中美碳联盟 (USCCC)

US-China Carbon Consortium

中国森林生态系统土壤呼吸温度敏感性空间变异特征及影响因素

Spatial variations and controlling factors of the temperature sensitivity of soil respiration in forest ecosystems across China

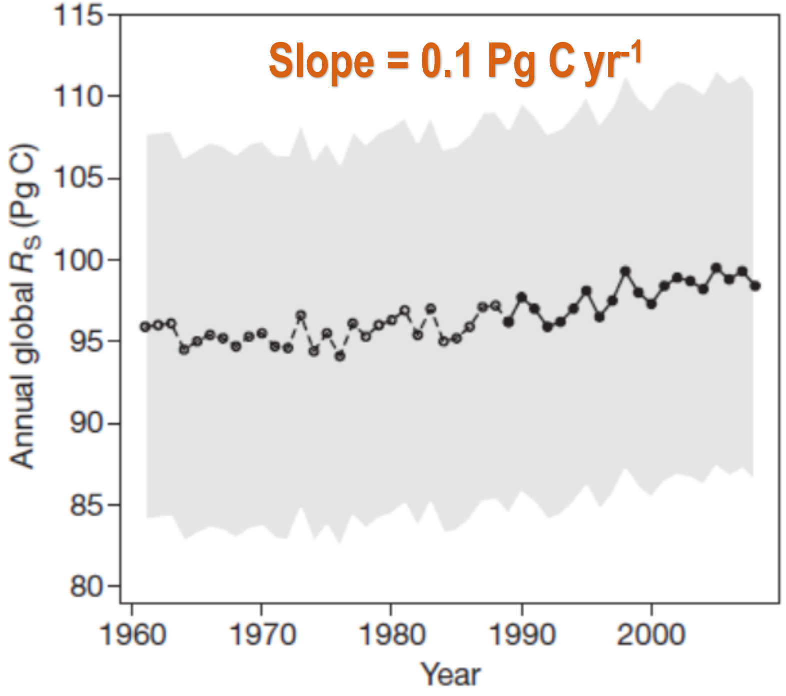
贾 昕、郑甲佳、查天山，等

北京林业大学

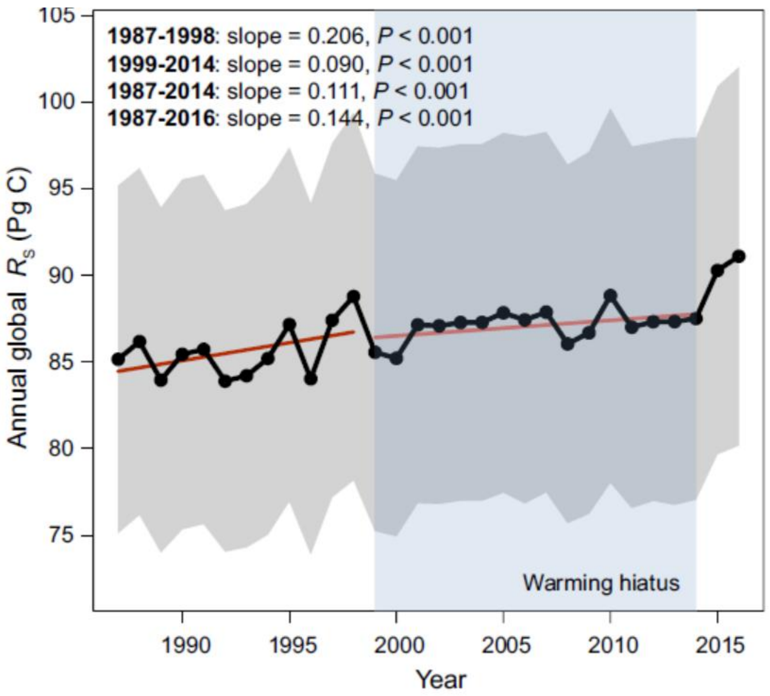
2021年7月31日, 重庆

Soil respiration and its temperature sensitivity

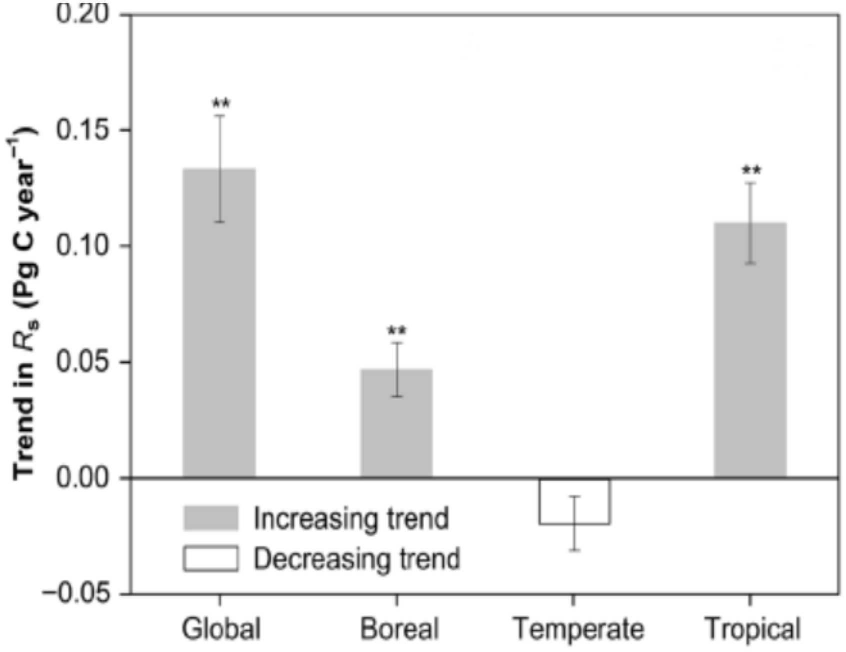
- 土壤呼吸是碳循环的重要组分
- Soil respiration (SR) is an important component of the carbon cycle
- 全球土壤呼吸速率持续增加
- Global SR rate has been increasing



Bond-Lamberty & Thomson 2010 Nature



Lei et al. 2021 NC



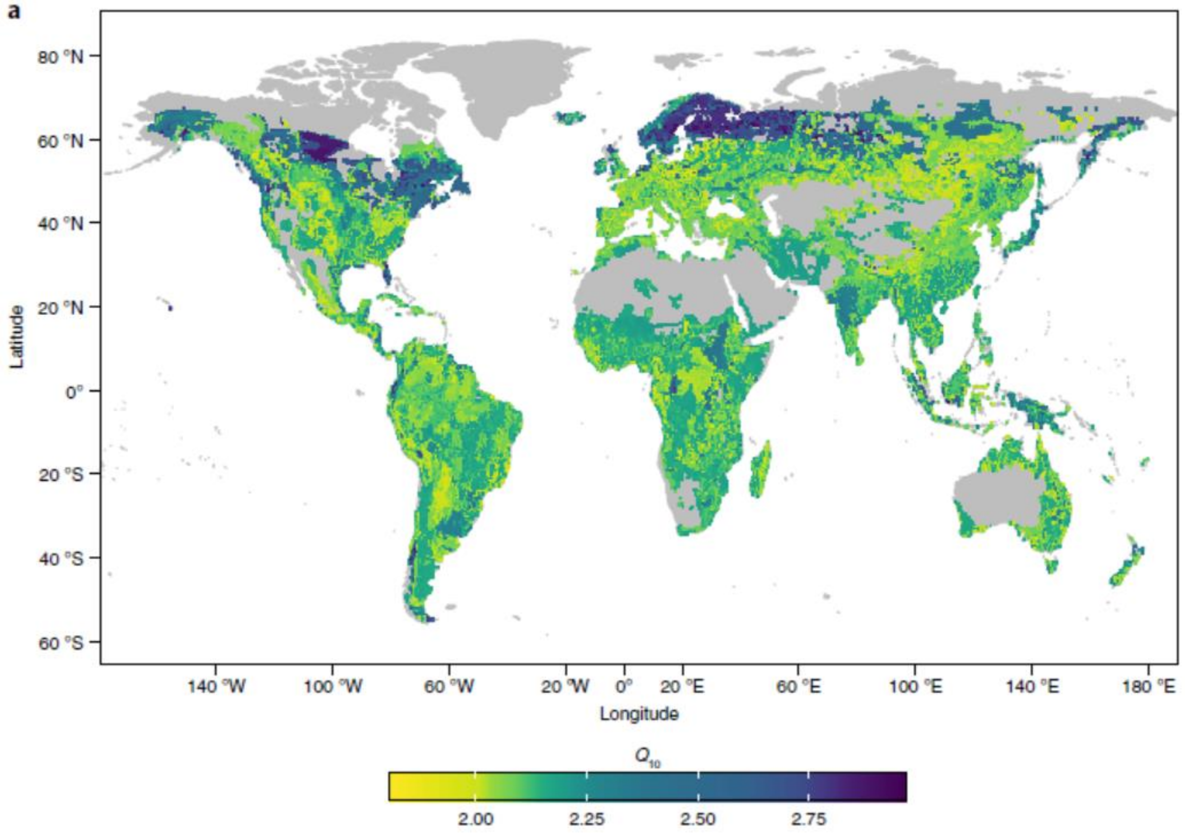
Huang et al. 2021 Sci Adv

Soil respiration and its temperature sensitivity

土壤呼吸的温度敏感性是决定陆地碳循环与气候变化间反馈关系的关键参数

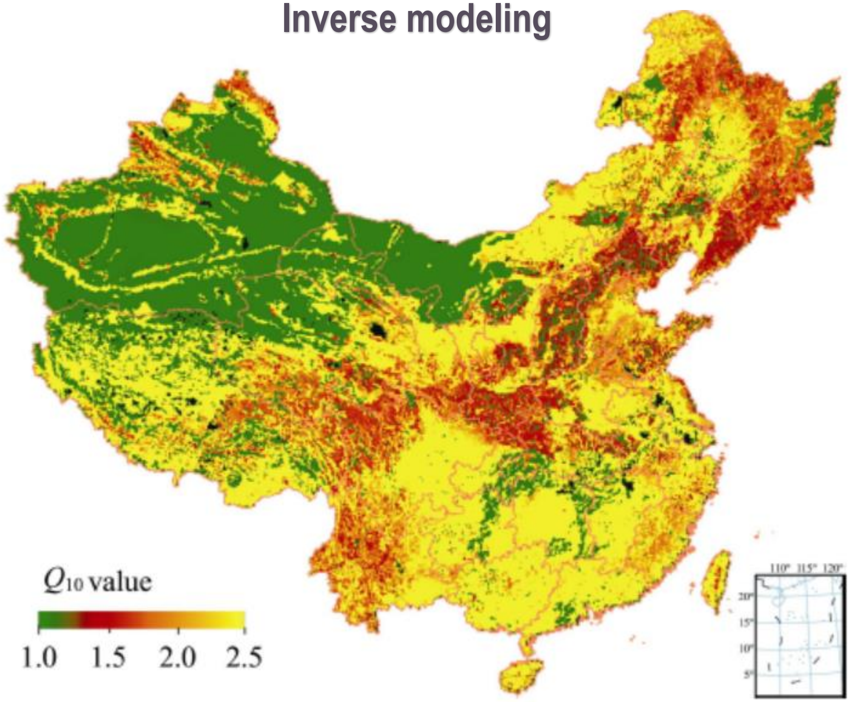
The temperature sensitivity of soil respiration is a key parameter determining the climate-carbon cycle feedback.

Random forest model



Haaf et al. 2021 NCC

Inverse modeling

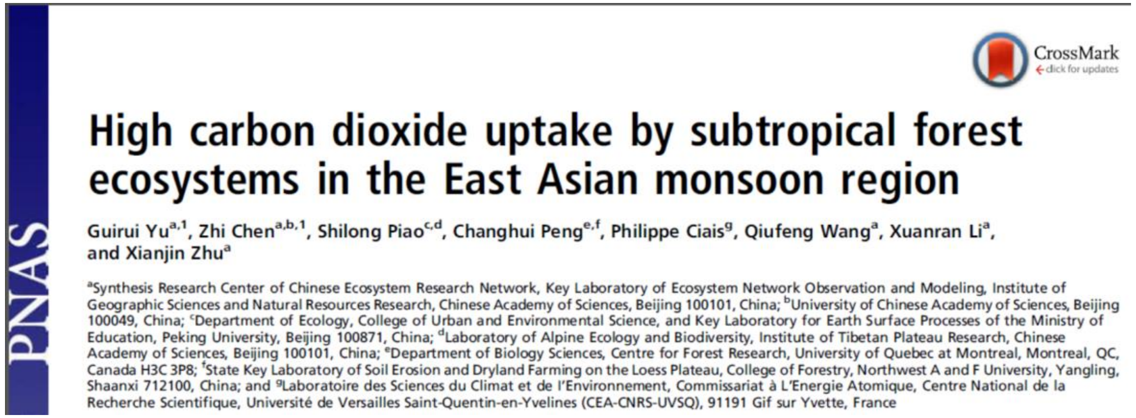


Zhou et al. 2009 Science in China Series C: Life Sciences

Forest ecosystems and the carbon cycle

全球森林的碳贮量约占全球植被碳贮量的77%，森林土壤的碳贮量约占全球土壤碳贮量的39% (FAO 2020)

我国陆地生态系统碳贮量为792亿吨，年均固碳2.01亿吨，可抵消同期化石燃料碳排放的14.1%，其中森林的贡献约为80% (Tang et al. 2018 PNAS)。

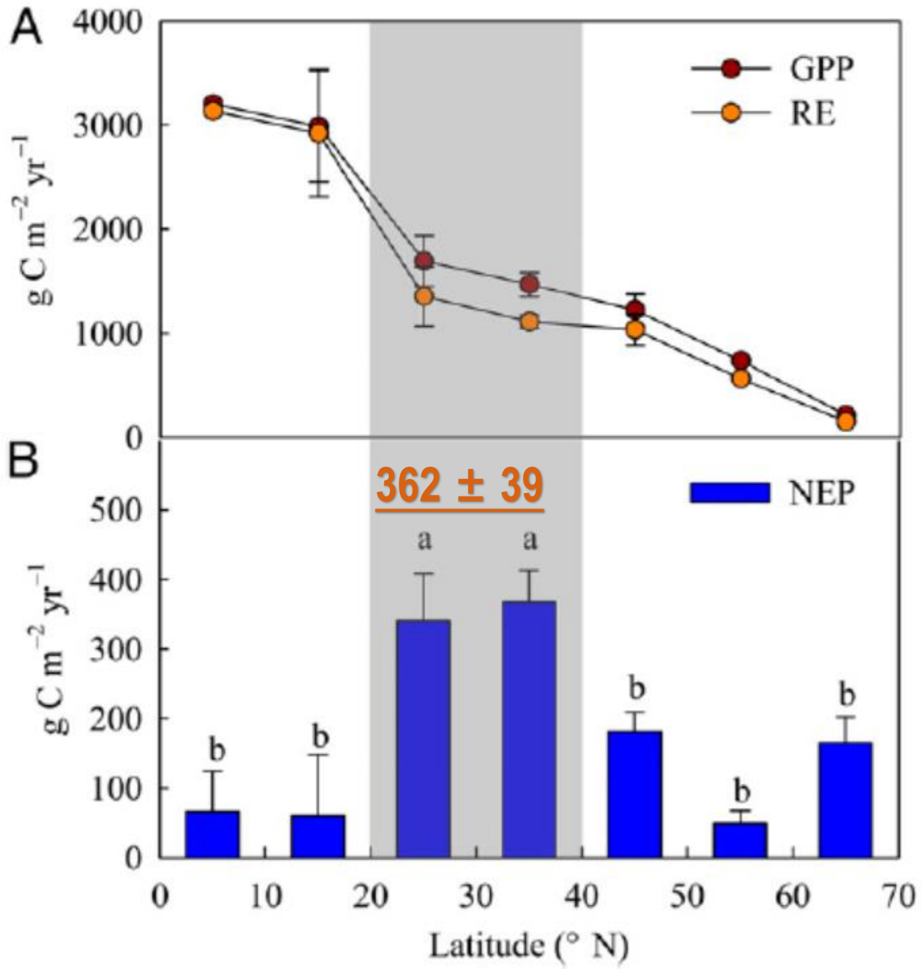


High carbon dioxide uptake by subtropical forest ecosystems in the East Asian monsoon region

Guirui Yu[a,1], Zhi Chen[a,b,1], Shilong Piao[c,d], Changhui Peng[e,f], Philippe Ciais[g], Qiufeng Wang[a], Xuanran Li[a], and Xianjin Zhu[a]

[a]Synthesis Research Center of Chinese Ecosystem Research Network, Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; [b]University of Chinese Academy of Sciences, Beijing 100049, China; [c]Department of Ecology, College of Urban and Environmental Science, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China; [d]Laboratory of Alpine Ecology and Biodiversity, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China; [e]Department of Biology Sciences, Centre for Forest Research, University of Quebec at Montreal, Montreal, QC, Canada H3C 3P8; [f]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, College of Forestry, Northwest A and F University, Yangling, Shaanxi 712100, China; and [g]Laboratoire des Sciences du Climat et de l'Environnement, Commissariat à L'Energie Atomique, Centre National de la Recherche Scientifique, Université de Versailles Saint-Quentin-en-Yvelines (CEA-CNRS-UVSQ), 91191 Gif sur Yvette, France

"The total NEP of East Asian monsoon subtropical forests was estimated to be 0.72 ± 0.08 Pg C yr−1, which accounts for 8% of the global forest NEP."



Yu et al. 2014 PNAS

Global variations in Q_{10} of soil respiration

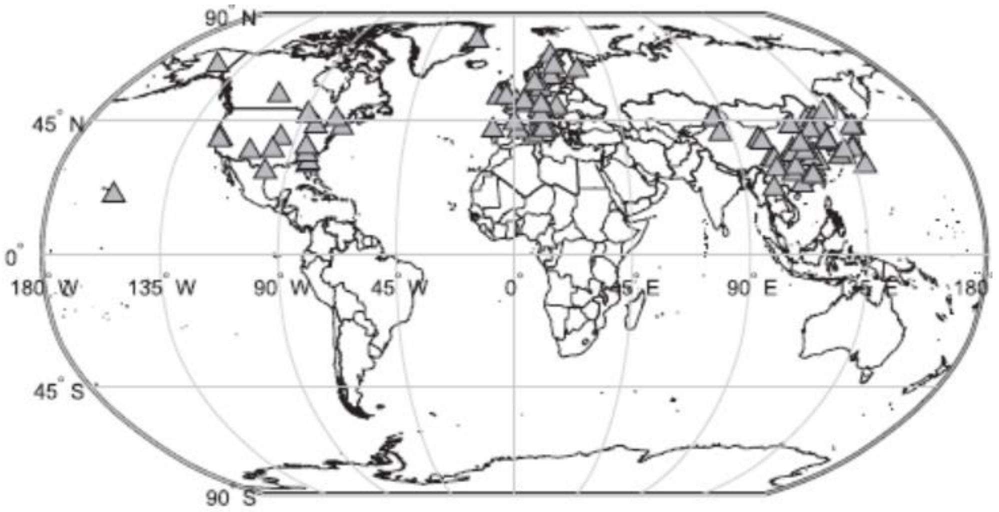
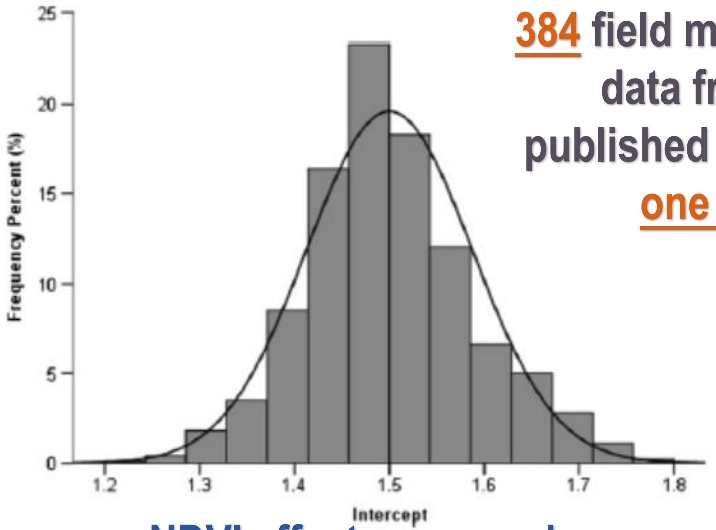
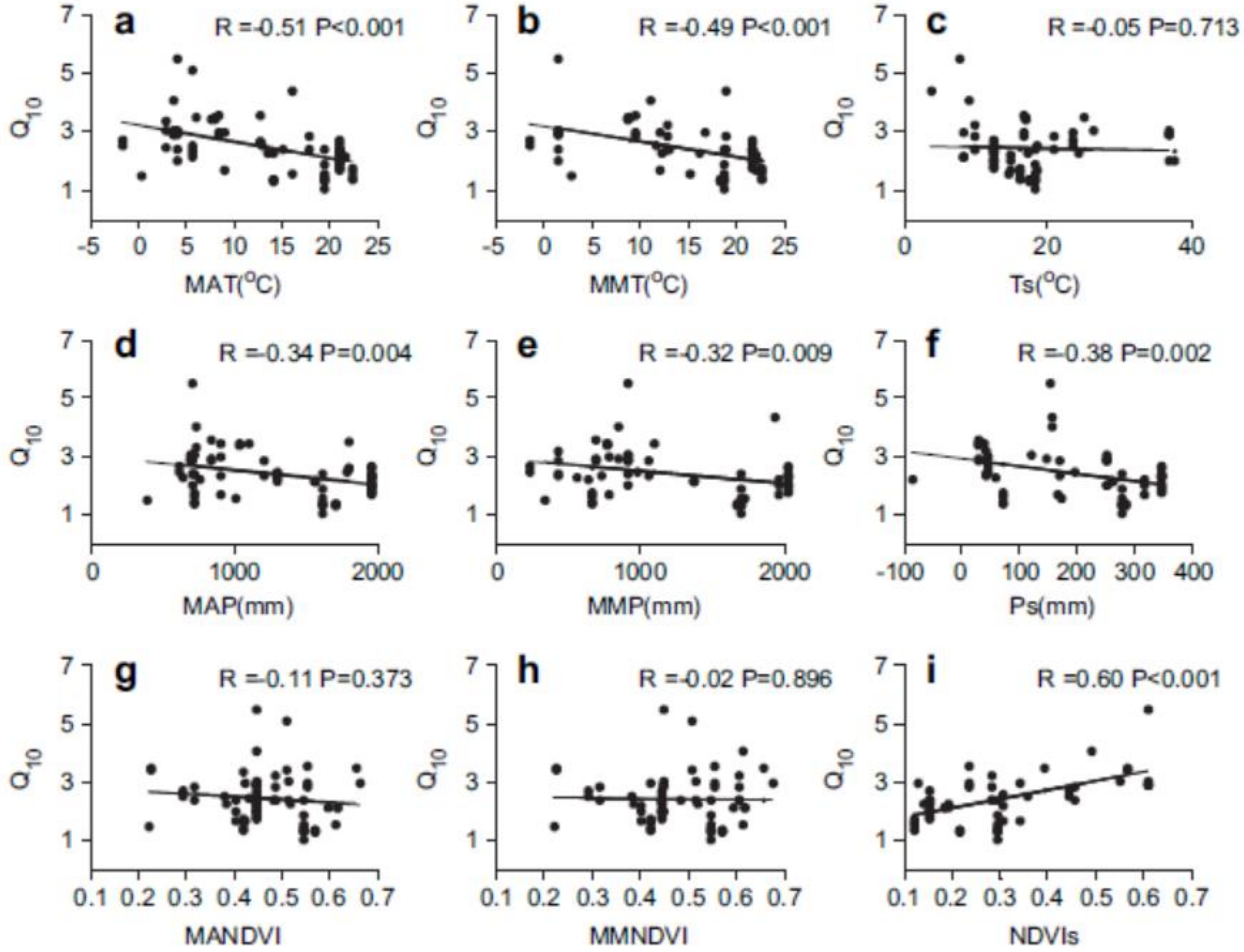


Fig. 1. Spatial distribution of sites included in the soil respiration Q_{10} database.



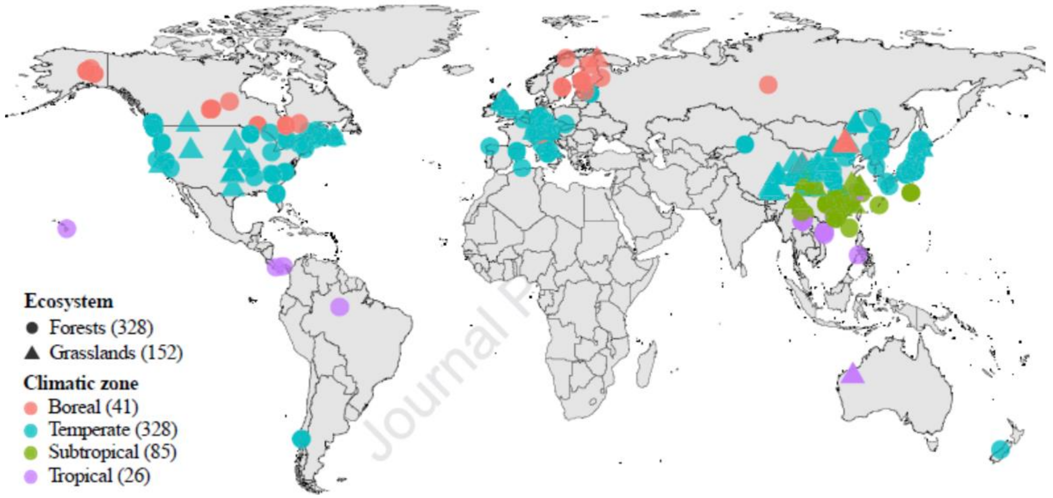
NDVI effects removed

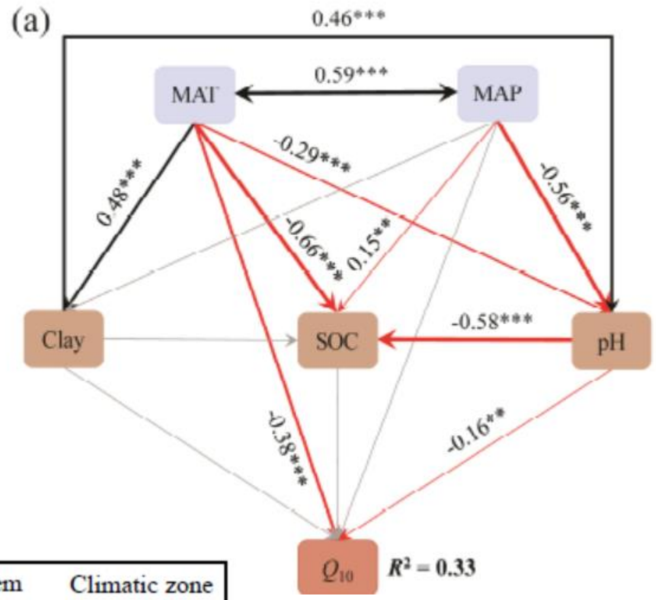
384 field measurement data from 114 published papers and one book

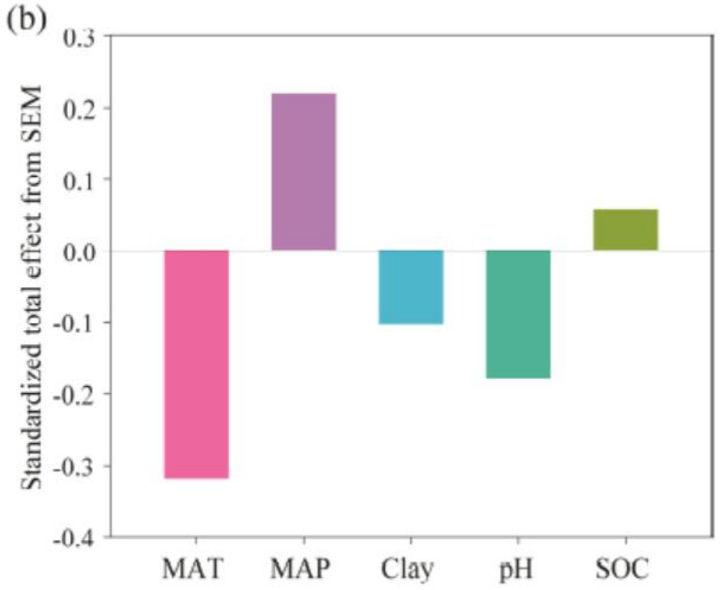


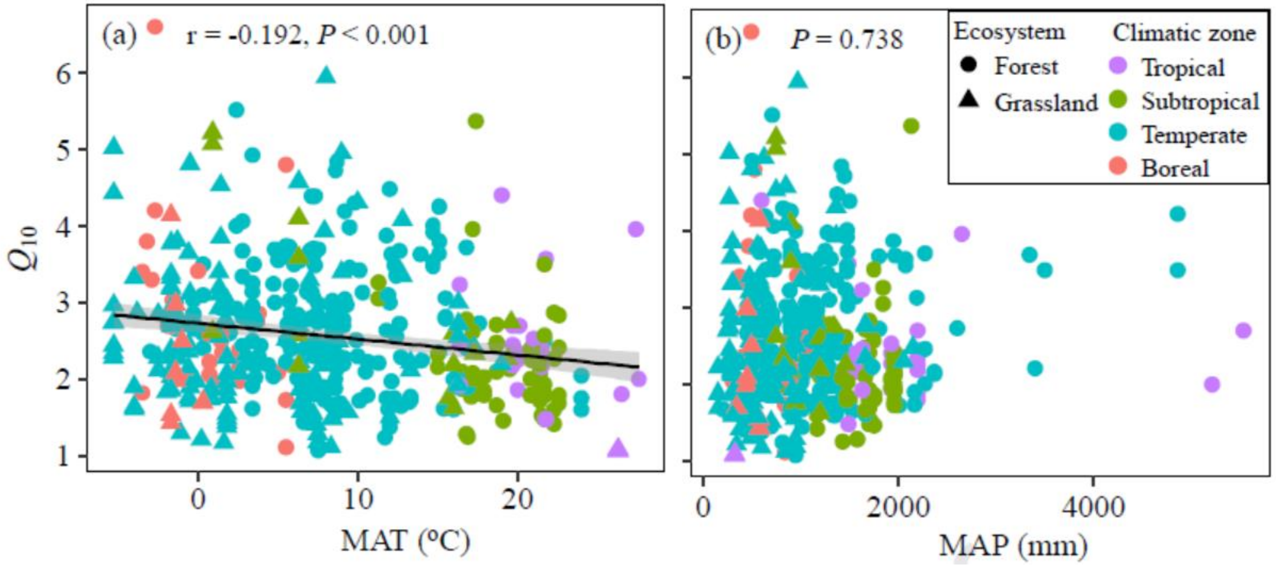
Wang et al. 2010 SBB

Global variations in Q_{10} of soil respiration









Data from

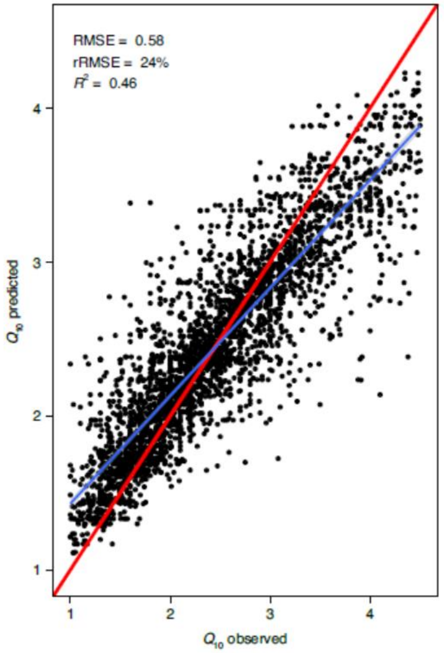
1) **published field experimental studies**
2) **Global Soil Respiration Database (SRDB) (Bond-Lamberty & Thomson 2010 BG)**

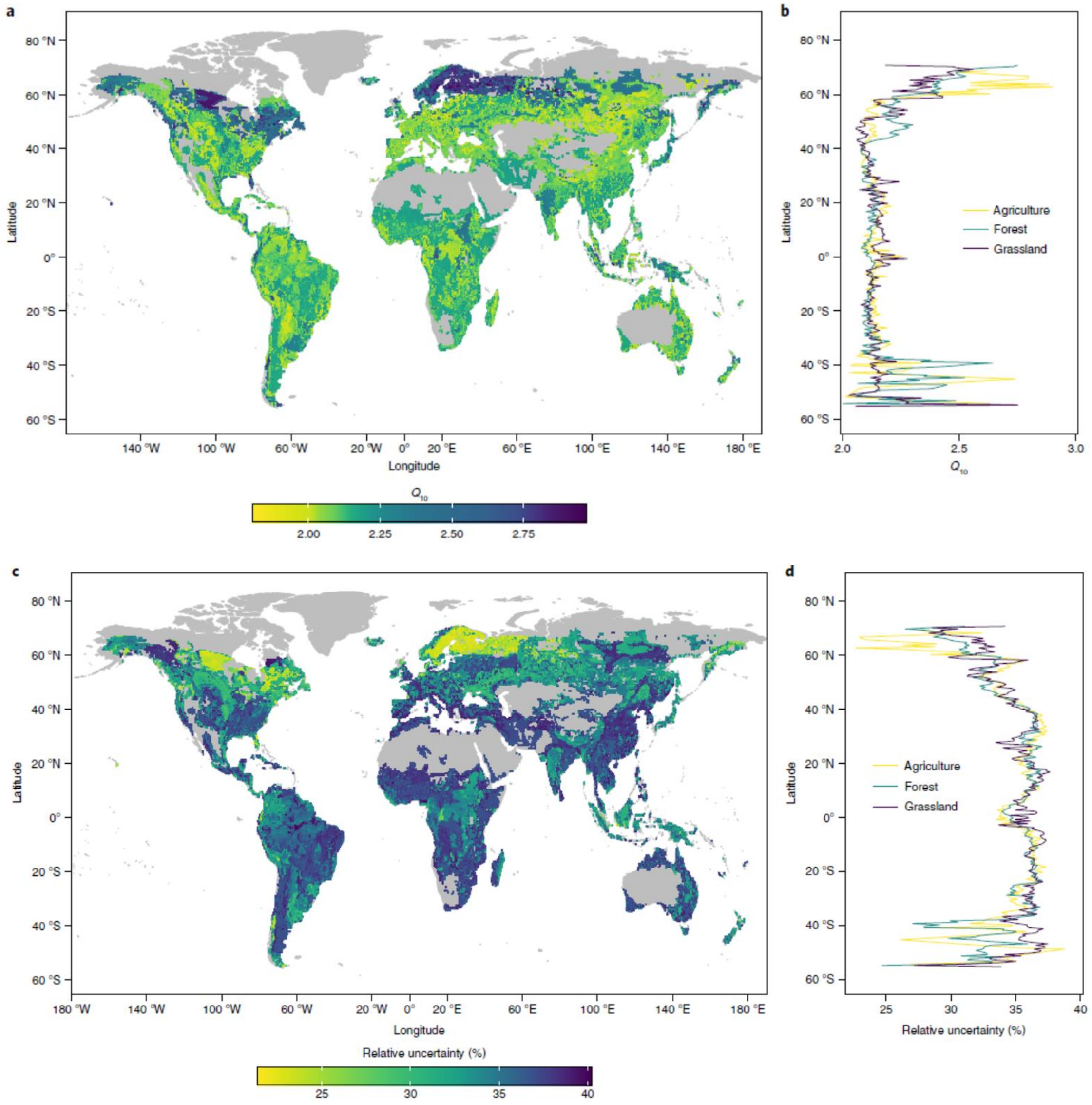
Li et al. 2020 SBB

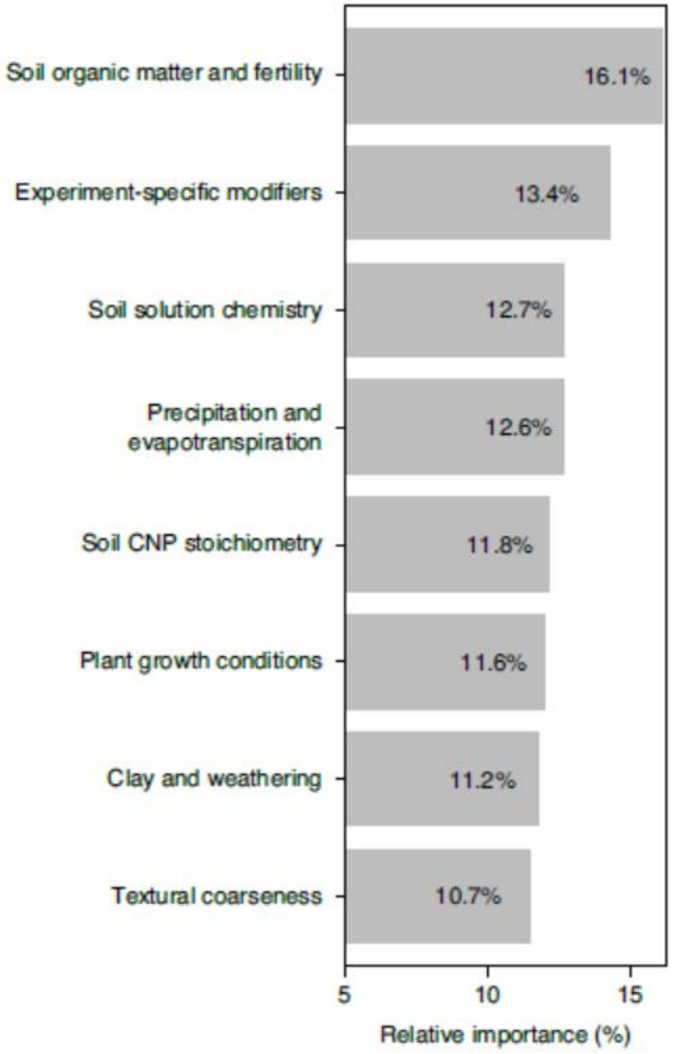
Global variations in Q_{10} of soil respiration

Haaf et al. 2021 NCC

Data collected from existing scientific databases and published laboratory and field studies



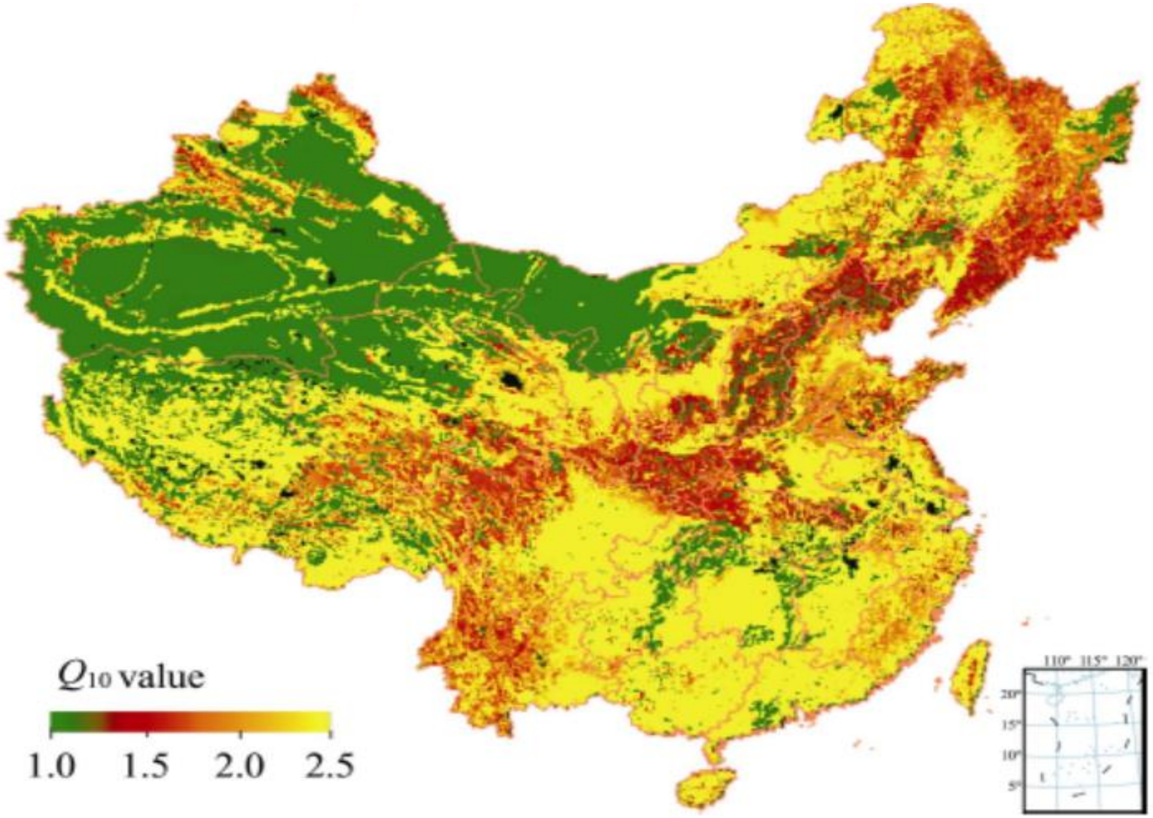


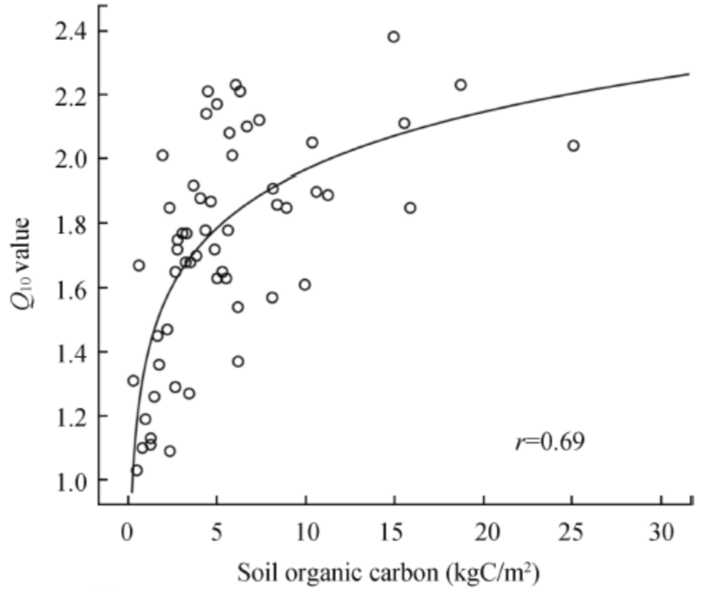


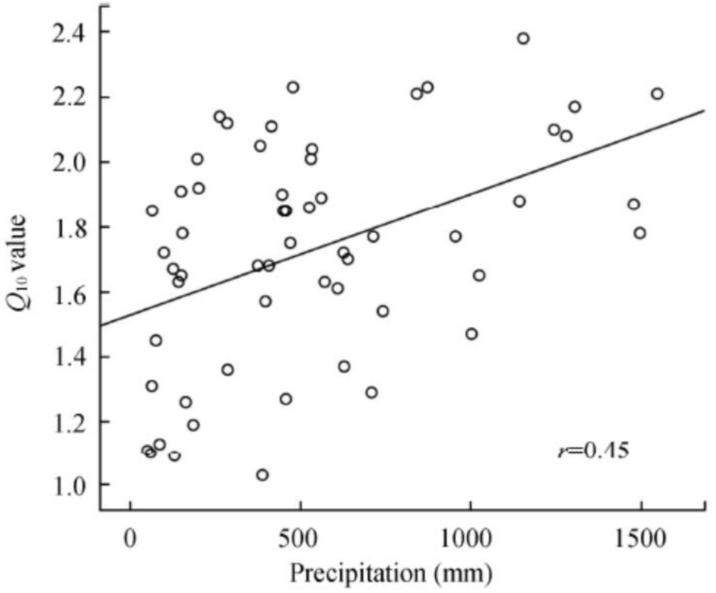
Machine learning approach

Variations in Q_{10} of soil respiration across China

Zhou et al. 2009 Science in China







… conducted an inverse modeling analysis to retrieve the spatial pattern of Q_{10} in China at 8 km spatial resolution by assimilating data of soil organic carbon into the CASA model.

Variations in Q_{10} of soil respiration across China

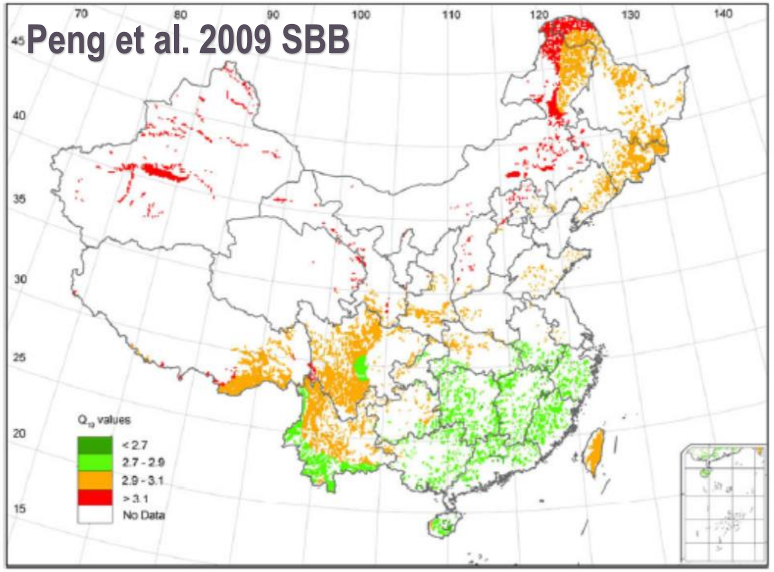
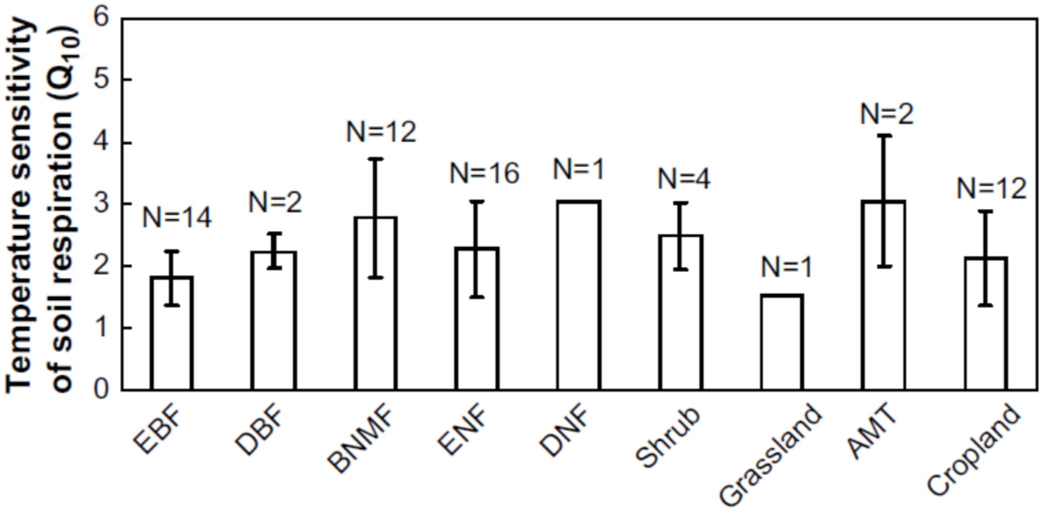
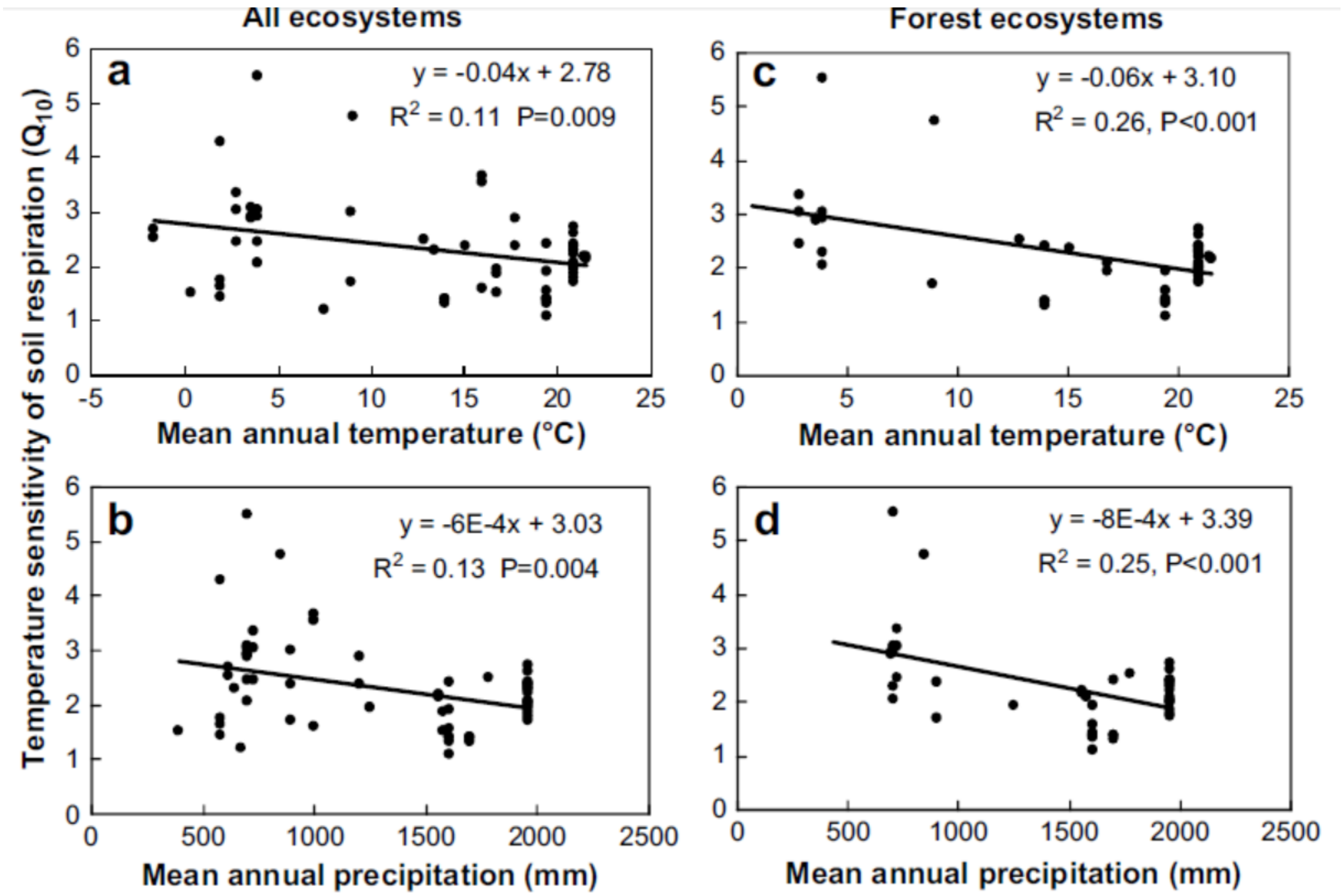


Fig. 6. The spatial distribution of sensitivity of forest soil respiration to temperature at the soil depth of 5 cm (Q_{10}) in China.



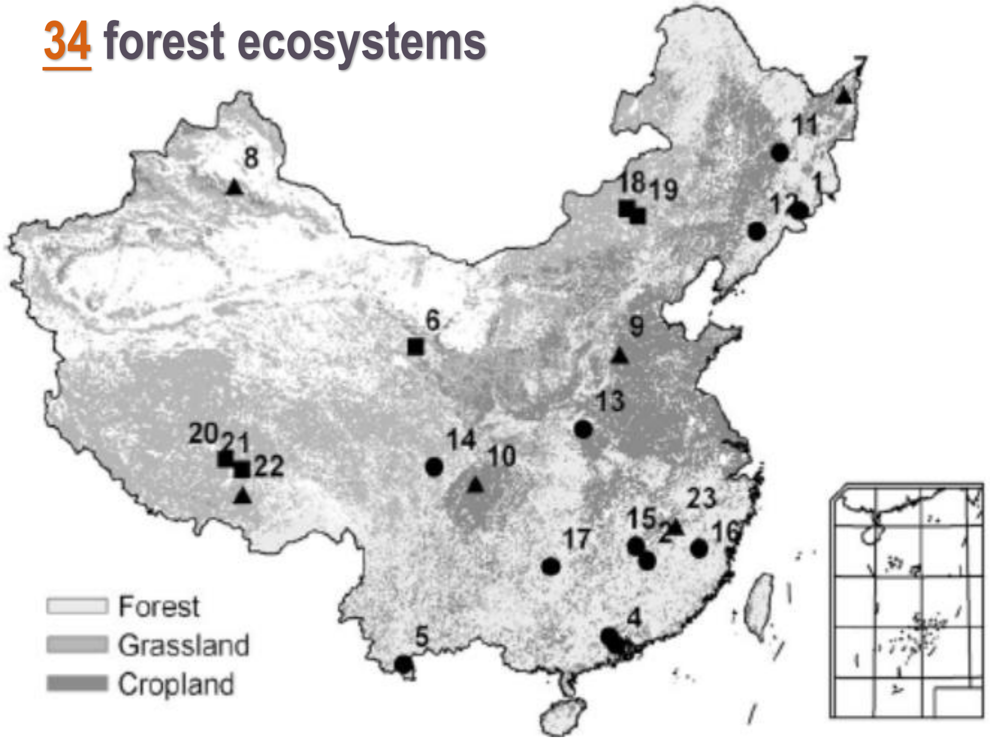


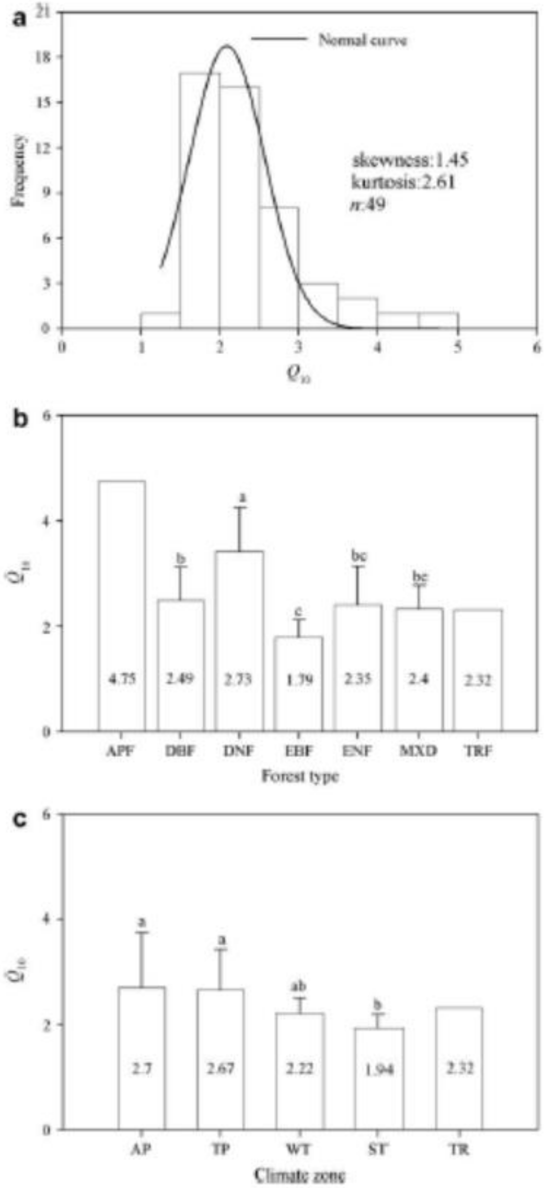
EBF, DBF, BNMF, ENF, DNF, and AMT represent evergreen broadleaf forests, deciduous broadleaf forests, broadleaf and needleleaf mixed forests, evergreen needleleaf forests, deciduous needleleaf forests, and alpine meadow and tundra, respectively.

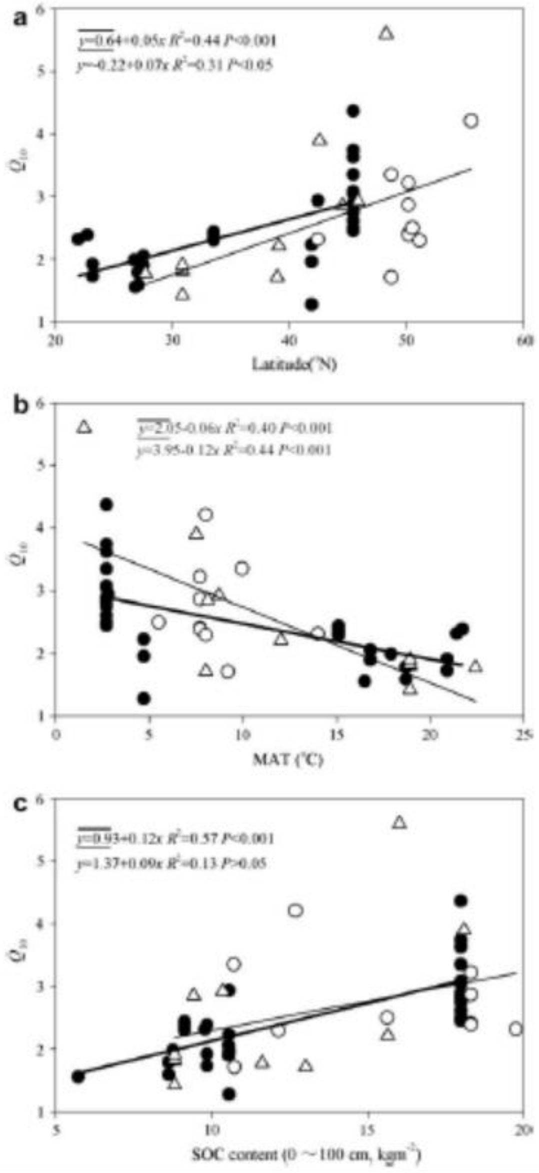
Variations in Q_{10} of soil respiration across China

Zheng et al. 2009 SBB

34 forest ecosystems





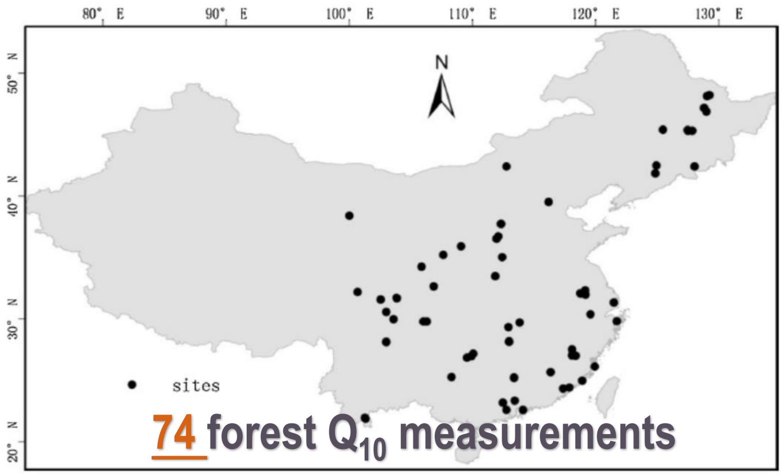


APF: Alpine forest in Tibet Plateau
DBF: Deciduous broadleaved forest
DNF: Deciduous needle-leaf forest
EBF: Evergreen broadleaved forest
ENF: Evergreen needle-leaf forest
MXD: Needle-leaf/broadleaved mixed forest
TRF: Tropical forest
TR: Tropical zone

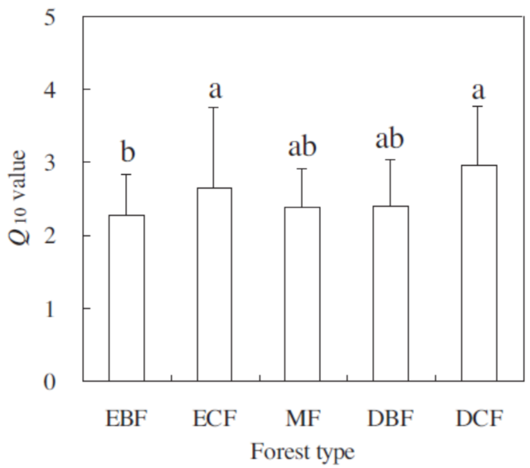
AP: Alpine zone
TP: Temperate zone
WT: Warm temperate zone
ST: Subtropical zone

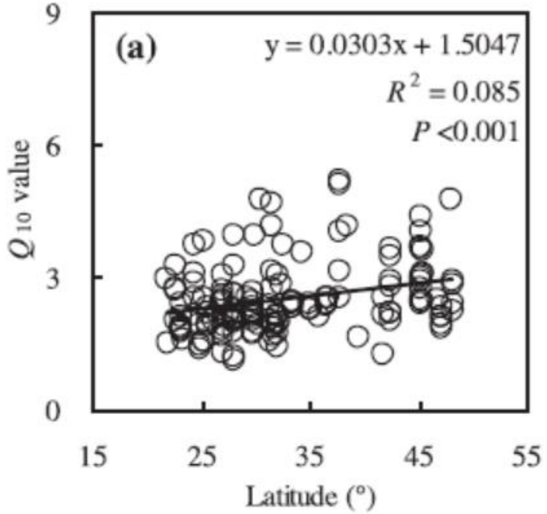
Variations in Q_{10} of soil respiration across China

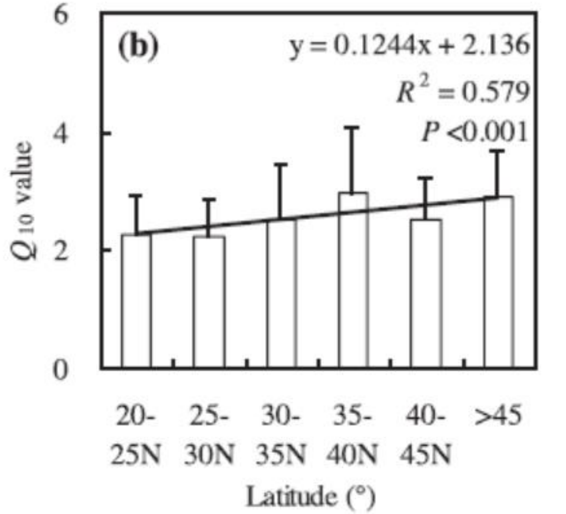
Xu et al. 2015 ASE

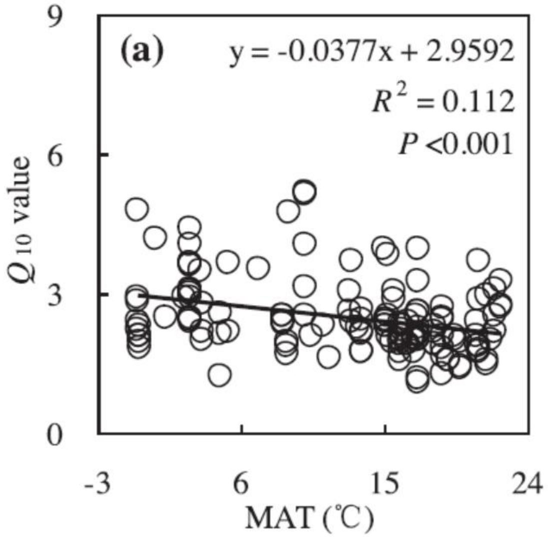


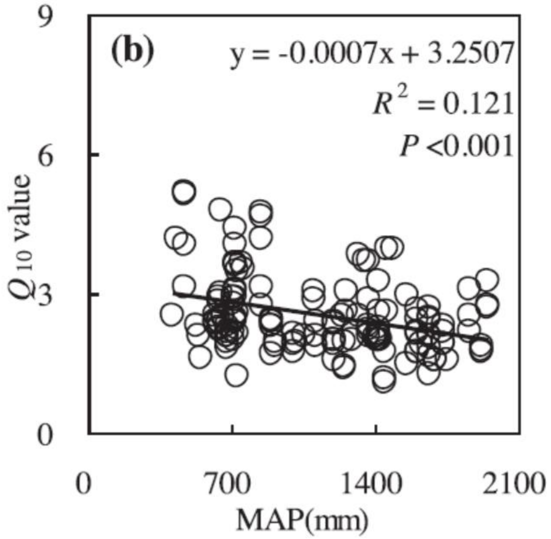
74 forest Q_{10} measurements

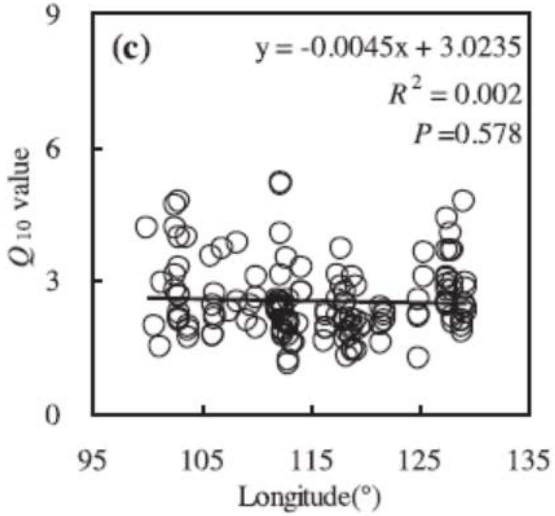


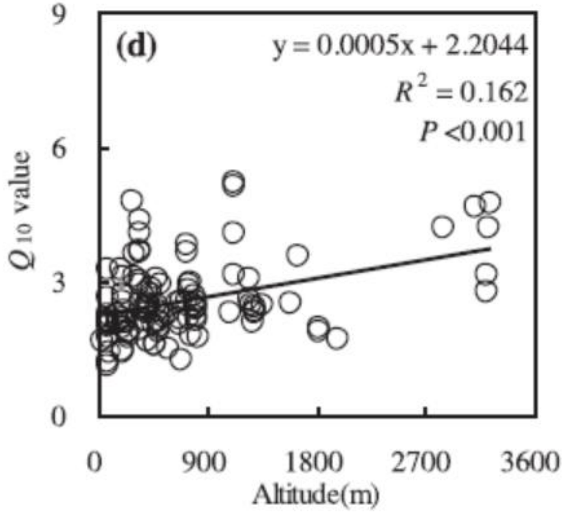






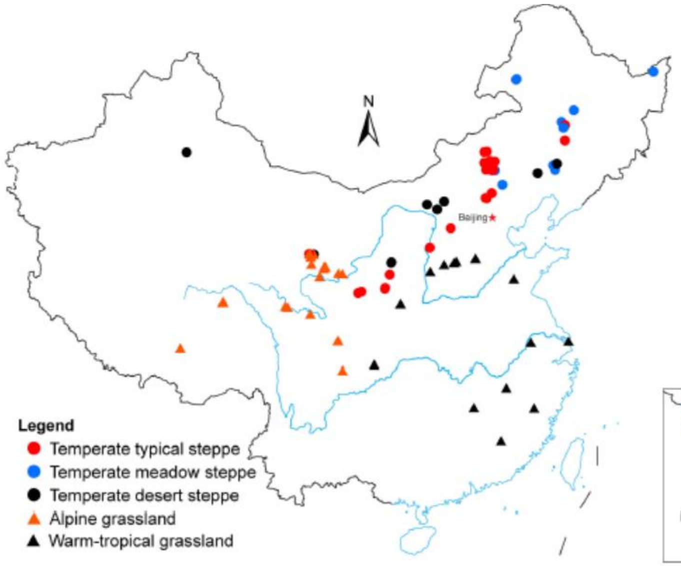






Variations in Q_{10} of soil respiration across China

Feng et al. 2018 BG



Grassland ecosystems

TTS: temperate typical steppe

TMS: temperate meadow steppe

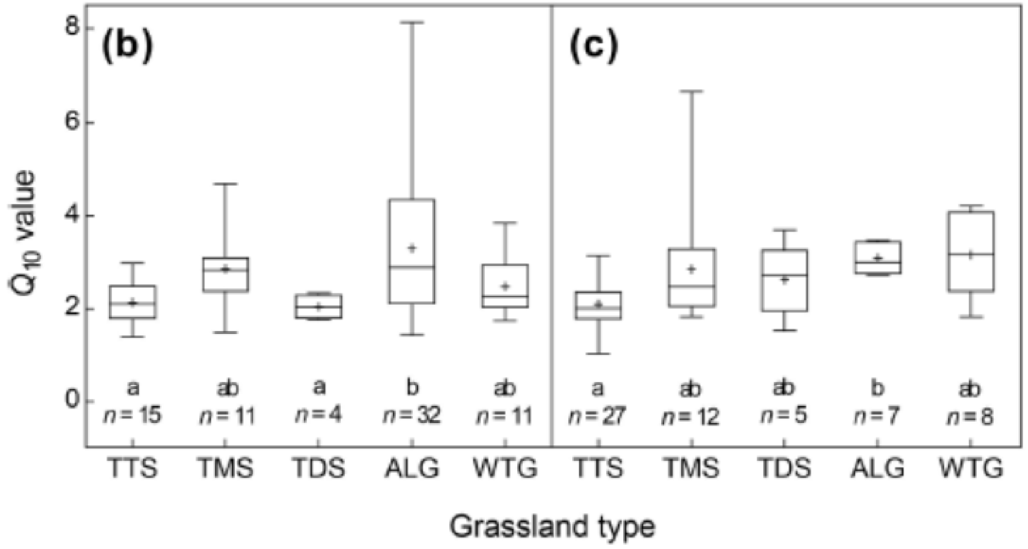
TDS: temperate desert steppe

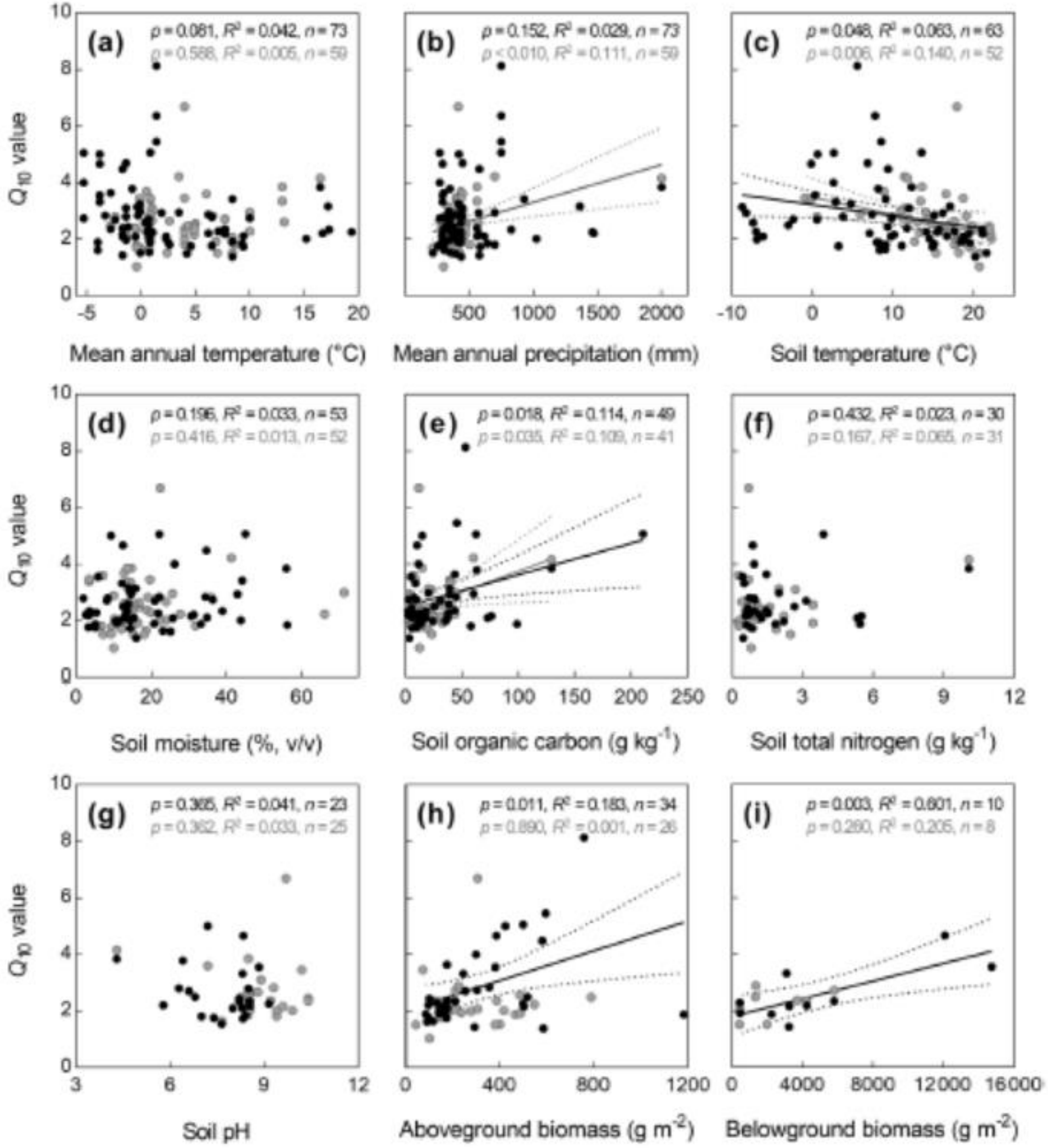
ALG: alpine grassland

WTG: warm tropical grassland

54 measurements of annual SR

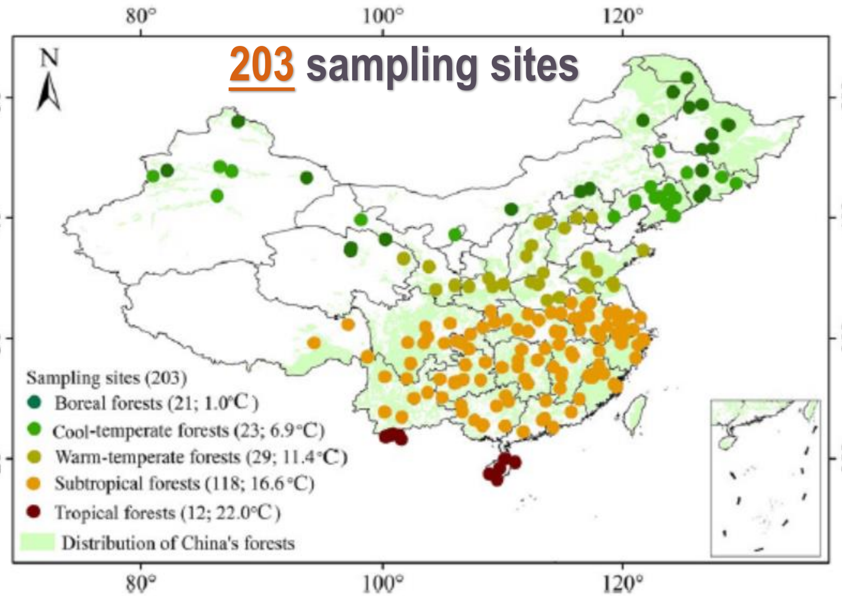
171 estimates of Q_{10}

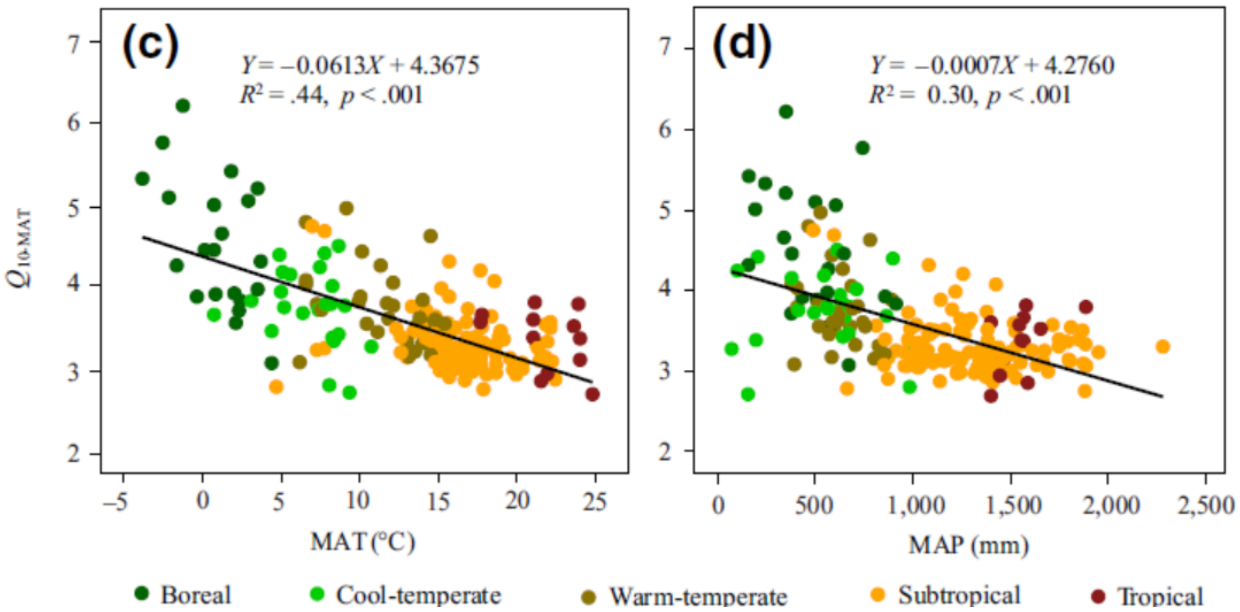




Variations in Q_{10} of soil respiration across China

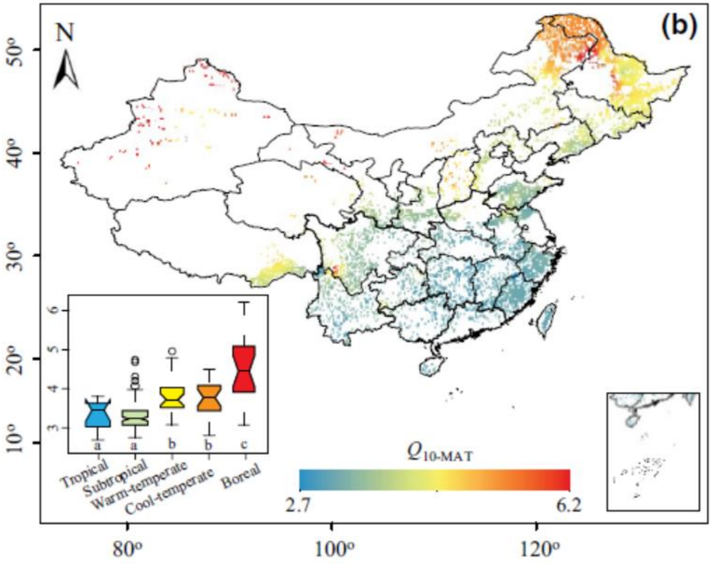
Li et al. 2020 GCB

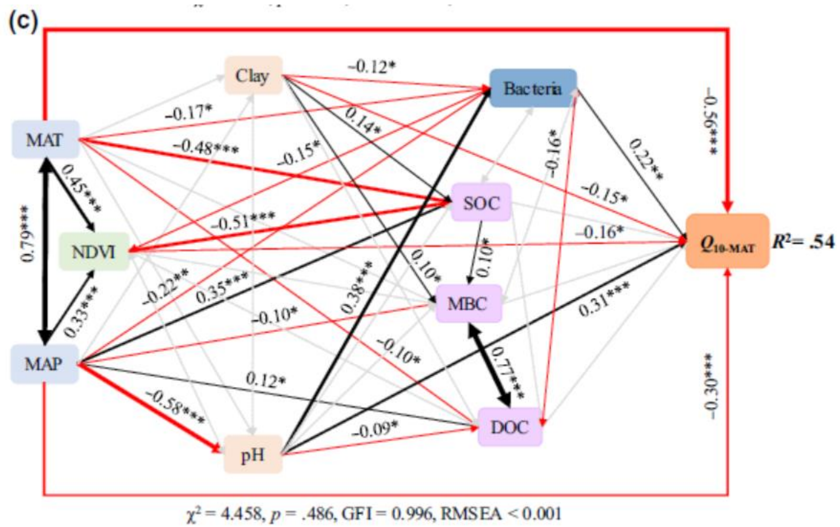




Soil sampling & lab incubation

Q_{10} of SOC decomposition





Questions remain to be asked

- Whether and how dataset update may modify previous conclusions?
- Does Q_{10} vary among forest types and along geographical gradients across China?
- What are the climatic and edaphic controls over spatial variations in Q_{10} of SR?
- Direct vs. indirect effects? Interactive effects? Differential responses to climatic and edaphic factors among forest types?




Synthesis of published studies

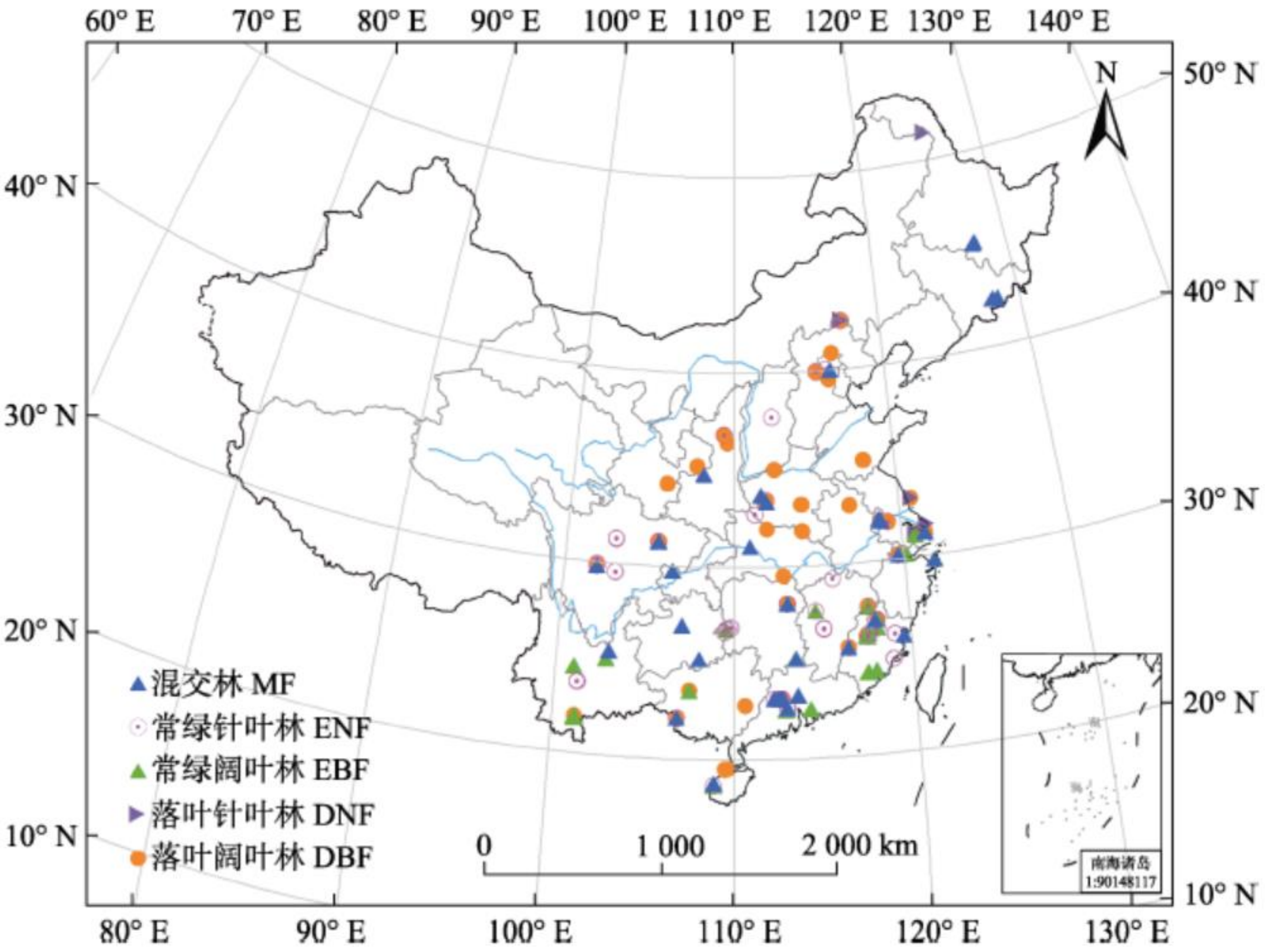
- 中国知网(http://www.cnki.net/)数据库
- Web of Science (http://www.isiknowledge.com/)数据库
- 2018年1月1日之前经过同行评审公开发表的论文(peer-reviewed publications prior to Jan 1, 2018)

数据筛选标准：

1. 只选择原位观测数据，野外控制实验只选取对照组数据(in situ measurements, control plots included for manipulative experiments)
2. 所有研究必须标明森林类型、实验开始和结束时间、研究地点位置信息等(information available on forest type, start and end dates, and location of measurements)
3. 实验周期至少1年，以避免时间尺度效应(即长期和短期温度敏感性)对分析结果造成影响 (at least one complete year of measurements)
4. Q_{10}是基于5 cm深处土壤温度推算的(Q_{10} values calculated from soil temperature at 5 cm depth)
5. 说明计算Q_{10}的方法，且提供计算Q_{10}的参数(Calculation of Q_{10} is clearly described, or regression coefficients for calculating Q_{10} are provided)

Synthesis of published studies

- 169 publications
- 399 records
- 25 provinces
- 5 forest types (88DBF, 8DNF, 118EBF, ENF110, MF75)
- Lat: 18.63°–51.38° N
- Long: 101.02°–128.47° E
- Alt: 0–3100 m
- MAP: 413–2449 mm

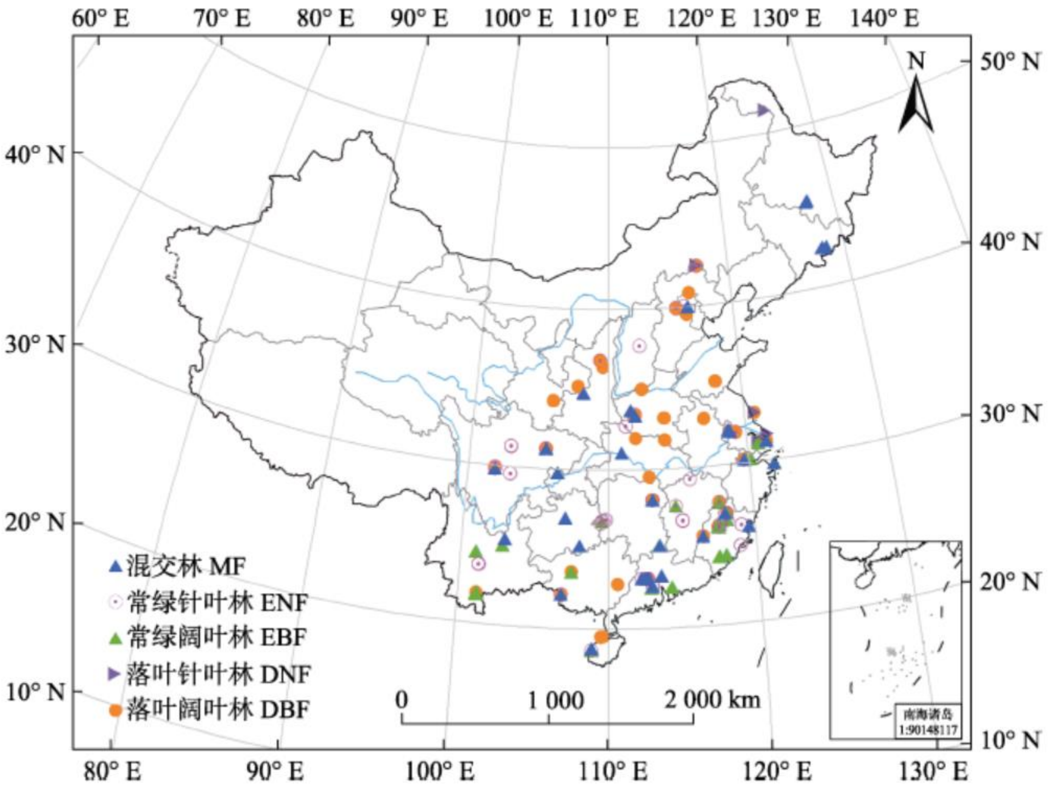


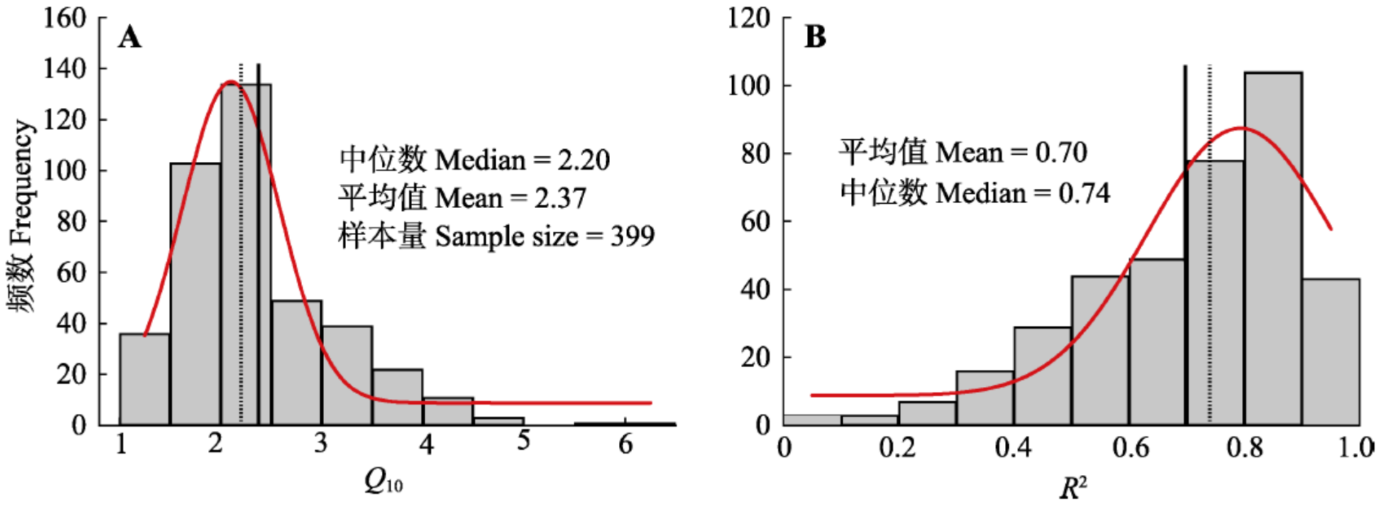
Synthesis of published studies

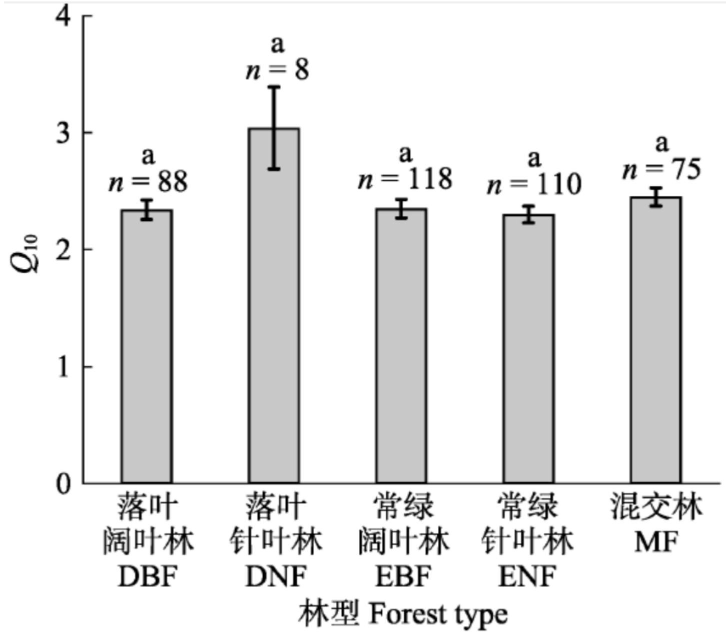
表1 中国森林生态系统年尺度Q_{10}数据集的相关信息
Table 1 Supporting information of the dataset of annual Q_{10} in forest ecosystems across China

变量所属类型 Type of variable	变量 Variable
地理位置 Site	纬度(° N)、经度(° E)、海拔(m) Latitude (° N), Longitude (° E), Altitude (m)
气象因素 Climate factor	年平均气温(℃), 年降水量(mm), 年蒸发散(mm), 干燥指数($mm\cdot mm^{-1}$), 试验地当年平均气温(℃), 试验地当年降水量(mm) Mean annual temperature (℃), mean annual precipitation (mm), annual evapotranspiration (mm), aridity index ($mm\cdot mm^{-1}$), mean annual temperature of study sites (℃), mean annual precipitation of study sites (mm)
植被因素 Vegetation factor	林分类型, 林龄(a), 叶面积指数($m^2\cdot m^{-2}$) Stand type, stand age (a), leaf area index ($m^2\cdot m^{-2}$)
土壤温湿度 Soil temperature and moisture	测量期间平均土壤温度(℃), 测量期间土壤温度振幅(℃), 测量期间土壤体积含水率($m^3\cdot m^{-3}$), 测量期间土壤质量含水率(%) Mean soil temperature during measurement (℃), soil temperature amplitude during measurement (℃), Soil volumetric water content during measurement ($m^3\cdot m^{-3}$), soil mass water content during measurement (%)
土壤理化性质 Soil physicochemical properties	土壤有机碳含量($g\cdot kg^{-1}$), 土壤全氮含量($g\cdot kg^{-1}$), 土壤碳氮比, 土壤容重($g\cdot cm^{-3}$), 土壤酸碱度 Soil organic carbon content ($g\cdot kg^{-1}$), soil total nitrogen content ($g\cdot kg^{-1}$), soil carbon-nitrogen ratio, soil bulk density ($g\cdot cm^{-3}$), soil pH
土壤呼吸温度敏感性 Temperature sensitivity of soil respiration	土壤呼吸温度敏感性(Q_{10}), Van't Hoff方程的决定系数(R^2) Temperature sensitivity of soil respiration (Q_{10}), the determination coefficient of Van't Hoff equation (R^2)
观测方法信息 Measurement method information	开始测量日期, 结束测量日期, CO_2测定方法(碱溶液吸收法, 气象色谱法, 红外法), 气室方法(静态密闭气室法, 动态密闭气室法、自动开闭气室法) Start date of measurement, end date of measurement, CO_2 measurement method (Alkali solution absorption, Gas chromatography, Infrared method), chamber method (Static closed chamber, Dynamic closed chamber, Automatic opening and closing chamber)
文献信息 Literature information	参考文献 References

Analysis







- **Q_{10}的频率分布为偏正态，分布范围为1.09–6.24，平均值(±标准误差)为2.37(± 0.04)(n = 399)，中位数为2.20，大多数(72%)分布在1.5–3.0之间**
- **Van't Hoff方程的决定系数R^2有85%大于0.60**
- **不同森林类型之间Q_{10}差异不显著**

郑甲佳等, 2020, 植物生态学报

Analysis

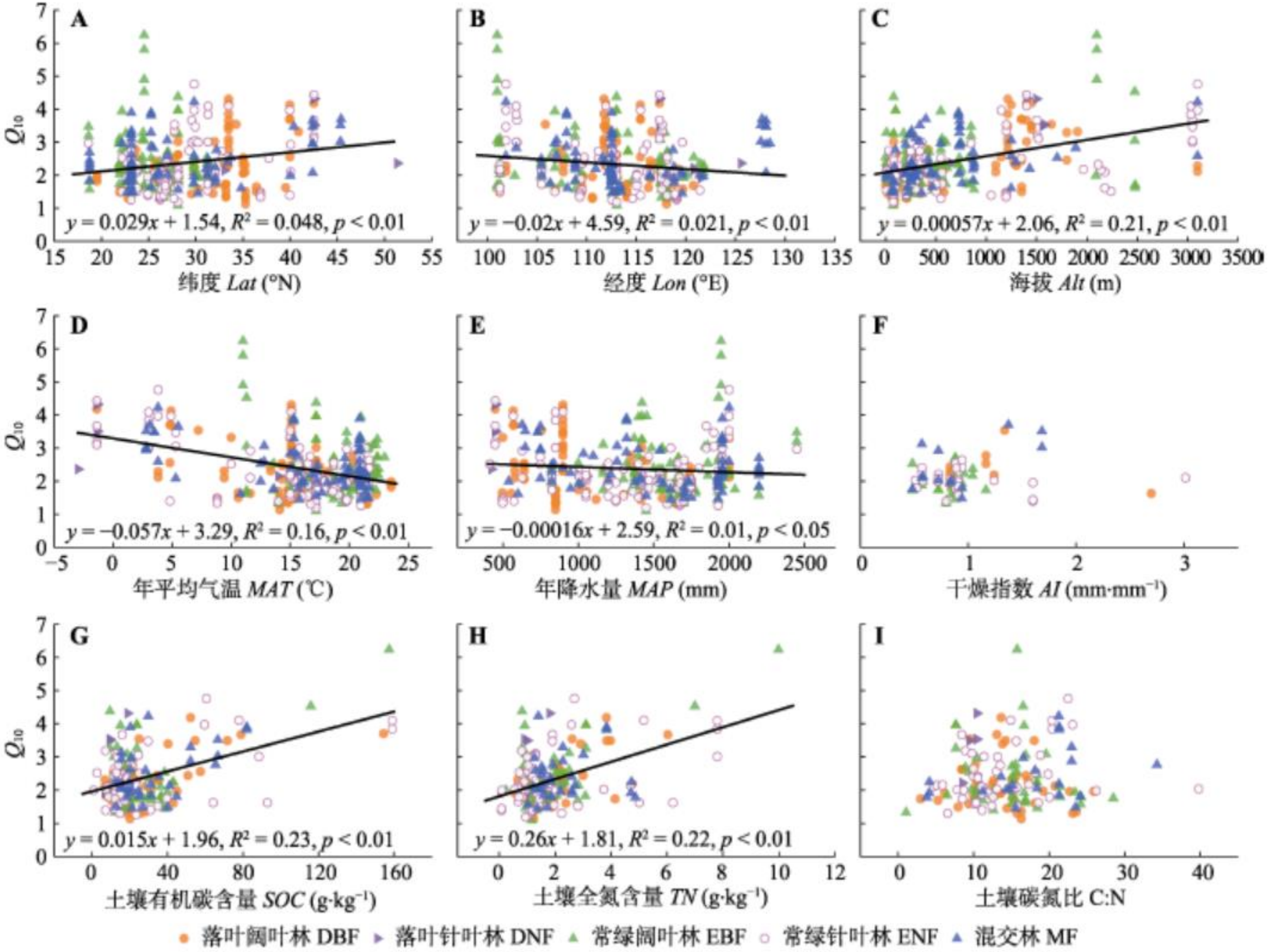
ANCOVA

Lon, $F_{1,398}$ = 9.03, p < 0.01
Stand type, $F_{4,398}$ = 3.21, p < 0.01
Lon × Stand type, $F_{4,398}$ = 4.78, p < 0.01

MAP, $F_{1,397}$ = 4.00, p = 0.04
Stand type, $F_{4,397}$ = 1.81, p = 0.13
MAP × Stand type, $F_{4,397}$ = 2.66, p = 0.03

AI, $F_{1,79}$ = 1.12, p = 0.29
Stand type, $F_{3,79}$ = 4.09, p < 0.01
AI × Stand type, $F_{3,79}$ = 4.05, p = 0.01

TN, $F_{1,206}$ = 62.50, p < 0.01
Stand type, $F_{4,206}$ = 2.27, p = 0.06
TN × Stand type, $F_{4,206}$ = 3.33, p = 0.02



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影响因素 Effect factor	森林类型 Forest type	回归方程 Regression equation	R^2	p	n
纬度 Latitude	DBF	$Y = 0.044x + 0.97$	0.09	<0.01	88
	ENF	$Y = 0.045x + 1.04$	0.10	<0.01	110
	MMF + MBF	$Y = 0.027x + 1.70$	0.08	0.01	75
	MMF	$Y = 0.027x + 1.70$	0.08	0.01	69
经度 Longitude	DNF	$Y = -0.26x + 34.10$	0.60	0.02	8
	EBF	$Y = -0.049x + 7.86$	0.12	<0.01	118
	ENF	$Y = -0.033x + 5.98$	0.06	0.01	110
海拔 Altitude	DBF	$Y = 0.00059x + 1.92$	0.26	<0.01	88
	DNF	$Y = 0.0012x + 2.03$	0.83	<0.01	8
	EBF	$Y = 0.00063x + 2.06$	0.17	<0.01	117
	ENF	$Y = 0.00044x + 2.01$	0.28	<0.01	104
	MMF+MBF	$Y = 0.00041x + 2.20$	0.13	<0.01	73
	MMF	$Y = 0.00041x + 2.20$	0.13	<0.01	67
年平均温度 Mean annual temperature	DBF	$Y = -0.052x + 3.11$	0.10	<0.01	85
	EBF	$Y = -0.076x + 3.78$	0.08	<0.01	118
	ENF	$Y = -0.067x + 3.35$	0.30	<0.01	110
	MMF+MBF	$Y = -0.053x + 3.31$	0.22	<0.01	75
	MMF	$Y = -0.051x + 3.30$	0.21	<0.01	69
平均年降水量 Mean annual precipitation	DNF	$Y = -0.0025x + 4.72$	0.59	0.03	8
干旱指数 Aridity Index	MMF+MBF	$Y = 1.06x + 1.45$	0.36	0.03	13
	MMF	$Y = 1.06x + 1.45$	0.36	0.03	13
土壤有机碳含量 Soil organic carbon content	DBF	$Y = 0.016x + 1.85$	0.31	<0.01	54
	EBF	$Y = 0.020x + 1.84$	0.26	<0.01	61
	ENF	$Y = 0.012x + 2.02$	0.22	<0.01	62
	MMF+MBF	$Y = 0.019x + 1.84$	0.26	<0.01	34
	MMF	$Y = 0.020x + 1.85$	0.25	<0.01	29
土壤全氮含量 Soil total nitrogen content	DBF	$Y = 0.35x + 1.54$	0.35	<0.01	46
	EBF	$Y = 0.41x + 1.59$	0.44	<0.01	61
	ENF	$Y = 0.18x + 1.89$	0.17	<0.01	62

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地理差异响应

- 在DBF、ENF、 MF中Q_{10}随纬度的增加而增大, 而在DNF和EBF中Q_{10}不随纬度变化
- 在DNF、EBF、ENF中Q_{10}随经度的增加而减小, 而在DBF和MF中Q_{10}不随经度变化
- 在5种森林类型中Q_{10}均随海拔增加而增大, 但DNF中Q_{10}随海拔增加而增大的幅度高于其他森林类型

气候差异响应

- 在DBF、EBF、ENF、MF中Q_{10}随MAT的增加而减小, 而在DNF中Q_{10}与MAT无显著关系
- 在DNF中Q_{10}随MAP的增加而减小, 而其余林型中Q_{10}与MAP无显著关系
- 在MF中Q_{10}随AI的增加而增大, 其余林型中Q_{10}与AI无显著关系。

土壤差异响应

- 在DBF、EBF、ENF、MF中Q_{10}随SOC的增加而增大, 在DNF中Q_{10}不随SOC变化
- 在EBF、DBF、ENF中Q_{10}随TN的增加而增大, 且Q_{10}对TN的敏感性在EBF中最高，在ENF中最低; 在DNF、MF中Q_{10}不随TN变化。

Analysis

表2 土壤呼吸温度敏感性(Q_{10})与气候(MAT、MAP)和土壤因素(SOC、TN)的多元线性回归

Table 2 Multiple linear regression of the temperature sensitivity of soil respiration (Q_{10}) with climate (MAT, MAP) and soil factors (SOC, TN)

森林类型 Forest type	回归方程 Regression equation	R^2	F	p	n
DBF	$Q_{10} = -0.027MAT + 0.334TN + 2.00$	0.38	13.06	<0.01	46
DNF	$Q_{10} = -0.099MAT + 0.066SOC + 2.81$	0.99	99.86	<0.01	6
EBF	$Q_{10} = -0.001MAP + 0.451TN + 2.92$	0.50	28.38	<0.01	61
ENF	$Q_{10} = -0.060MAT + 0.006SOC + 3.11$	0.44	22.97	<0.01	61
MF	$Q_{10} = -0.041MAT + 0.014SOC + 2.72$	0.33	6.30	<0.01	29
All	$Q_{10} = -0.047MAT + 0.012SOC + 2.83$	0.33	49.55	<0.01	208

n, 样本量大小。DBF, 落叶阔叶林; DNF, 落叶针叶林; EBF, 常绿阔叶林; ENF, 常绿针叶林; MF, 混交林。*MAP*, 年降水量; *MAT*, 年平均气温; *SOC*, 土壤有机碳含量; *TN*, 土壤全氮含量.

n, sample size. DBF, deciduous broadleaf forest; DNF, deciduous needleleaf forest; EBF, evergreen broadleaf forest; ENF, evergreen needleleaf forest; MF, mixed forest. *MAP*, mean annual precipitation; *MAT*, mean annual temperature; *SOC*, soil organic carbon content; *TN*, soil total nitrogen content.

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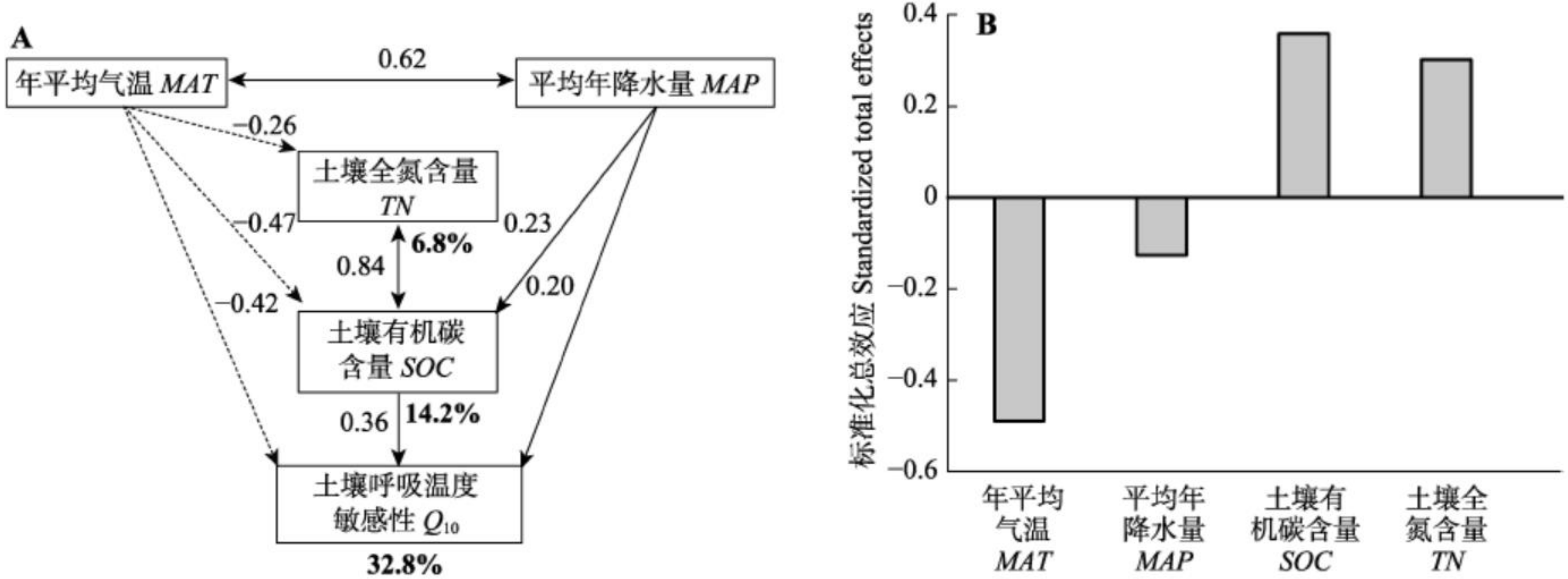
Analysis



- Q_{10}的空间变异受气候(MAT、 MAP)和土壤(SOC、 TN)因素的综合影响
- SOC和MAP直接提高Q_{10}, MAP还通过SOC间接提高Q_{10}; MAT既能直接降低Q_{10}, 也能通过TN和SOC间接降低Q_{10}
- Q_{10}的空间变异主要受MAT和SOC影响, 其次是TN和MAP。

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Take-home message

- Q_{10}在空间上有一定的集中趋势, 但仍存在较大空间变异(Q_{10} did not differ significantly among forest types, but showed large spatial variability)
- Q_{10}随MAT和MAP的增加而减小, 随SOC和TN的增加而增大(Q_{10} decreased with increasing MAT and MAP, and increased with SOC and TN)
- 气候和土壤因子可解释33%的Q_{10}空间变异, MAT和SOC是Q_{10}空间变异的主要影响因素 (Climatic and edaphic factors explained 33% of spatial variability in Q_{10}, MAT and SOC are the primary factors affecting Q_{10})
- 不同森林类型中Q_{10}的主要影响因素存在差异, 且对环境因子的响应不一致(Environmental controls on Q_{10} differ among forest types, and Q_{10} responded differently to environmental factors among forest types)

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中国森林生态系统土壤呼吸温度敏感性空间变异特征及影响因素

郑甲佳[1,2] 黄松宇[1,2] 贾 昕[1,2,3*] 田 赟[1,3] 牟 钰[1,2] 刘 鹏[1,2] 查天山[1,2,3]

[1]北京林业大学水土保持学院, 北京 100083; [2]宁夏盐池毛乌素沙地生态系统国家定位观测研究站, 北京 100083; [3]北京林业大学水土保持国家林业和草原局重点实验室, 北京 100083

摘 要 土壤呼吸的温度敏感性(Q_{10})是陆地碳循环与气候系统间相互作用的关键参数。尽管已有大量关于不同类型森林土壤呼吸Q_{10}季节和年际变化规律的研究, 但是对Q_{10}在区域尺度的空间变异特征及其影响因素仍认识不足, 已有结果缺乏一致结论。该研究通过整合已发表论文, 构建了中国森林生态系统年尺度Q_{10}数据集, 共包含399条记录、5种森林类型(落叶阔叶林(DBF)、落叶针叶林(DNF)、常绿阔叶林(EBF)、常绿针叶林(ENF)、混交林(MF))。分析了不同森林类型土壤呼吸Q_{10}的空间变异特征及其与地理、气候和土壤因素的关系。结果显示, 1) Q_{10}介于1.09到6.24之间, 平均值(±标准误差)为2.37 (± 0.04), 且在不同森林类型之间无显著差异; 2)当考虑所有森林类型时, Q_{10}随纬度、海拔、土壤有机碳含量(*SOC*)和土壤全氮含量(*TN*)的增加而增大, 随经度、年平均气温(*MAT*)、平均年降水量(*MAP*)的增加而减小。气候(*MAT*、*MAP*)和土壤(*SOC*、*TN*)因素间存在相互作用, 共同解释了33%的Q_{10}空间变异, 其中*MAT*和*SOC*是Q_{10}空间变异的主要驱动因素; 3)不同类型森林土壤呼吸Q_{10}对气候和土壤因素的响应存在差异。在DNF中Q_{10}随*MAP*的增加而减小, 而其他类型森林中Q_{10}与*MAP*无显著相关性; 在EBF、DBF、ENF中Q_{10}随*TN*的增加而增大, 但Q_{10}对*TN*的敏感性在EBF中最高, 在ENF中最低。这些结果表明, 尽管Q_{10}有一定的集中分布趋势, 但仍有较大范围的空间变异, 在进行碳收支估算时应注意尺度问题。Q_{10}的主要驱动因素和Q_{10}对环境因素的响应随森林类型而变化, 在气候变化情景下, 不同森林类型间Q_{10}可能发生分异。因此, 未来的碳循环-气候模型还应考虑不同类型森林碳循环关键参数对气候变化的响应差异。

关键词 土壤呼吸; 温度敏感性; 碳循环; CO_2通量; 土壤碳通量

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Spatial variation and controlling factors of temperature sensitivity of soil respiration in forest ecosystems across China

ZHENG Jia-Jia[1,2], HUANG Song-Yu[1,2], JIA Xin[1,2,3*], TIAN Yun[1,3], MU Yu[1,2], LIU Peng[1,2], and ZHA Tian-Shan[1,2,3]

[1]School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China; [2]Yanchi Ecology Research Station of Mau Us Desert, Beijing 100083, China; and [3]Key Laboratory of State Forestry and Grassland Administration on Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

Abstract

Aims Our objective was to determine the spatial variation of the temperature sensitivity of soil respiration (Q_{10}) and it's controlling factors in forest ecosystems across China.

Methods Based on published papers, the field measurement data of soil respiration were collected to build the dataset of annual Q_{10} in forest ecosystems across China. Further, the spatial variation and the drivers of Q_{10} in different forest types were analyzed.

Important findings The results showed that 1) Q_{10} ranges from 1.09 to 6.24, with a mean value (± standard error) of 2.37 (± 0.04) and no significant difference among different forest types; 2) When all forest types were considered, Q_{10} increased with increasing latitude, altitude, soil organic carbon content (*SOC*) and soil total nitrogen content (*TN*), but decreased with increasing longitude, mean annual temperature (*MAT*) and mean annual precipitation (*MAP*). Climate (*MAT, MAP*) and soil (*SOC, TN*) factors together explained 32.8% variations in Q_{10}. *MAT*

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* 通信作者Corresponding author (xinjia@bjfu.edu.cn)

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1. 附录I 中国森林生态系统年尺度土壤呼吸温度敏感性(Q10)数据集.xlsx (242KB)
2. 附录II 不同森林类型的土壤呼吸温度敏感性(Q10)与影响因素之间的线性回归.pdf (302KB)
3. 附录III 不同森林类型的土壤呼吸温度敏感性(Q10)(平均值±标准误差)。.pdf (295KB)

Dataset freely available at
https://www.plant-ecology.com/CN/10.17521/cjpe.2019.0300


谢 谢!
Thanks for your attention!