	5.9981	50.3051	1999-2005	1154.71	7.8	1062
CN-Cha	中国	MF	128.096	42.4025	2003-2005	1192.38	3.62	713
JP-SMF	日本	MF	137.079	35.2617	2002-2005	1678.91	/	/
US-PFa	美国	MF	269.728	45.9459	1999-2005	1139.46	4.33	823
US-Syv	美国	MF	270.652	46.242	2001-2005	1127.81	3.81	826
AT-Neu	奥地利	GRA	11.3175	47.1167	2002-2005	2220.96	6.3	852
CH-Oel	瑞士	GRA	7.7319	47.2858	2002-2005	1507.95	9	1100
CN-HaM	中国	GRA	101.18	37.37	2002-2004	383.99	-1.7	580
DE-Gri	德国	GRA	13.5125	50.9495	2004-2005	1349.51	7.2	853
NL-Hor	荷兰	GRA	5.0713	52.2404	2004-2005	1256.04	10	800
RU-Ha1	俄罗斯	GRA	90.0022	54.7252	2002-2004	411.03	/	/
US-SRM	美国	GRA	249.134	31.8214	2004-2005	313.92	17.9	380
US-Ton	美国	GRA	239.034	38.4316	2001-2005	710.43	15.8	559
US-Wkg	美国	GRA	250.058	31.7365	2004-2005	157.57	15.64	407
AU-How	澳大利亚	GRA	131.152	-12.4943	2001-2005	1002.76	/	/
ZA-Kru	南非	GRA	31.4969	-25.0197	2000-2005	1120.23	21.9	547
CA-NS1	加拿大	ENF	261.516	55.8792	2002-2005	655.26	-2.89	500
CA-NS2	加拿大	ENF	261.475	55.9058	2001-2005	527.43	-2.88	500
CA-NS3	加拿大	ENF	261.618	55.9117	2001-2005	618.34	-2.87	502
CA-NS4	加拿大	ENF	261.618	55.9117	2002-2005	403.75	-2.87	502
CA-NS5	加拿大	ENF	261.515	55.8631	2001-2005	640.51	-2.86	500
CA-Qfo	加拿大	ENF	285.658	49.6925	2003-2005	589.22	-0.36	962
CA-SF1	加拿大	ENF	254.182	54.485	2003-2005	863.91	0.4	470
CA-SF2	加拿大	ENF	254.123	54.2539	2003-2005	1071.08	0.4	470
CN-Qia	中国	ENF	115.058	26.7414	2003-2005	1179.71	17.9	1485
CZ-BK1	捷克	ENF	18.5369	49.5021	2004-2005	684.46	6.7	1316
DE-Tha	德国	ENF	13.5669	50.9636	1999-2005	1275.82	7.7	820
FI-Hyy	芬兰	ENF	24.295	61.8475	1999-2005	878.34	3.8	709
IT-La2	意大利	ENF	11.2853	45.9542	2000-2005	1049.42	7.2	1150
IT-Lav	意大利	ENF	11.2813	45.9562	2003-2005	432.31	7.8	1281
IT-Ren	意大利	ENF	11.4337	46.5869	1999-2005	596.71	4.7	809
IT-SRo	意大利	ENF	10.2844	43.7279	1999-2005	1336.05	14.2	920
NL-Loo	荷兰	ENF	5.7436	52.1666	1999-2005	1262.99	9.8	786
RU-Fyo	俄罗斯	ENF	32.9221	56.4615	1999-2005	1634.50	3.9	711
US-Me1	美国	ENF	238.5	44.5794	2004-2005	676.58	7.88	705
US-Me2	美国	ENF	238.443	44.4523	2002-2005	968.27	6.28	523
US-NR1	美国	ENF	254.454	40.0329	1999-2005	657.39	1.5	800
US-Wi0	美国	ENF	268.919	46.6188	2002-2005	790.05	/	/
US-Wi4	美国	ENF	268.834	46.7393	2003-2005	620.05	/	/
CN-Din	中国	EBF	112.536	23.1733s	2003-2005	975.95	22.16	1473
FR-Pue	法国	EBF	3.5958	43.7414	2000-2005	1085.84	13.5	883
AU-Wac	澳大利亚	EBF	145.188	-37.4259	2005-2005	1493.21	/	/

续附表1 Table S1 (Continued)

站点 Site	国家 Country	植被型 PFT	经度 Longitude (α/°E)	纬度 Latitude (β/°N)	研究时段 Time	观测生态系统呼吸 Observed RE (RE/g m ⁻² a ⁻¹)	年均温 MAT (θ/°C)	年降水量 MAP (h/mm)
AU-Tum	澳大利亚	EBF	148.152	-35.6566	2001-2005	2584.52	/	/
BR-Sa1	巴西	EBF	305.041	-2.8567	2002-2005	3349.45	26.13	2075
BR-Sa3	巴西	EBF	305.029	-3.018	2000-2004	3032.90	26.12	2044
MY-PSO	马来西亚	EBF	102.306	2.973	2003-2005	1465.02	/	/
DE-Hai	德国	DBF	10.453	51.0792	2000-2005	1037.61	8.3	720
DK-Sor	丹麦	DBF	11.6446	55.4859	1999-2005	1811.38	8.2	660
FR-Fon	法国	DBF	2.7801	48.4764	2005-2005	1202.43	10.2	720
IT-PT1	意大利	DBF	9.061	45.2009	2002-2004	1057.37	12.7	984
IT-Ro1	意大利	DBF	11.93	42.4081	2000-2005	1348.95	15.2	876
IT-Ro2	意大利	DBF	11.9209	42.3903	2002-2005	851.12	15.2	876
US-Ha1	美国	DBF	287.829	42.5378	1999-2005	1189.99	6.6	1071
US-MMS	美国	DBF	273.587	39.3232	1999-2005	1305.32	10.9	1032
US-WCr	美国	DBF	269.92	45.8059	1999-2005	889.29	4.02	787
US-Wi3	美国	DBF	268.901	46.6347	2004-2004	368.64	/	/
ZM-Mon	赞比亚	DBF	23.2528	-15.4378	2000-2000	2416.06	25	945
BE-Lon	比利时	CRO	4.7461	50.5516	2004-2005	1034.28	10	800
DE-Kli	德国	CRO	13.5225	50.8929	2004-2005	1296.21	9	750
FI-Jok	芬兰	CRO	23.5135	60.8986	2000-2000	591.61	4.6	627
FR-Gri	法国	CRO	1.9519	48.8442	2004-2005	1007.46	12	650
US-ARM	美国	CRO	262.511	36.6058	2003-2005	538.30	14.76	843
US-Ne1	美国	CRO	263.523	41.1651	2001-2005	1192.94	10.07	790
US-Ne2	美国	CRO	263.53	41.1649	2001-2005	1062.50	10.08	789
US-Ne3	美国	CRO	263.56	41.1797	2001-2005	931.95	10.11	784

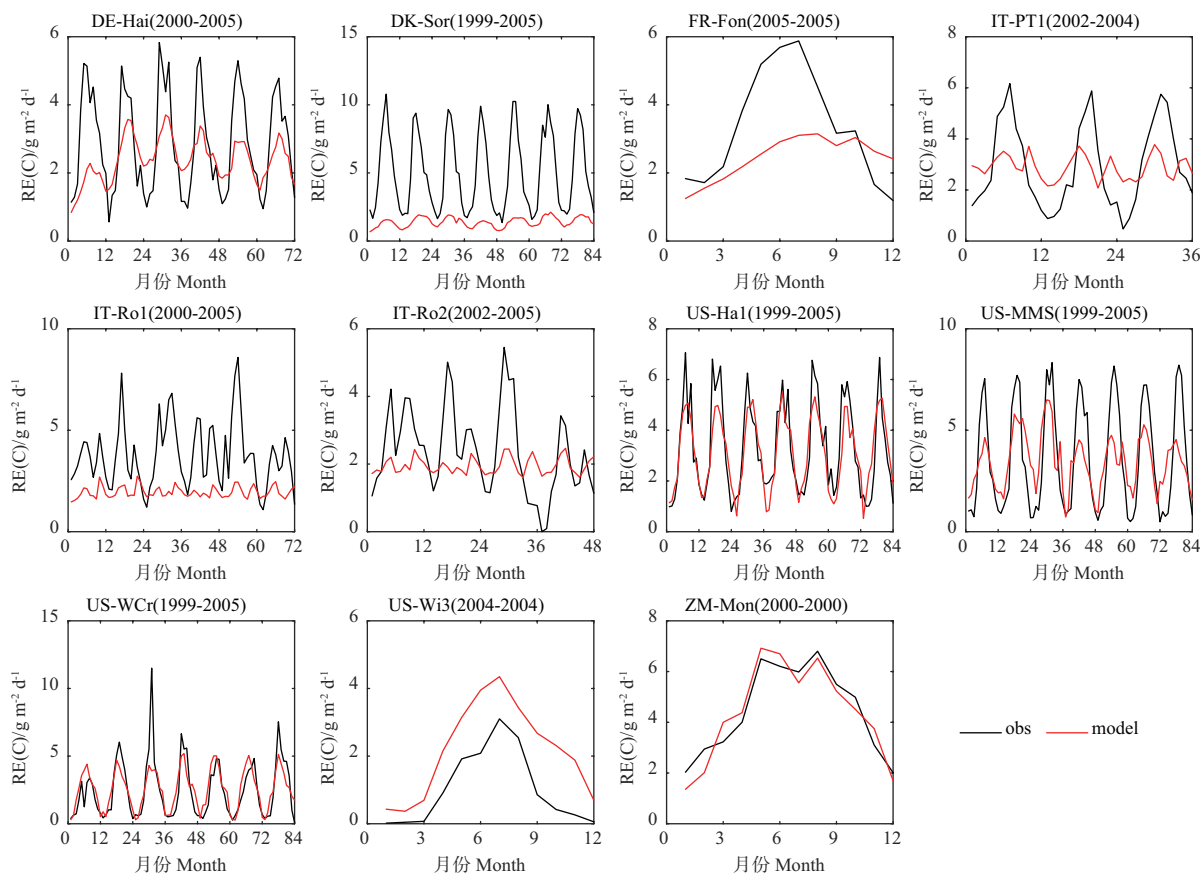
PFT: 植被功能型; MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田; Observed RE: 观测生态系统呼吸; MAT: 年均温; MAP: 年降水量; “/”: 无数据。
PFT: Plant functional type; MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland; Observed RE: Observed ecosystem respiration; MAT: Mean annual temperature; MAP: Mean annual precipitation; “/”: No data

农田 Cropland (CRO)

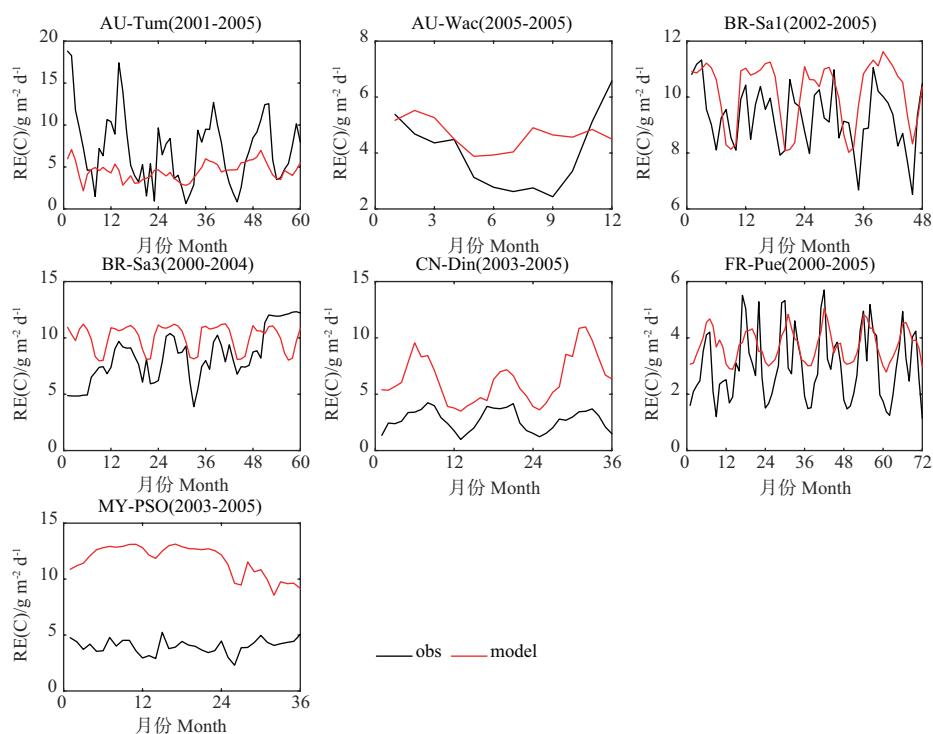


附图1 各植被型RE季节变异模拟效果。
Fig. S1 The seasonal simulation performance of RE for all plant functional types.

落叶阔叶林 Deciduous broadleaf forest (DBF)

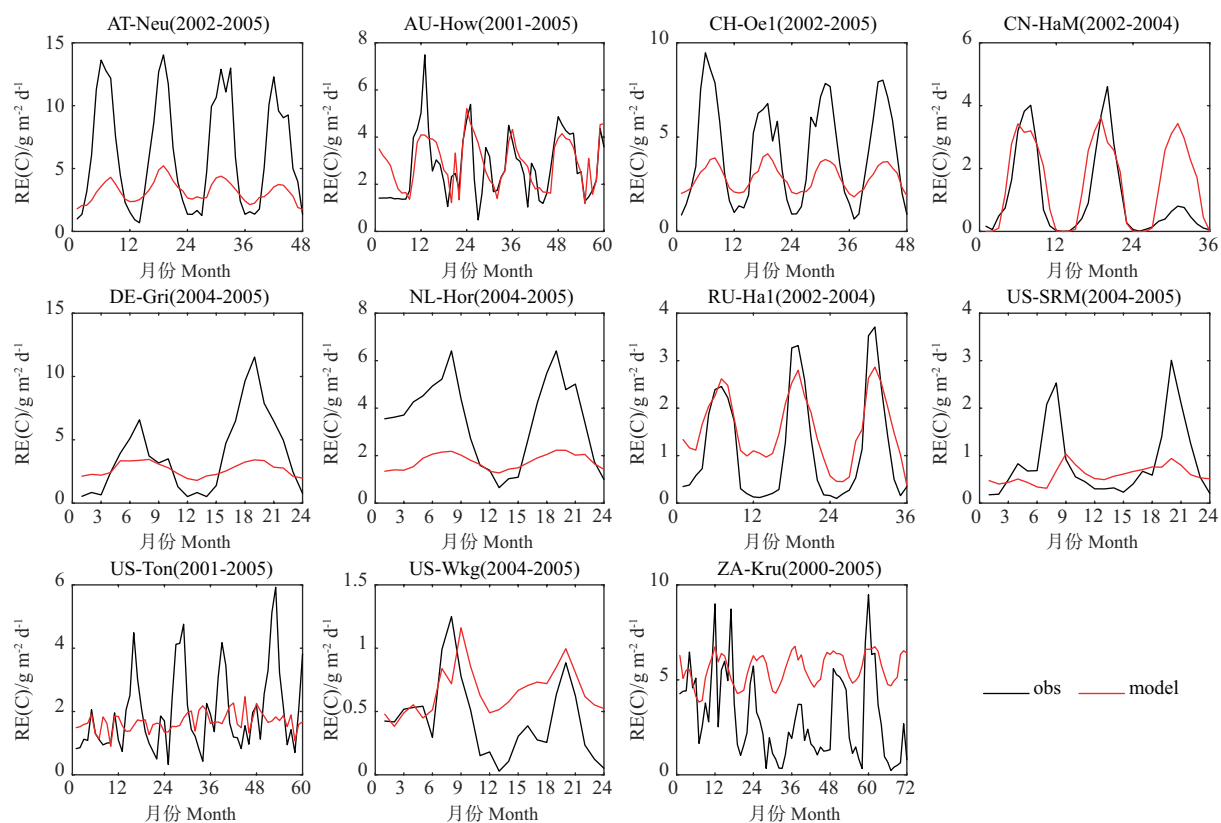


常绿阔叶林 Evergreen broadleaf forest (EBF)

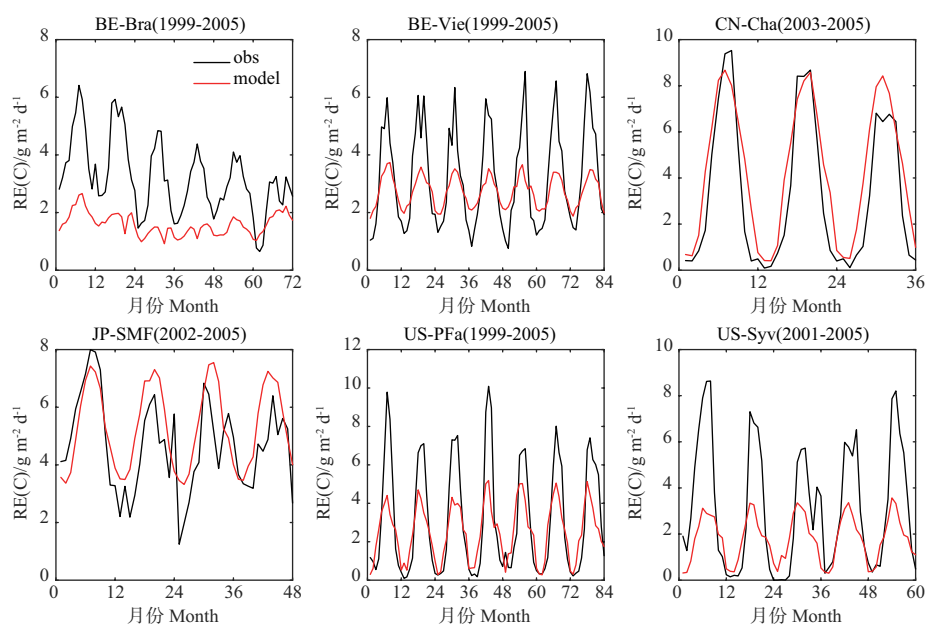


续附图1 Fig. S1 (Continued)

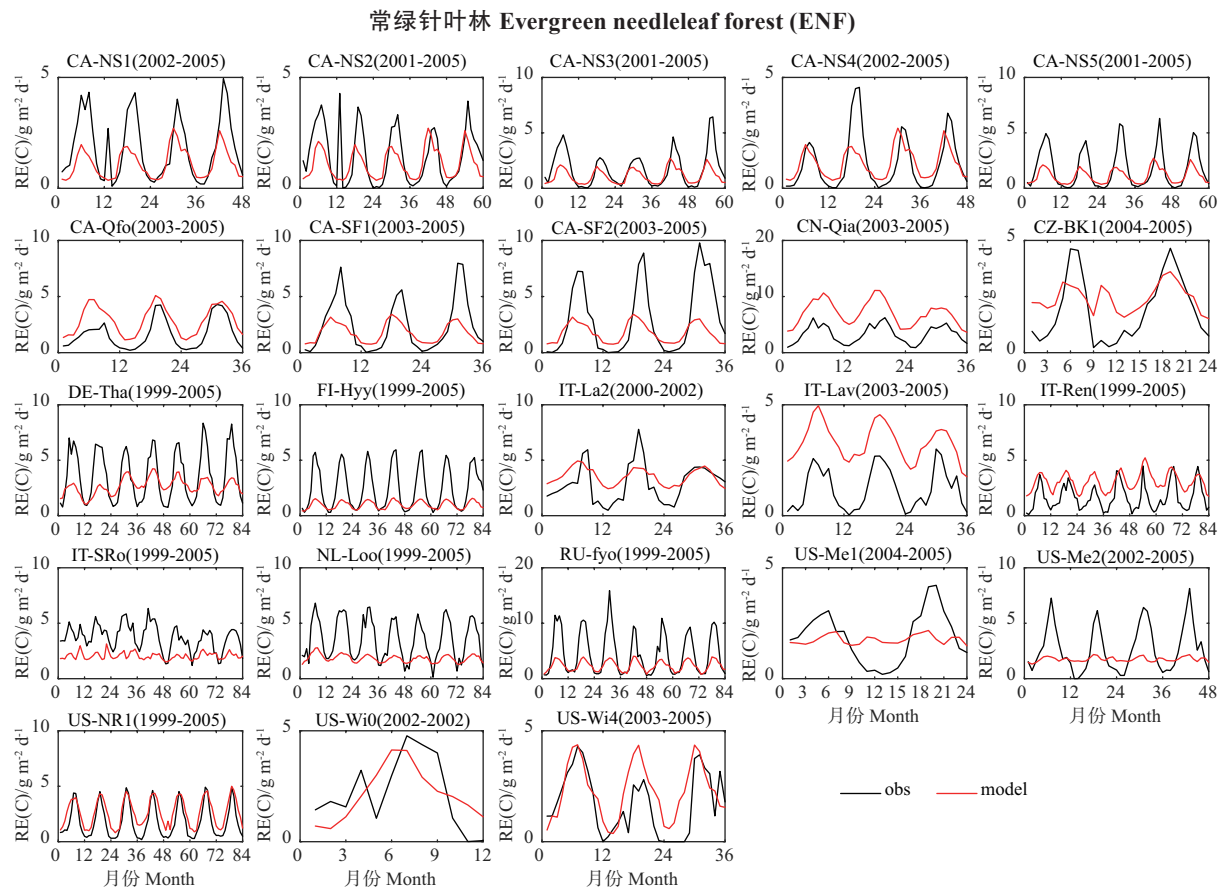
草地 Grasslands (GRA)



混交林 Mixed forest (MF)



续附图1 Fig. S1 (Continued)

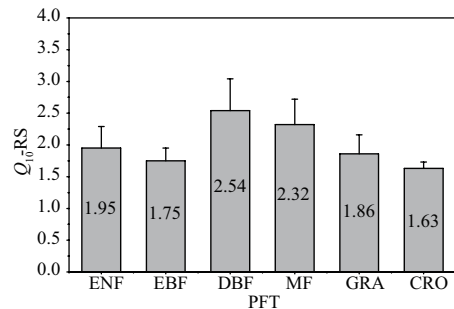


续附图1 Fig. S1 (Continued)

附表2 CLM 模型呼吸作用参数对模拟结果的影响
Table S2 Effects of respiration of CLM model on simulation results

参数 Parameter	RS 对各参数的敏感度系数 Sensitivity coefficient of RS to parameters (β -RS)	RA 对各参数的敏感度系数 Sensitivity coefficient of RS to parameters (β -RA)	RE 对各参数的敏感度系数 Sensitivity coefficient of RE to parameters (β -RE)
Q_{10} -RS	0.88	0.57	0.82
Q_{10} -RA	0.16	0.31	0.13
K	0.63	0.46	0.60
MR_{base}	0.19	0.35	0.15

Q_{10} -RS: 土壤呼吸温度敏感性; Q_{10} -RA: 自养呼吸温度敏感性; K : 土壤碳库周转速率; MR_{base} : 基础维持呼吸速率; β -RS = $\Delta Run / \Delta P$, ΔP 为参数 P 的变化率(10%), ΔRun 为参数 P 发生 ΔP 变化率时RS的相应变化率(%), β -RA和 β -RE计算方法同 β -RS.
 Q_{10} -RS: The temperature sensitivity of soil respiration; Q_{10} -RA: The temperature sensitivity of autotrophic respiration; K : Turnover rate of the soil carbon pool; MR_{base} : The base rate of maintenance respiration; β -RS = $\Delta Run / \Delta P$, in which ΔP is the change rate of P , ΔRun is the corresponding change rate of RS as P changed, and the calculation of β -RA and β -RE are the same as β -RS.



附图2 各植被型 Q_{10} -RS大小. PFT: 植被功能型; Q_{10} -RS: 土壤呼吸温度敏感性; MF: 混交林; GRA: 草地; ENF: 常绿针叶林; EBF: 常绿阔叶林; DBF: 落叶阔叶林; CRO: 农田.
Fig. S2 The size of Q_{10} -RS for all plant functional types. PFT: Plant functional type; Q_{10} -RS: The temperature sensitivity of soil respiration; MF: Mixed forest; GRA: Grasslands; ENF: Evergreen needleleaf forest; EBF: Evergreen broadleaf forest; DBF: Deciduous broadleaf forest; CRO: Cropland.