LPICEA | Lab of Plant Interactions: Climate, Ecosystem & Atmosphere
Department of Earth System Science | Tsinghua University

Understanding and Predicting Ecosystem Processes from Eco-evolutionary Optimality Theory

Han Wang

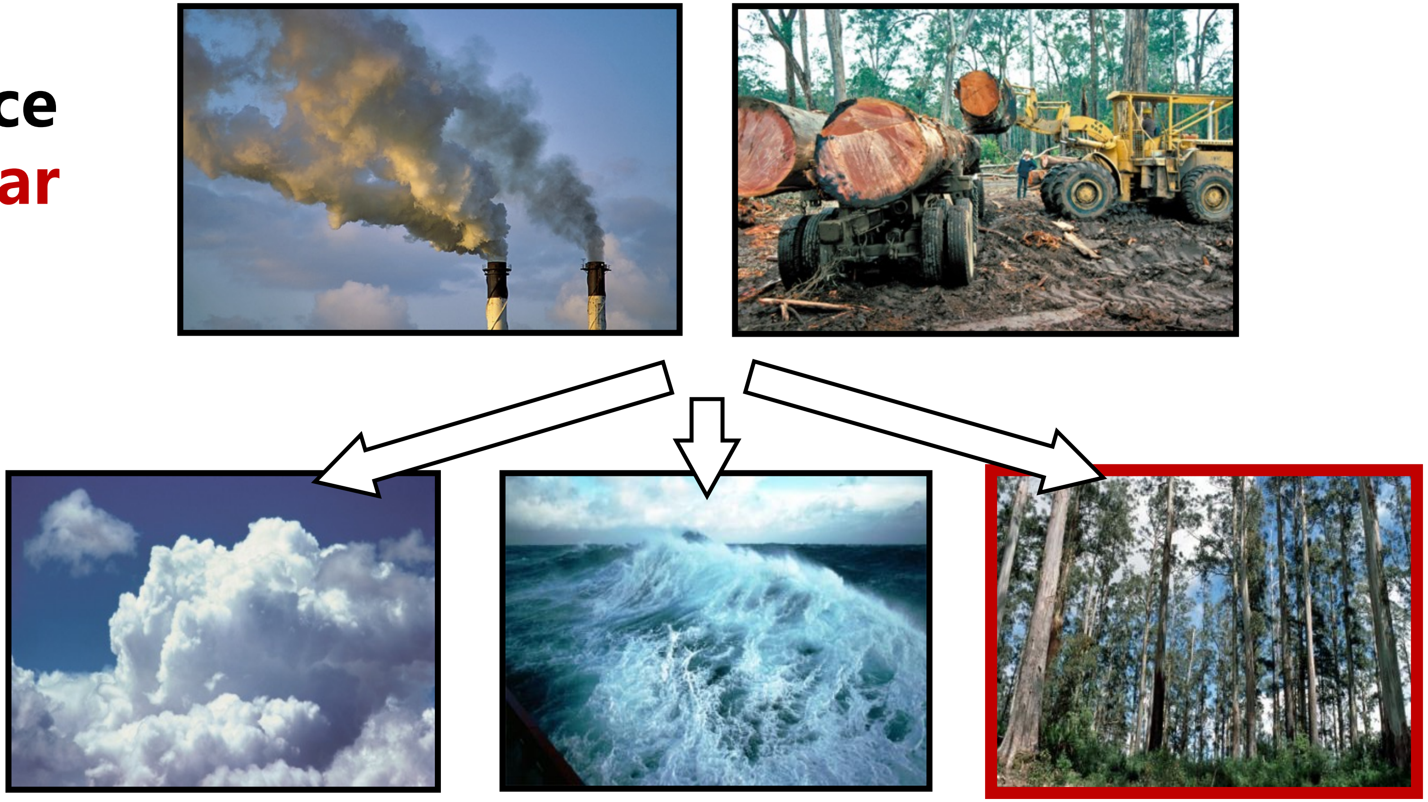
Department of Earth System Science, Tsinghua University

2021-10-27

Background

Understanding and predicting plant carbon processes is key for modelling the global carbon cycle and developing the natural-based solutions

Carbon source
10.7 PgC/year



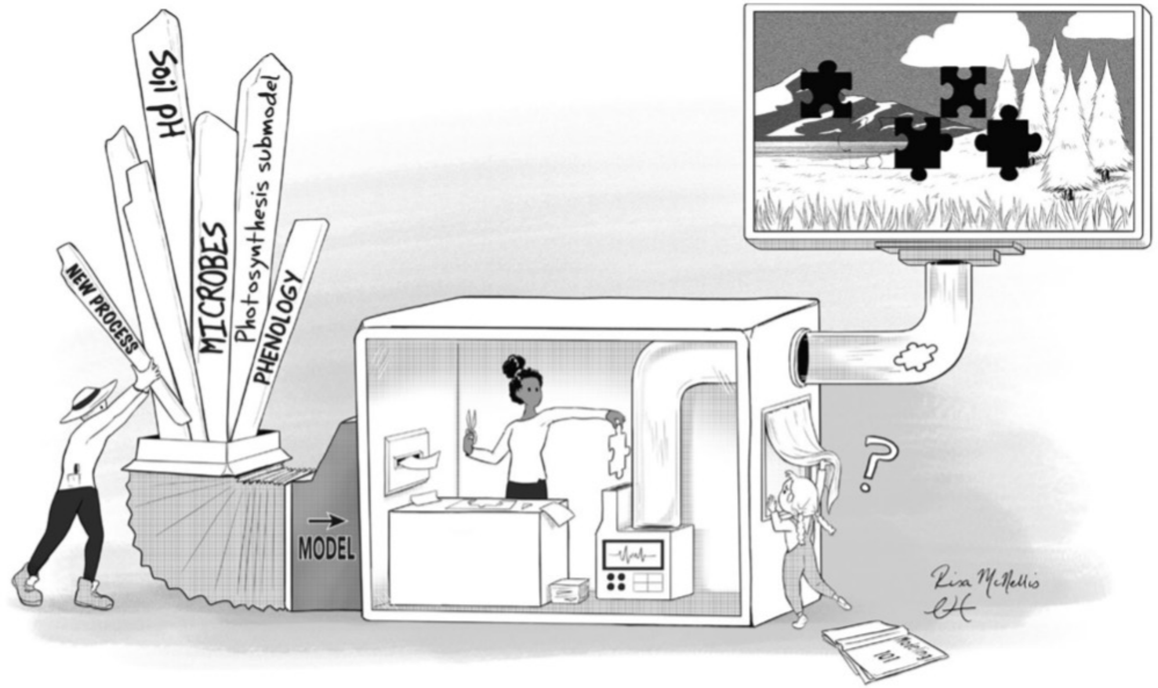
Carbon sink

Atmosphere 43% Ocean 22% **Land 28%**

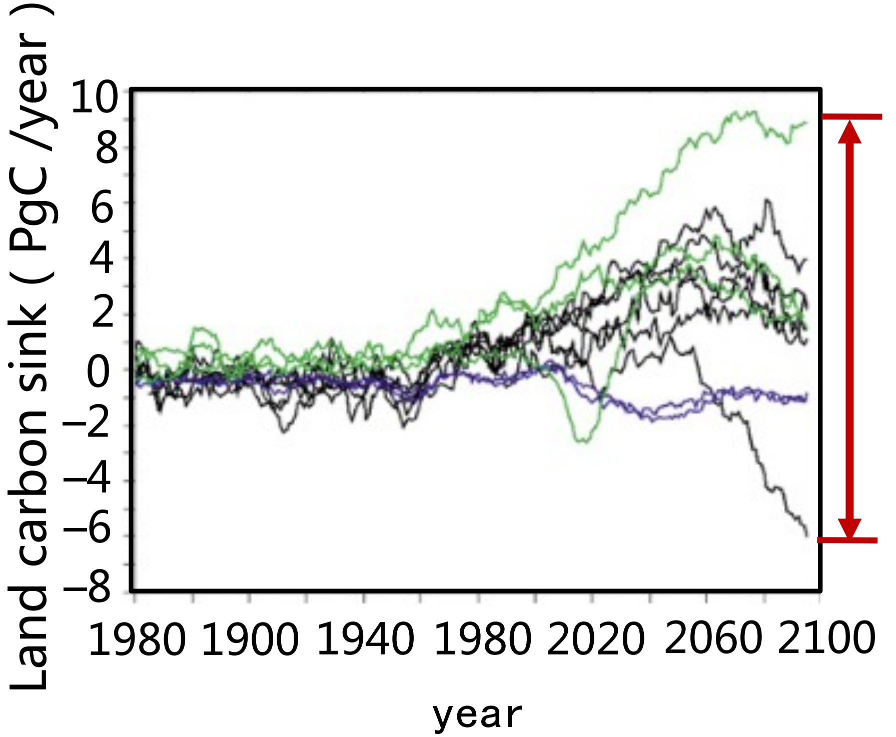
Le Quere *et al.* 2018, *Earth System Science Data*

Challenges

- **Unsatisfactory collaboration between ecologists and modellers**
- **Unreliable prediction on future land carbon sink**



Dorothy pulled back the curtain to find that the model wasn't magic after all...

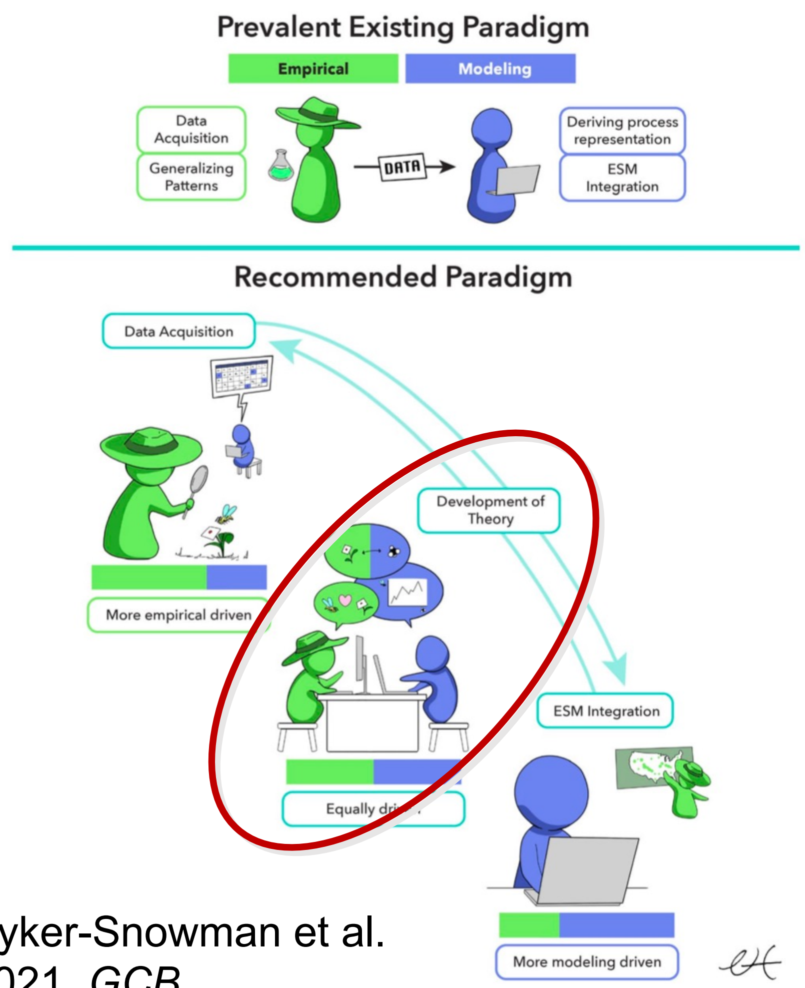


Kyker-Snowman et al. 2021,
Global Change Biology

Friedlingstein *et al.* 2014,
Journal of Climate

Opportunities : EEO theory

- **Eco-evolutionary Optimality Theory: plants adapt to their surrounding environments to maximize their net carbon gain in a long-term run**



Kyker-Snowman et al. 2021, *GCB*

PERSPECTIVE
https://doi.org/10.1038/s41477-020-0655-x
nature plants

Organizing principles for vegetation dynamics

Oskar Franklin[1,2], Sandy P. Harrison[3], Roderick Dewar[4,5], Caroline E. Farrior[6], Åke Brännström[1,7], Ulf Dieckmann[1,8], Stephan Pietsch[1], Daniel Falster[9], Wolfgang Cramer[10], Michel Loreau[11], Han Wang[12], Annikki Mäkelä[13], Karin T. Rebel[14], Ehud Meron[15,16], Stanislaus J. Schymanski[17], Elena Rovenskaya[1], Benjamin D. Stocker[18,19], Sönke Zaehle[20], Stefano Manzoni[21,22], Marcel van Oijen[23], Ian J. Wright[24], Philippe Ciais[25], Peter M. van Bodegom[26], Josep Peñuelas[19,27], Florian Hofhansl[1], Cesar Terrer[28], Nadejda A. Soudzilovskaia[26], Guy Midgley[29] and I. Colin Prentice[12,24,30]

New Phytologist
TANSLEY REVIEWS

Eco-evolutionary optimality as a means to improve vegetation and land-surface models

Sandy P. Harrison[1,2], Wolfgang Cramer[3], Oskar Franklin[4,5], Iain Colin Prentice[2,6,7], Han Wang[2], Åke Brännström[4,8], Hugo de Boer[9], Ulf Dieckmann[4,10], Jaideep Joshi[4], Trevor F. Keenan[11,12], Aliénor Lavergne[13], Stefano Manzoni[14], Giulia Mengoli[6], Catherine Morfopoulos[6], Josep Peñuelas[15,16], Stephan Pietsch[4,17], Karin T. Rebel[9], Youngryel Ryu[18], Nicholas G. Smith[19], Benjamin D. Stocker[20,21] and Ian J. Wright[7]

Opportunities：LEMONTREE

➢ **Succeed in international grant application to make the big idea happen**

Providing Support for Cutting-edge Climate Models

Overview

To advance this goal, we solicited ambitious proposals from multidisciplinary and multinational groups focusing on the most fundamental and important questions in Earth system science. The VESRI Advisory Board helped select four projects that demonstrated the greatest potential for transformative improvements in models of the Earth system and its components, Earth observations, and computational tools, and for bringing tools and approaches from outside the climate sciences to bear within it. The groups will train graduate students and postdoctoral fellows in their fields of expertise, in an effort to develop exceptional talent in the climate sciences for decades to come.

Land Ecosystem Models based On New Theory, obseRvations, and ExperimEnts (LEMONTREE)

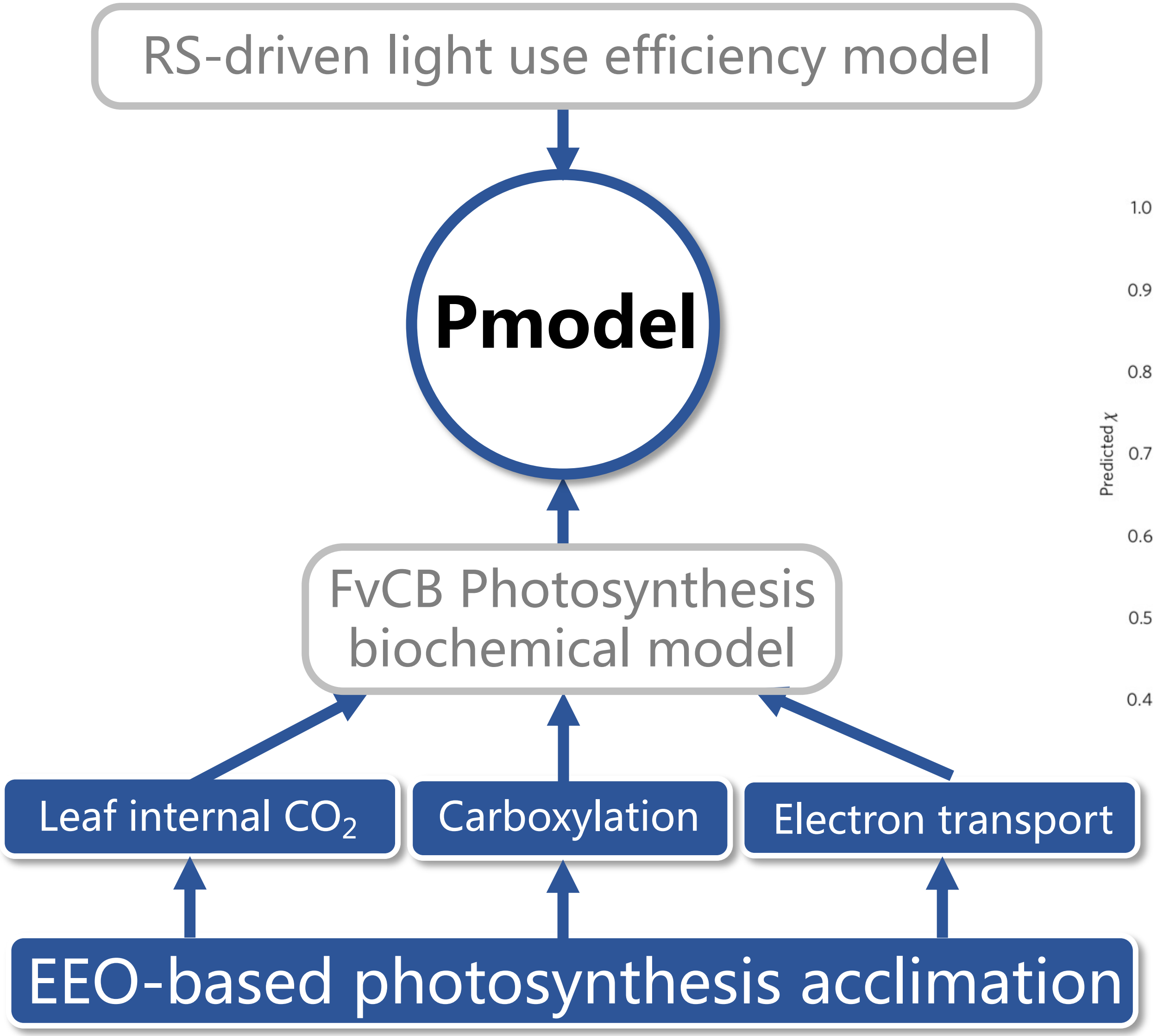
Principal Investigator: Sandy Harrison

Participating Institutions: Reading University, Imperial College London, Columbia, University of Pittsburgh, UC Berkeley, Utrecht University, Seoul National University, Texas Tech University, Tsinghua University, Swiss Federal Institute of Technology in Zurich

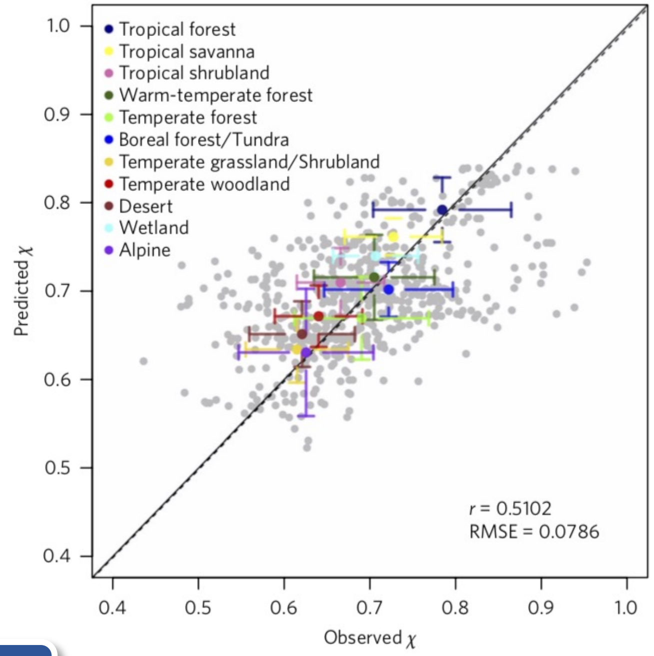
LEMONTREE proposes to develop a next-generation model of the terrestrial biosphere and its interactions with the carbon cycle, water cycle and climate. Their approach would lead to ecosystem models that rest on firm theoretical and empirical foundations, and should eventually yield more reliable projections of future climates. This could give a newfound ability to address issues in sustainability, including the potential to maintain the biosphere’s capacity to regulate the carbon cycle while benefiting human well-being and development.

Opportunities : Pmodel (P for Productivity)

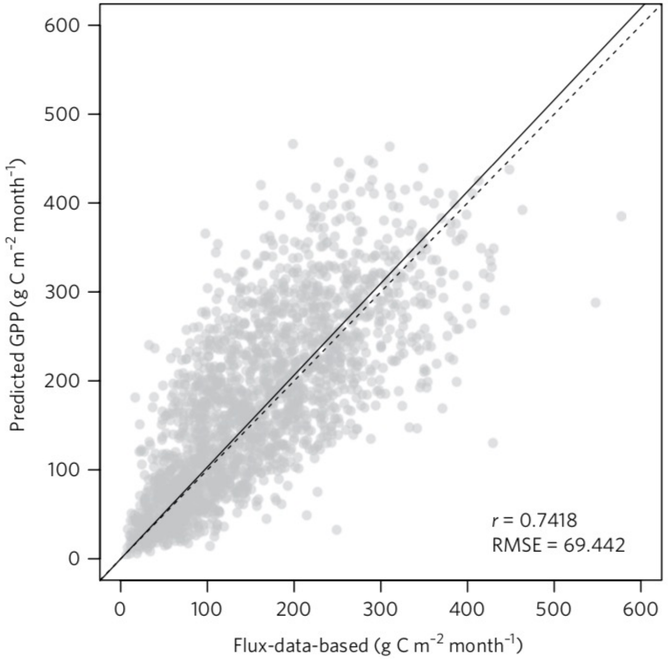
- **Towards a universal model of carbon uptake by plants**



Leaf internal CO_2 concentration



Gross primary Productivity



Wang et al., 2017 *Nature Plants*

Opportunities : Pmodel

- **Pmodel: a universal model for plant carbon uptake with one equation and two parameters**

nature COMMUNICATIONS

Received 24 Mar 2016 | Accepted 30 Sep 2016 | Published 8 Nov 2016 DOI: 10.1038/ncomms13428 OPEN

Recent pause in the growth rate of atmospheric CO_2 due to enhanced terrestrial carbon uptake

Trevor F. Keenan[1,2], I. Colin Prentice[2,3], Josep G. Canadell[4], Christopher A. Williams[5], Han Wang[2,6], Michael Raupach[4,‡] & G. James Collatz[7]

ARTICLES
https://doi.org/10.1038/s41561-019-0318-6
nature geoscience

Drought impacts on terrestrial primary production underestimated by satellite monitoring

nature geoscience
ARTICLES
https://doi.org/10.1038/s41561-019-0436-1

Field-experiment constraints on the enhancement of the terrestrial carbon sink by CO_2 fertilization

seom
scientific exploitation of operational missions
esa

OVERALL GOAL OF TERRA-P https://terra-p.vito.be

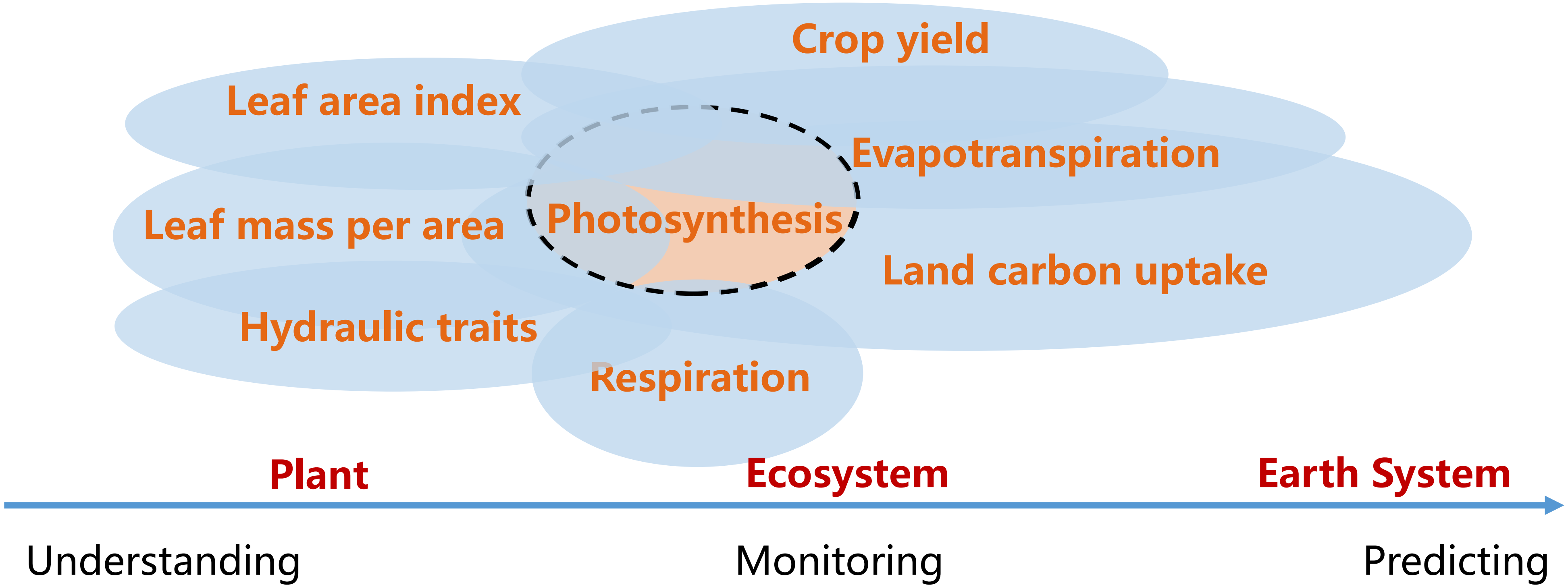
Estimate Gross Primary Production and Aboveground Biomass Production from MERIS and Sentinel-3 data.

The P-model developed by Imperial College London (Wang, H., IC. Prentice, WM Cornwell, TF. Keenan, TW. Davis, IJ. Wright, B.J. Evans and C. Peng (2016) A universal model for carbon dioxide uptake by plants, http://dx.doi.org/10.1101/040246) will be used as a basis for the estimation of GPP. This model starts from first principles, has a firm basis in theory and provides the optimum combination of parsimony, theoretical foundation, and empirical support. It is based on the standard (Farquhar, von Caemmerer and Berry) photosynthesis model while also accounting for acclimation processes that lead to a proportional relationship between GPP and light absorbed, the constant or proportionality varying as a function of environmental variables (temperature, vapour pressure deficit, atmospheric pressure and CO_2). The model has been tested using eddy covariance GPP data derived from flux sites worldwide. This

Starting from Pmodel

Research interests

- **Understanding: environmental effects on plant functional traits**
- **Applying: agriculture and hydrology**
- **Predicting: carbon flux in Land Surface Models**

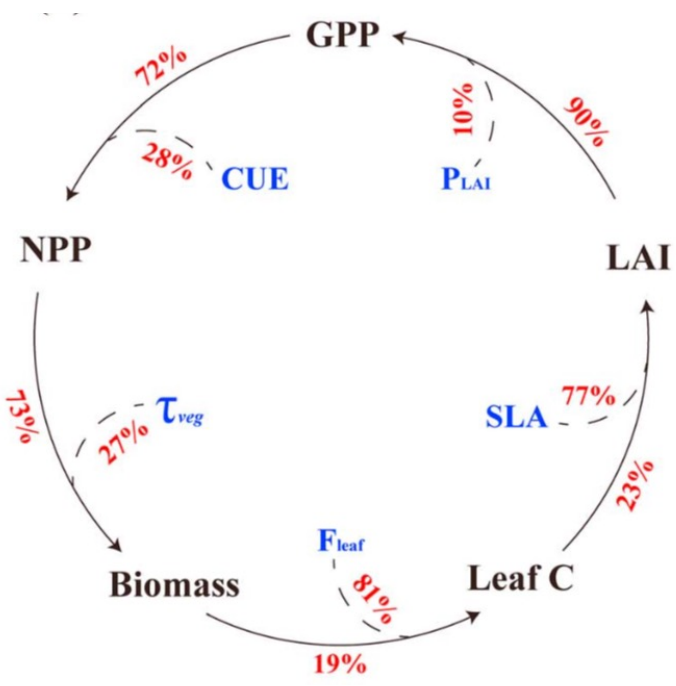


Understanding plant functional traits

Research interests

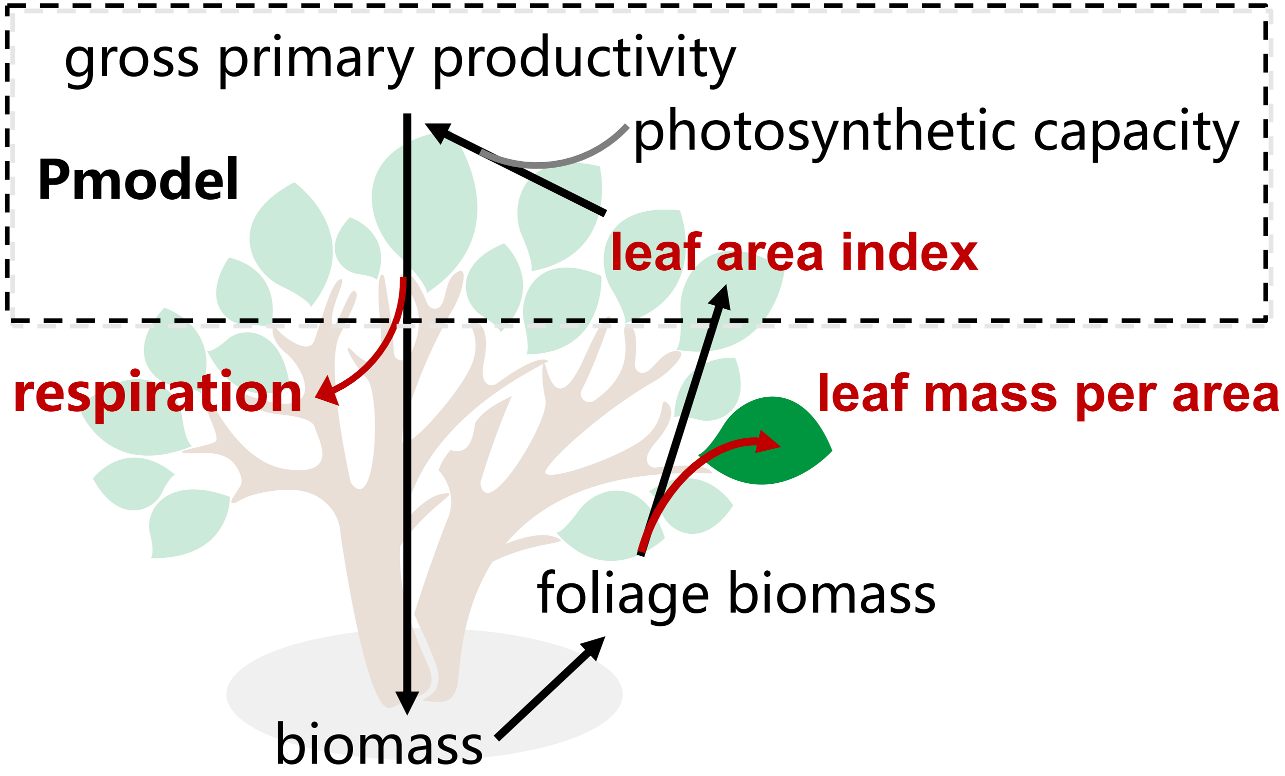
- **Understanding: environmental effects on plant functional traits （photosynthetic capacity, respiration，leaf mass per area，hydraulics，leaf area index）**

Large uncertainties from LAI



Xia et al. 2018 GBC

Plant carbon cycle

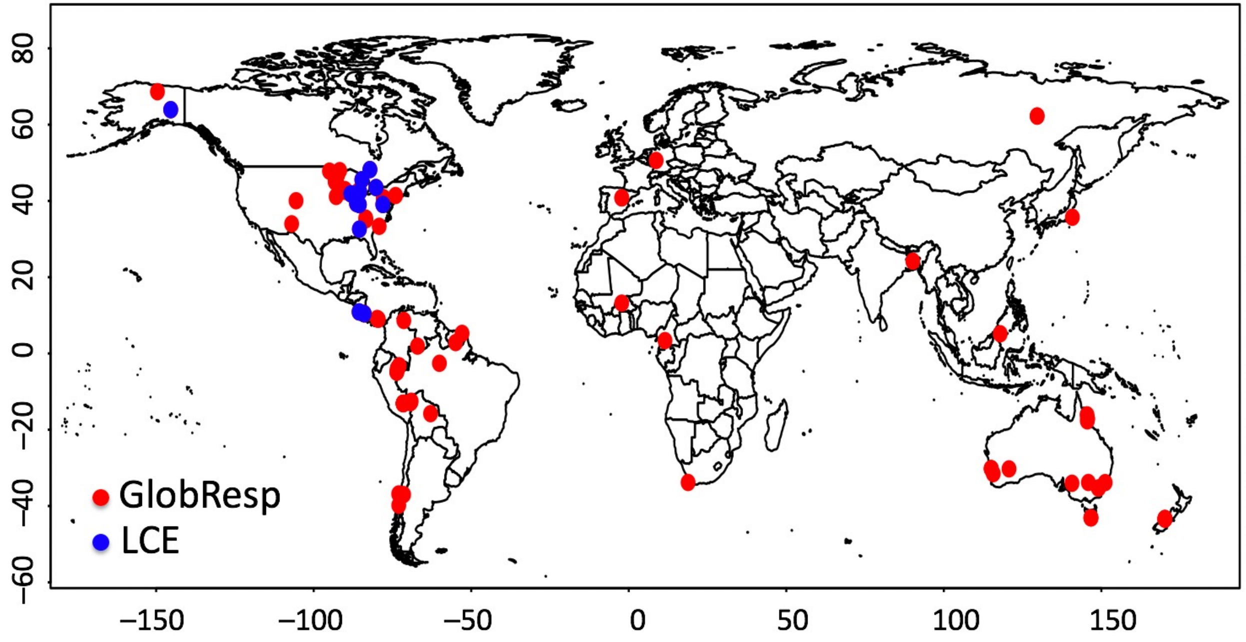


Understanding: leaf respiration acclimation

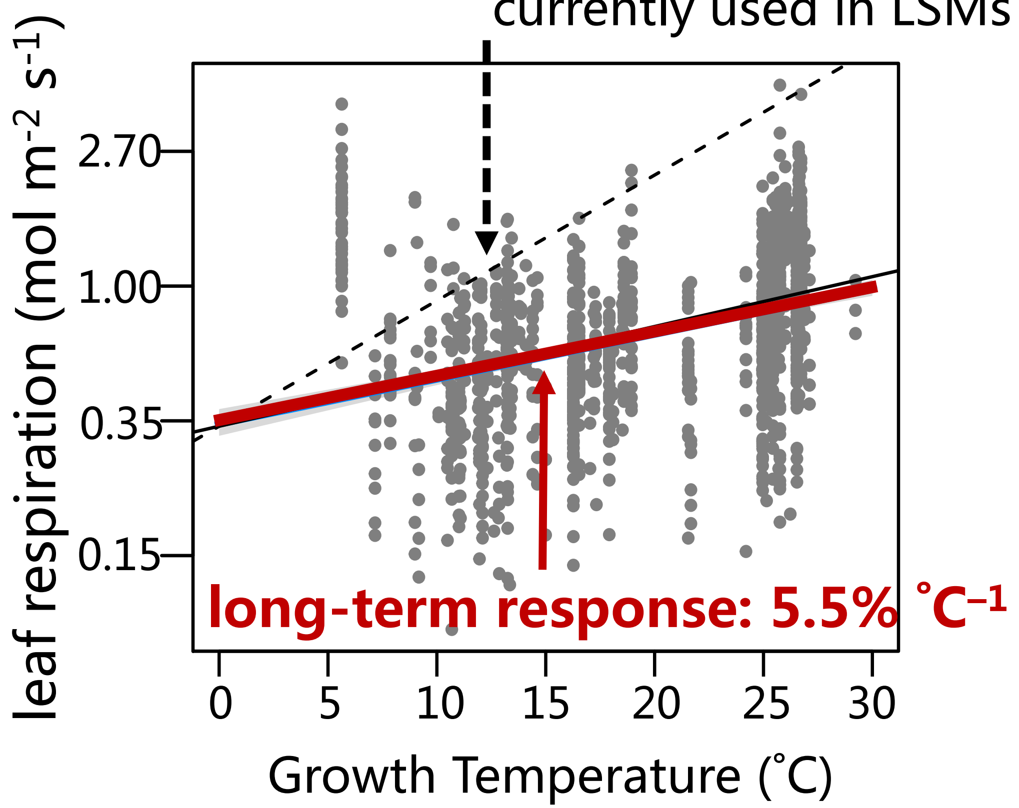
Question

Why warming experiments showed leaf respiration increased in a short-term, but declined in a long-term?

Leaf respiration dataset: 112 field sites globally



Results



Wang* et al., 2020, ***Global Change Biology***

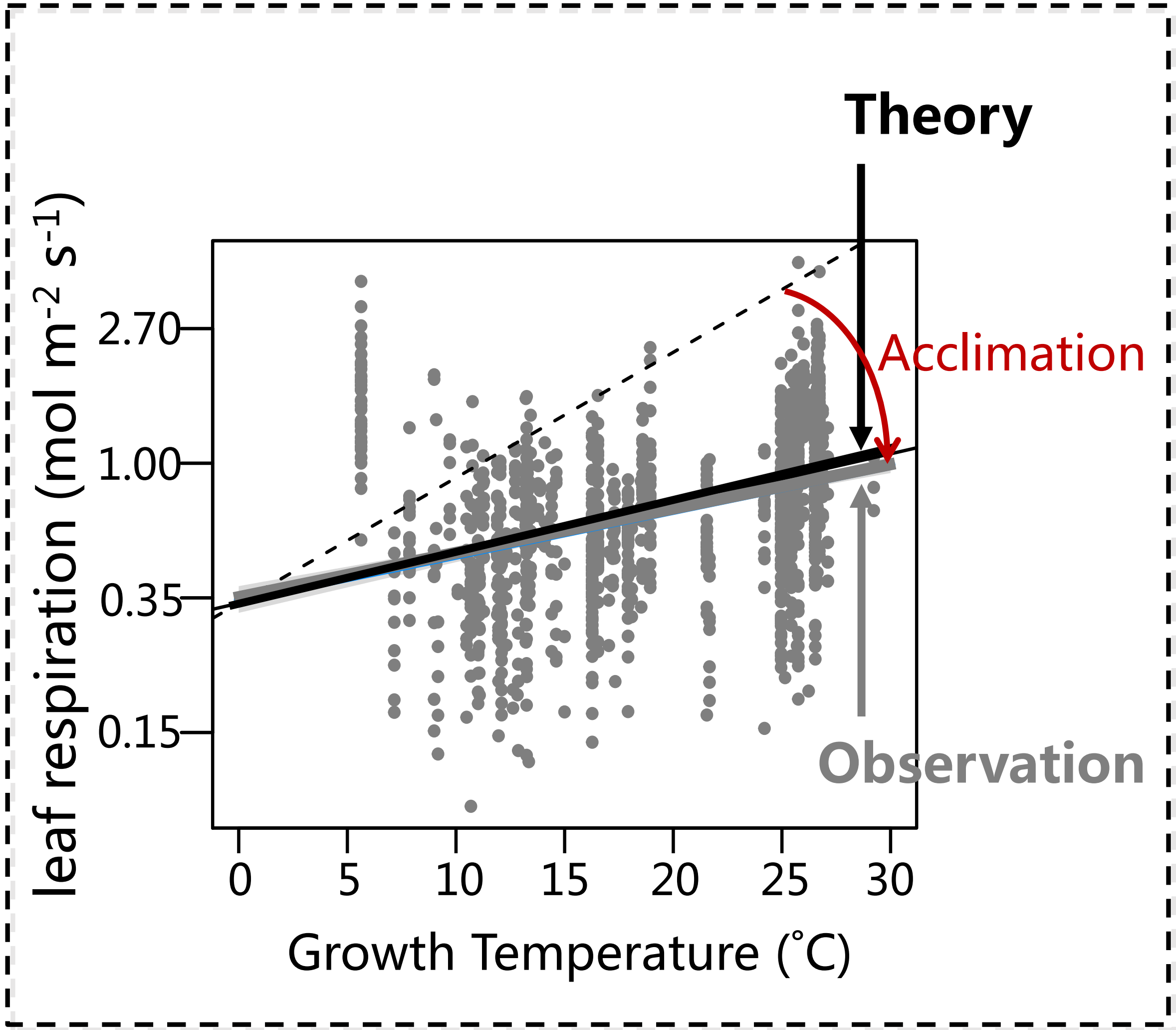
Understanding: leaf respiration acclimation

New theory

A universal leaf respiration acclimation behavior for maintaining the optimal carboxylation capacity

Impacts

Providing a theoretical and empirical basis for implementing respiration acclimation in LSMs



Wang* et al., 2020, ***Global Change Biology***

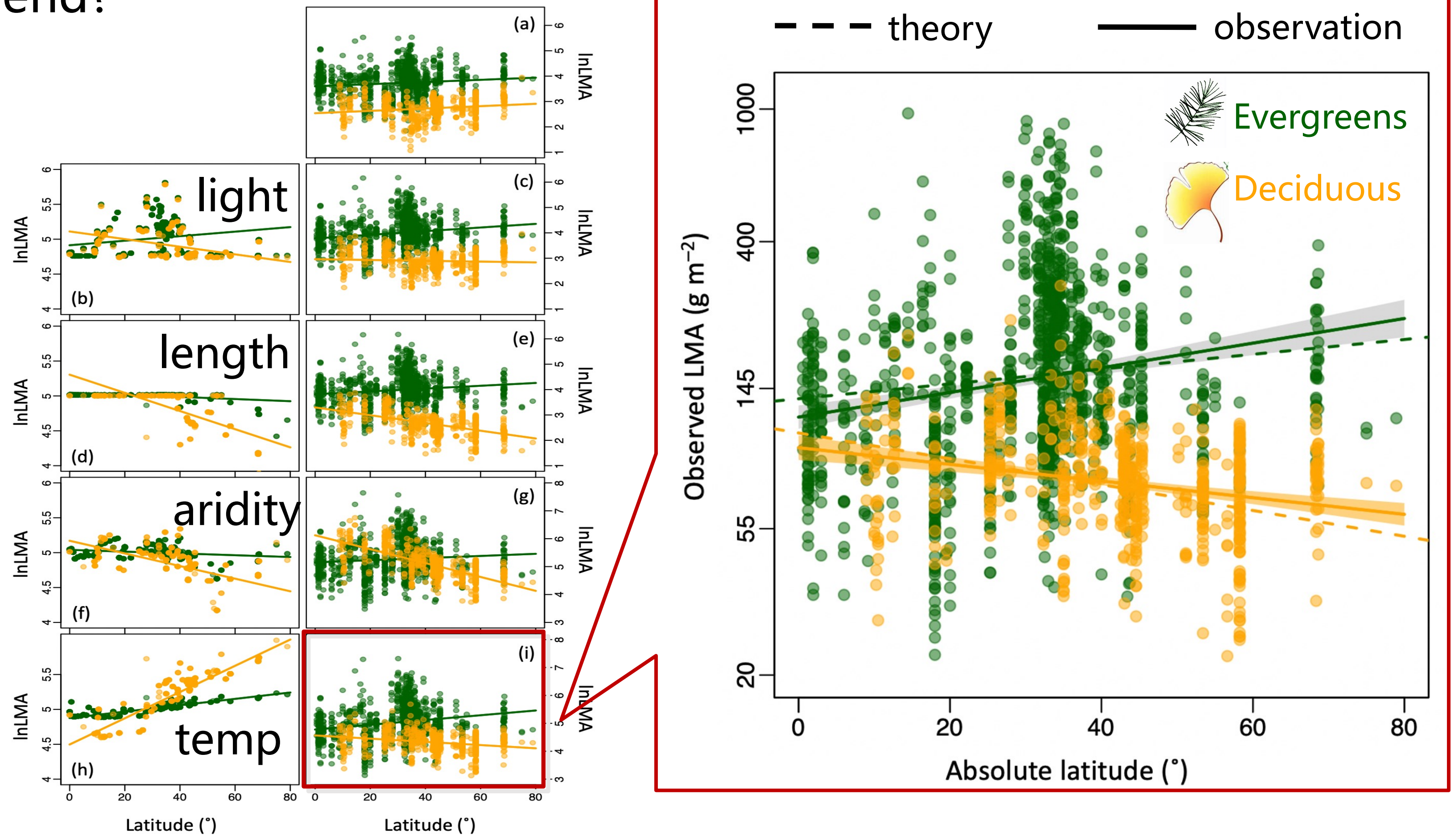
Understanding: leaf mass per area (LMA)

Question

Why do the deciduous leaves become thinner (low LMA) and shorter-lived poleward, while the evergreen leaves show opposite trend?

New theory

Plants maximize their net carbon gain through leaf life cycle. This optimality leads to different natural selection pressures from light, temperature and growing-season length



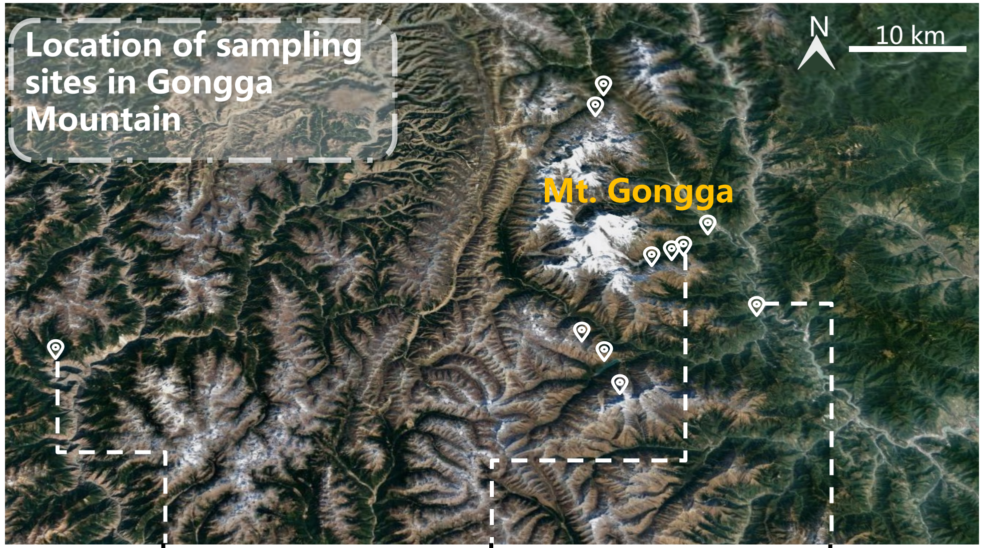
Wang* et al., bioRxiv

Understanding: hydraulics

Question

How do the photosynthesis and water transpiration coordinate?

How do environments affect this coordination?



2019.08
4361 m
Deciduous shrubland

2018.07
2782 m
Deciduous broadleaf forest

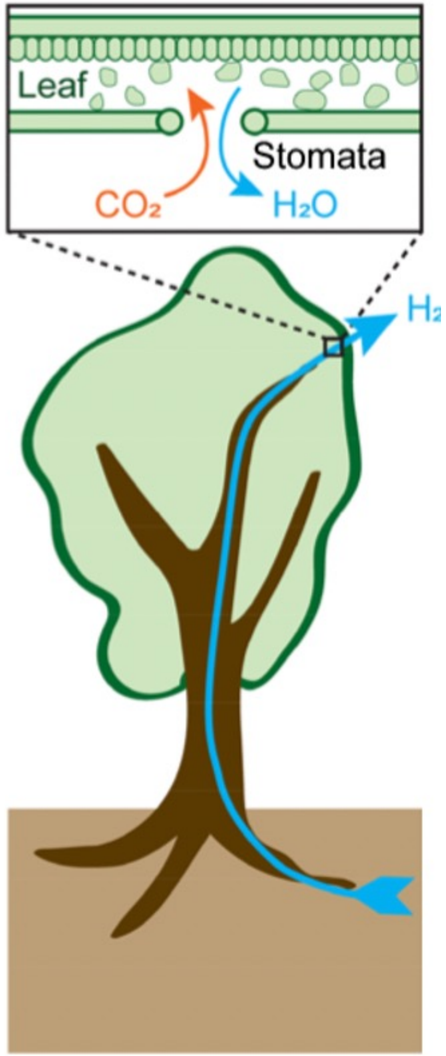
2019.08
1143 m
Deciduous broadleaf forest

11 sites, 176 samples, 107 species
3000-m elevational transect

Hydraulic traits:
- K_S: sapwood conductivity
- π_{tlp}: turgor loss point
- WD: wood density
- v_H: sapwood to leaf area ratio

Photosynthetic trait:
- V_{cmax}: photosynthetic capacity
- χ: c_i/c_a

Leaf economics spectrum trait:
- LMA: leaf mass per area
- N_{area}: leaf nitrogen content



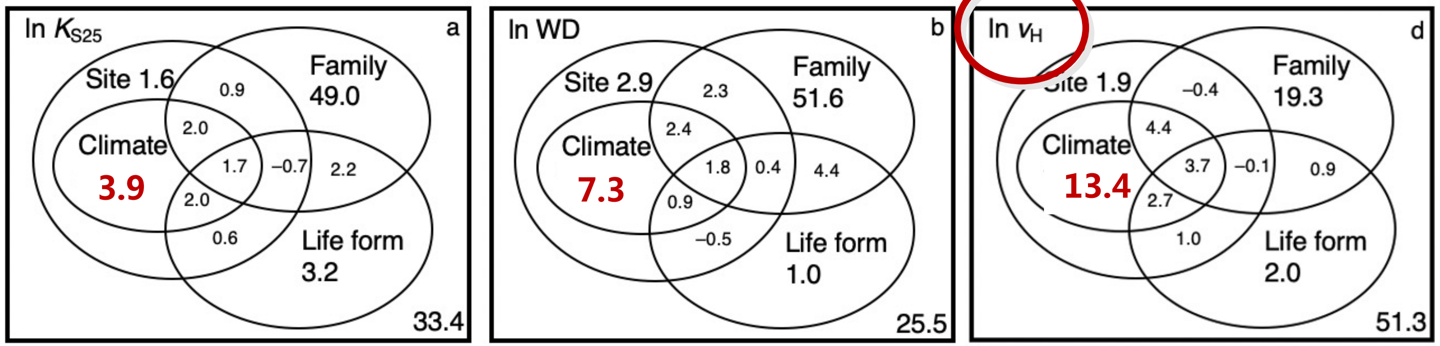
Xu, **Wang*** et al., 2021 ***New Phytologist***

New findings

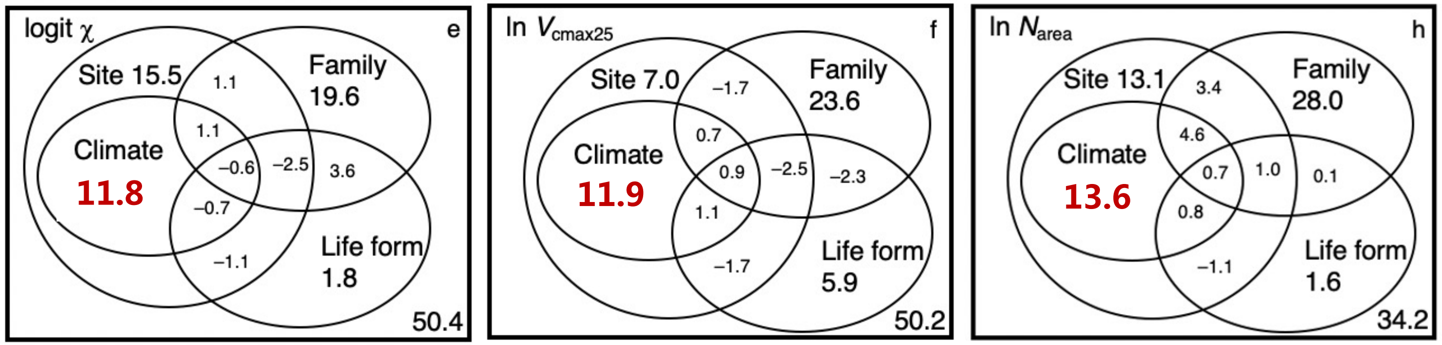
How do the water transpiration and photosynthesis coordinate?

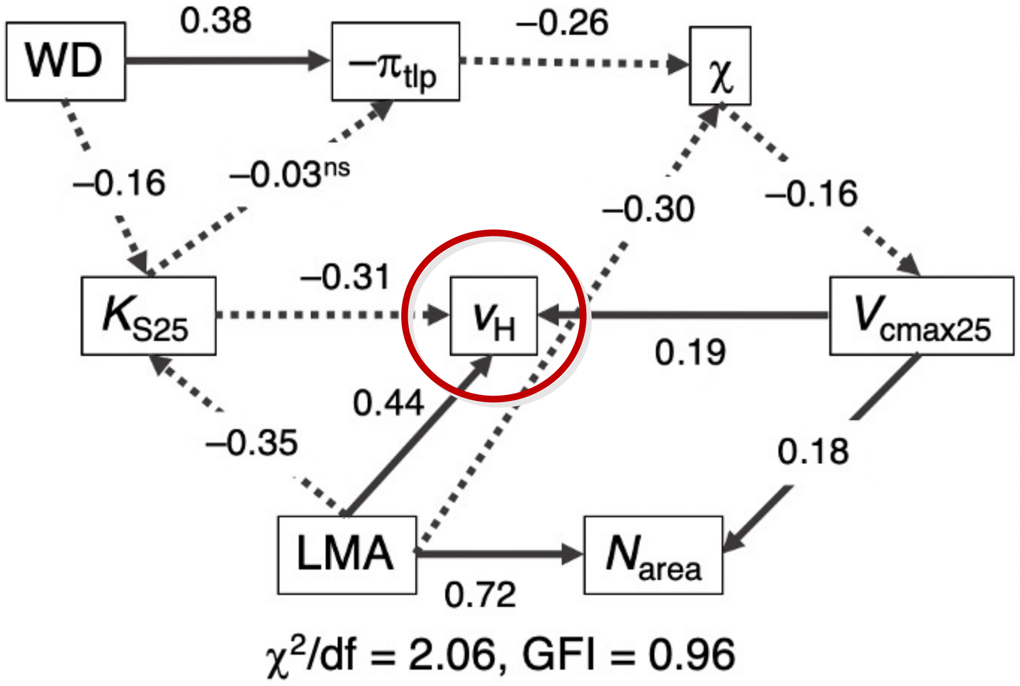
- ➢ **Huber value is the key traits for regulating this coordination**

Hydraulic traits:



Photosynthetic traits:





Xu, **Wang*** et al., 2021 ***New Phytologist***

Understanding: hydraulics

New theory

How do environments affect this coordination? And why in such as way?

- **To maintain the continuous water flow required by the photosynthesis demand**

Water supply

$E = K_S\, \Delta\Psi_{max}\, SA\, \rho_w /(LA\, h)$

$= v_H\, K_S\, \Delta\Psi_{max}\, \rho_w / h$ (Darcy's law)

- K_S ($kg\ s^{-1}\ m^{-1}\ MPa^{-1}$): sapwood conductivity
- $\Delta\Psi_{max}$ (MPa): the maximum difference between leaf and soil water potential
- h (m): path length, approximately equal to plant height
- LA (m^2): leaf area
- SA (m^2): sapwood area
- ρ_w ($kg\ m^{-3}$): water density
- v_H (Huber Value): sapwood to leaf area ratio

=

Water demand

$E = 1.6\, g_s\, D\,,\ \ g_s = A /[c_a(1 - \chi)]$ (Fick's law)

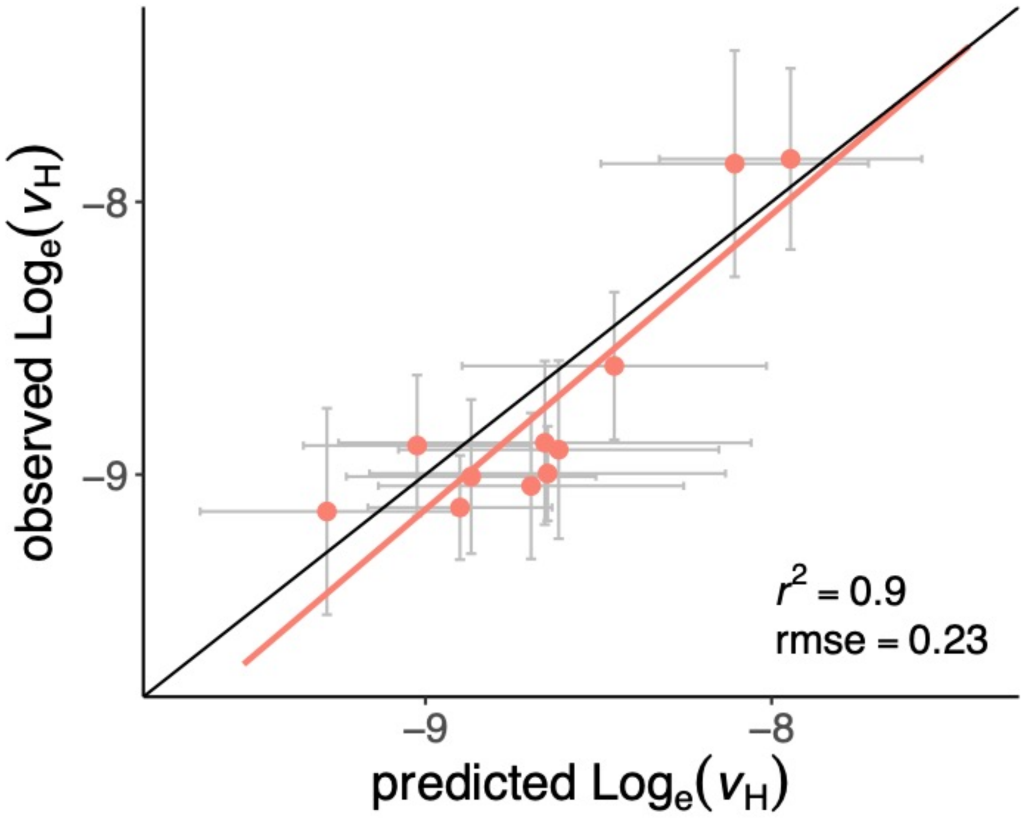
$A = m_C\, V_{cmax}\,,\ \ m_C = (c_i - \Gamma^*)/(c_i + K)$ (Pmodel)

- g_s is stomatal conductance (to CO_2)
- D is leaf-to-air vapour pressure deficit (vpd)
- A is the assimilation (photosynthesis) rate
- c_a is the ambient partial pressure of CO_2
- $\chi = c_i/c_a$
- c_i is the leaf-internal partial pressure of CO_2.
- Γ^* is the photorespiratory compensation point
- K is the effective Michaelis-Menten coefficient of Rubisco
- V_{cmax} is the maximum carboxylation capacity

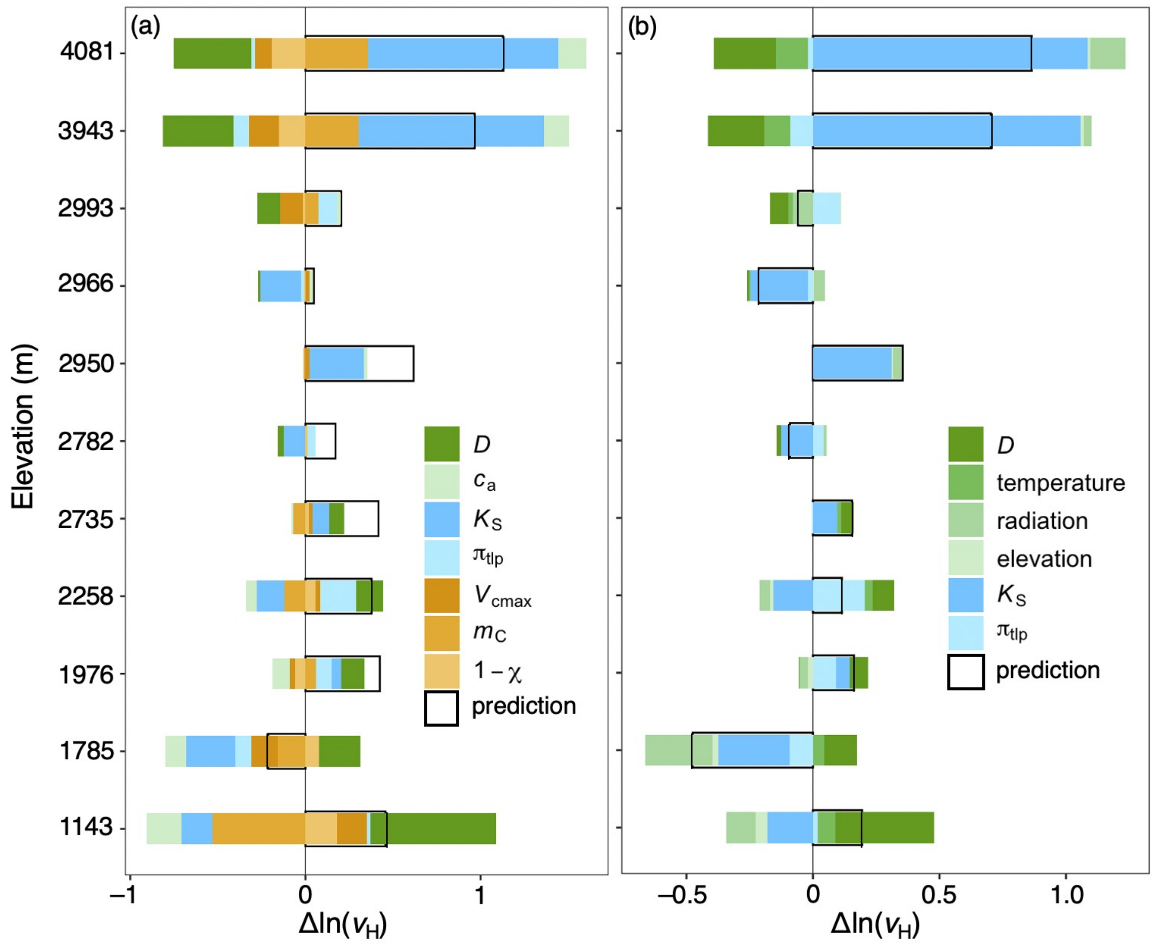
$$\ln v_H = -\ln K_S - \ln \Delta\Psi_{max} + \ln m_C + \ln V_{cmax} - \ln (1-\chi) + \ln D - \ln c_a + \ln h$$

Understanding: hydraulics

- **Predicting site-level Huber value from climate and hydraulic traits**



- **Ks and VPD are the most important variables regulating Huber value in this study**

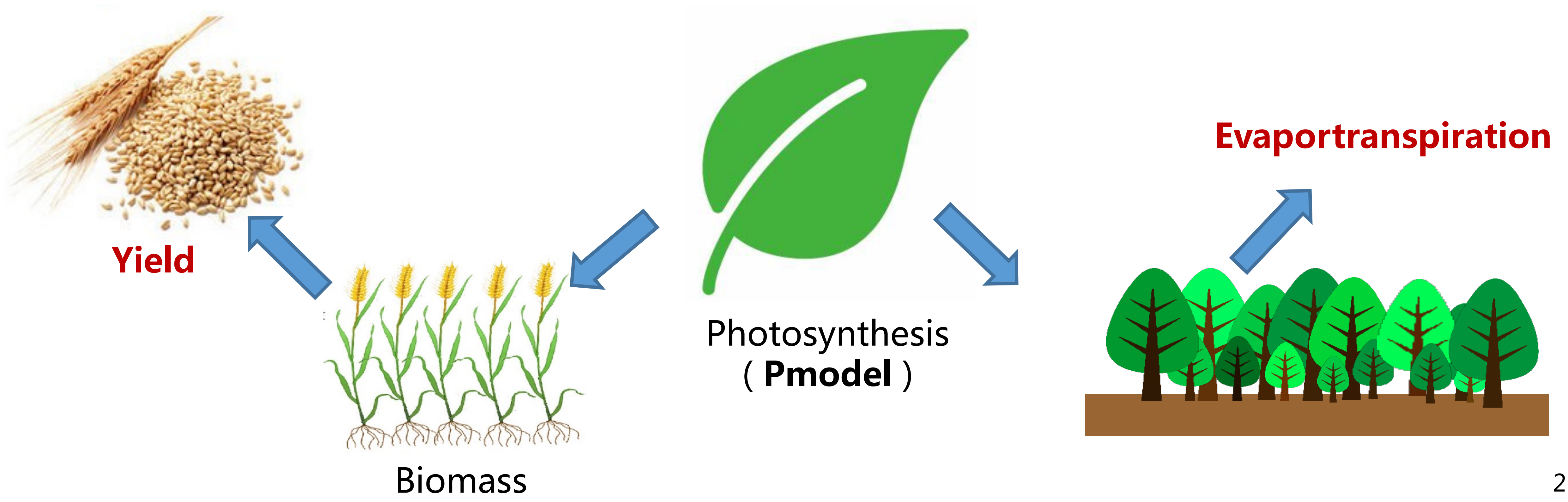


Xu, **Wang*** et al., 2021 ***New Phytologist***

Applying: agriculture and hydrology

Research interest

- Understanding: environmental effects on plant respiration, leaf mass per area
- Applying: agriculture and hydrology



Applying: PCmodel for Crop yield

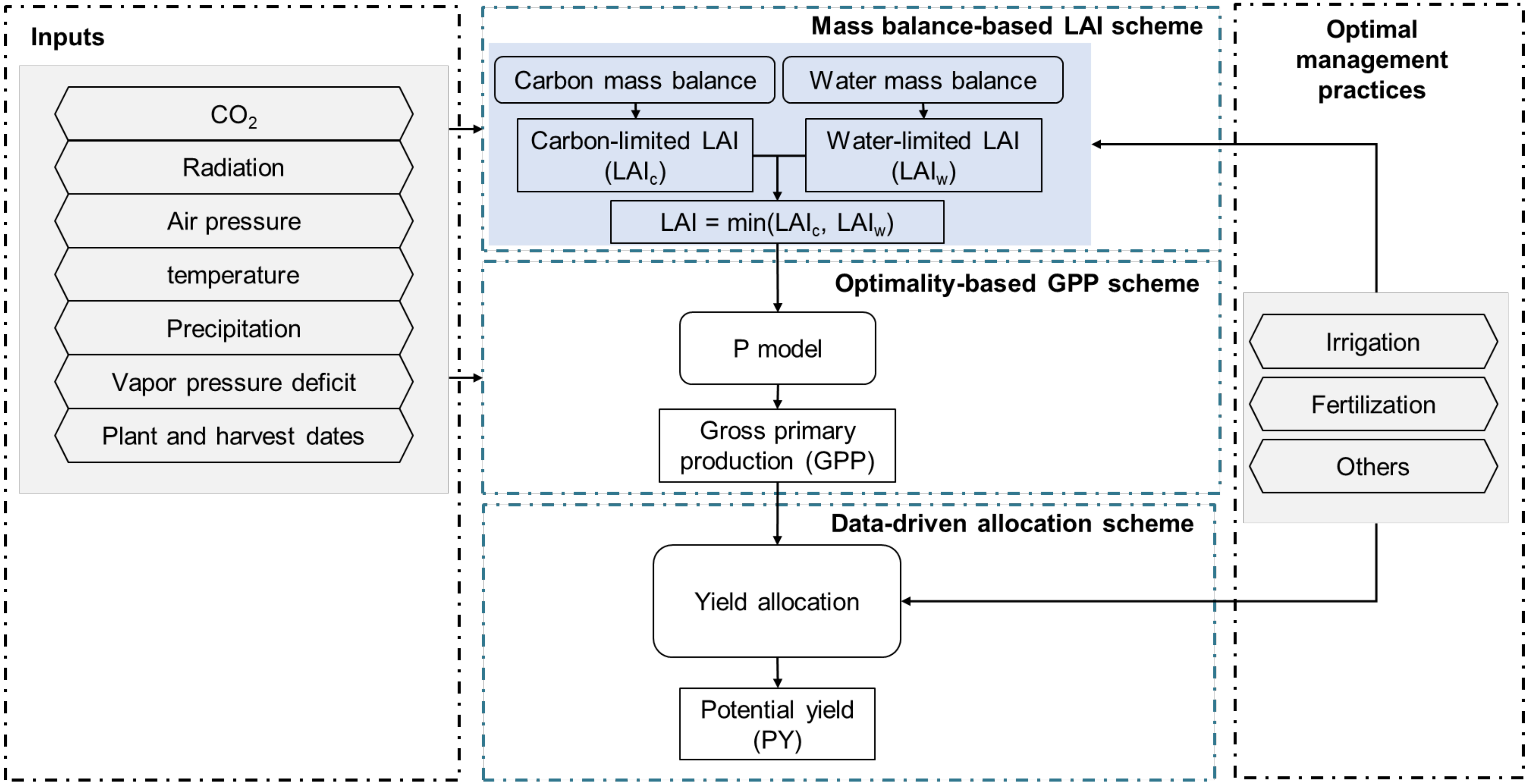
New model

- Less parameters
- Better performance
- EEO theory-based

Significance

- Monitoring crop yield at large scale
- Diagnosing the climatic impacts

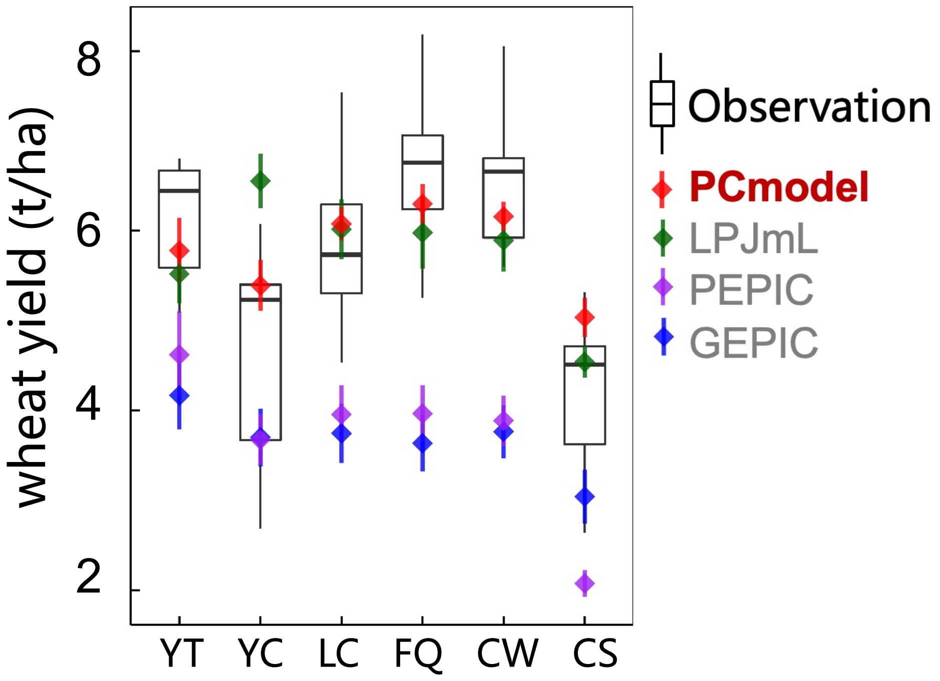
The structure of PC model (C for Crop)

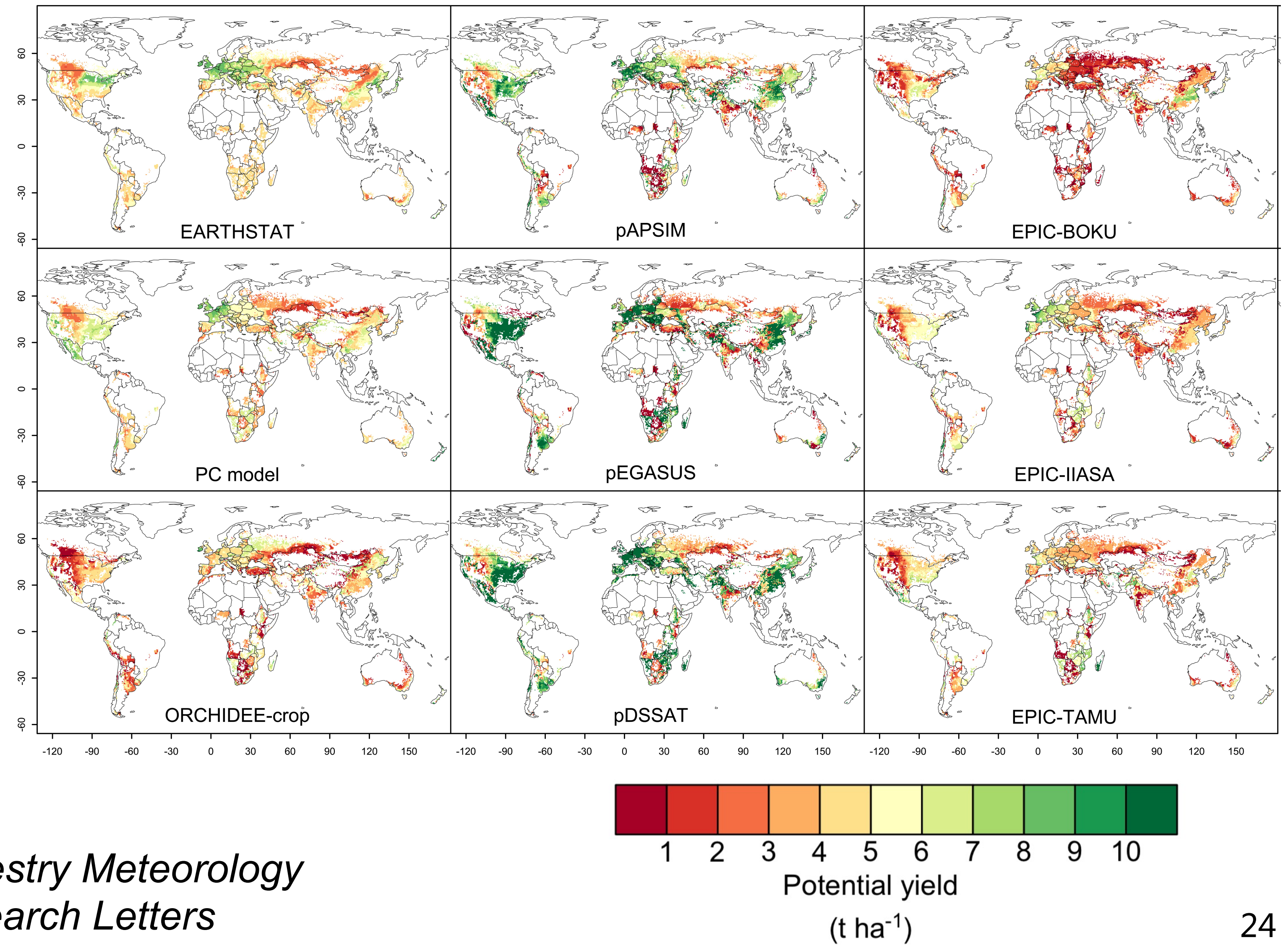


Qiao, **Wang*** et al., 2020 *Agriculture and Forestry Meteorology*
Qiao, **Wang*** et al., 2021 *Environmental Research Letters*

Applying: PCmodel for Crop yield

➢ **Multiple model comparison at site and global level**



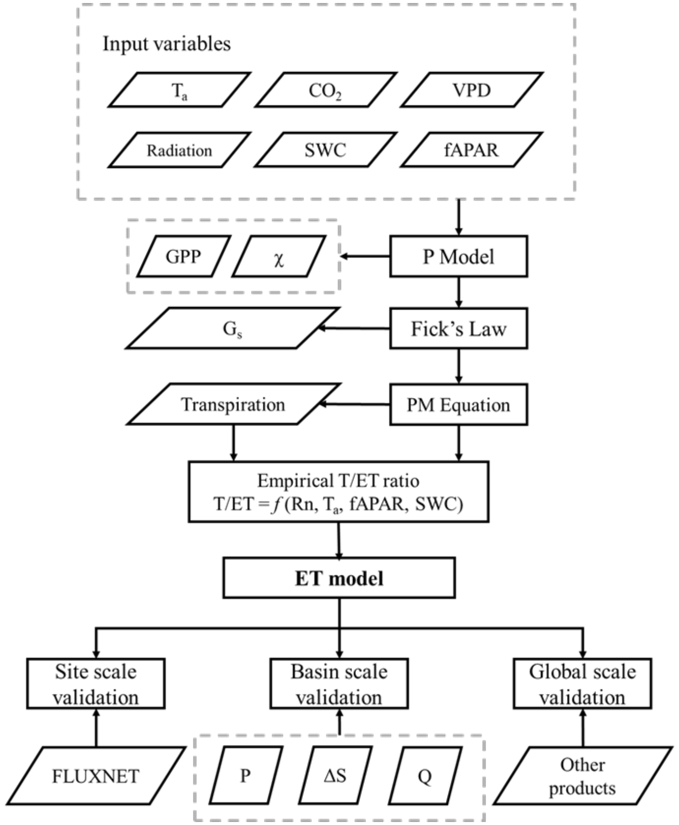


Qiao, **Wang*** et al., 2020 *Agriculture and Forestry Meteorology*
Qiao, **Wang*** et al., 2021 *Environmental Research Letters*

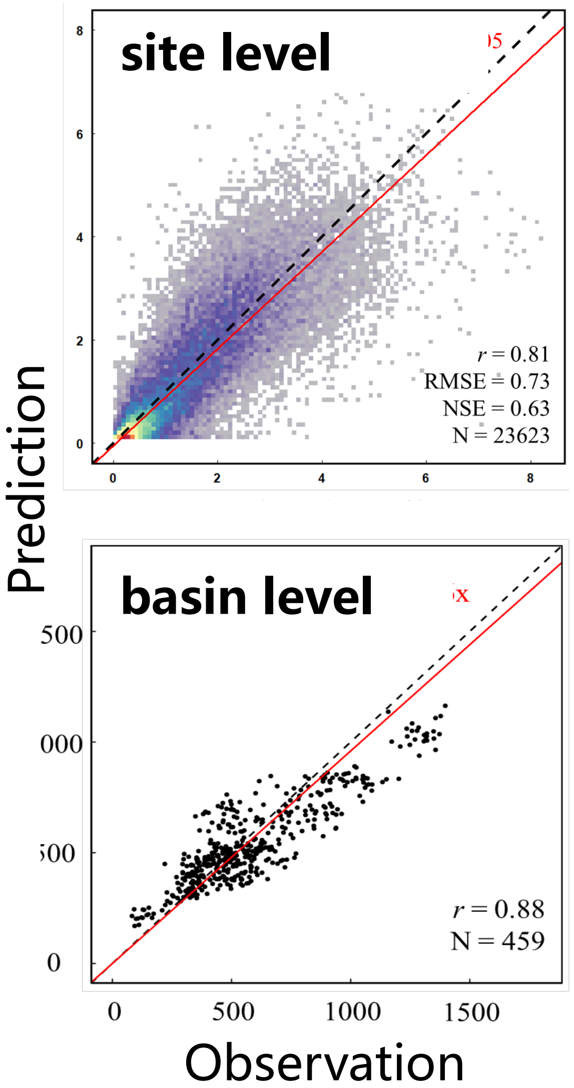
Applying: evaportranspiration (ET)

New framework

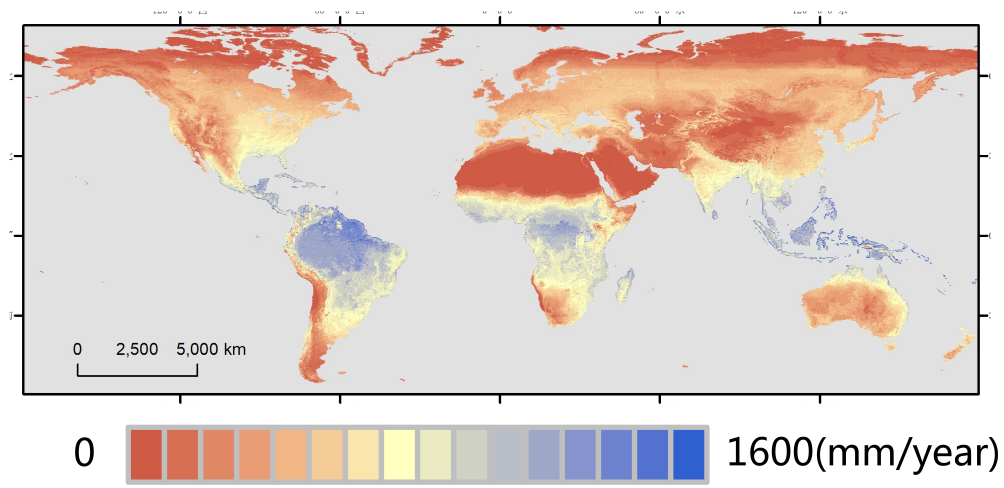
- Calibration-free ET
- None type-based parameters

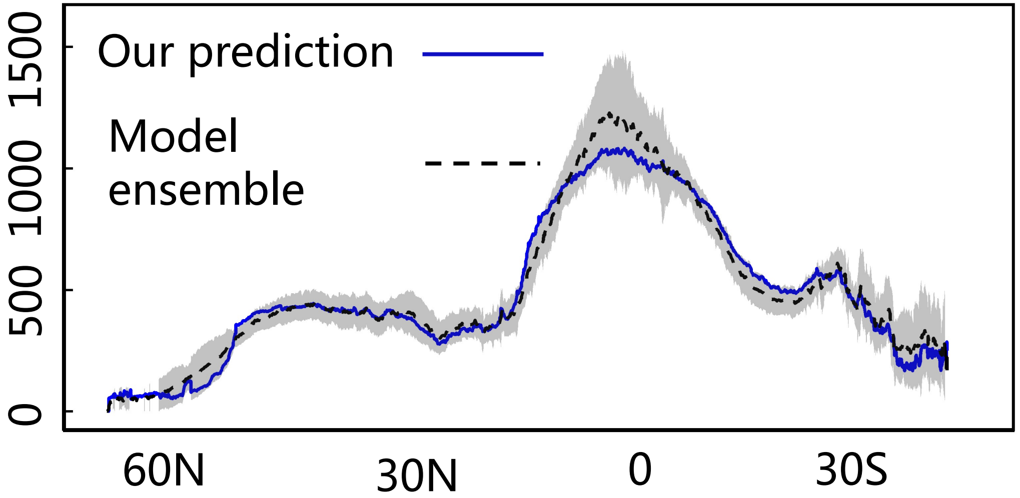


ET at flux site



Global ET distribution (8-day, 500m)

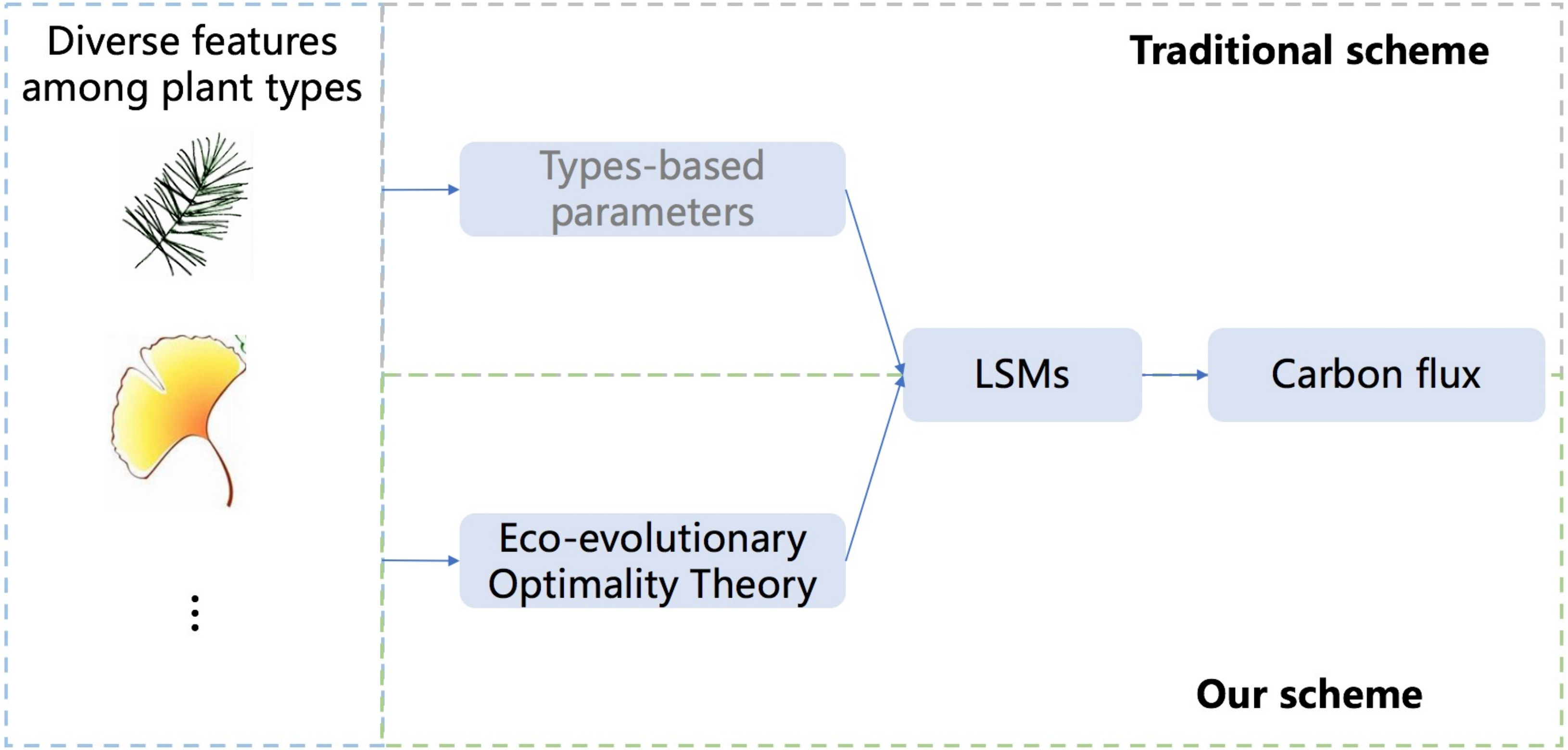




Tan, **Wang*** et al., *Environmental Research Letters* ; Tan, **Wang*** et al., *under review*

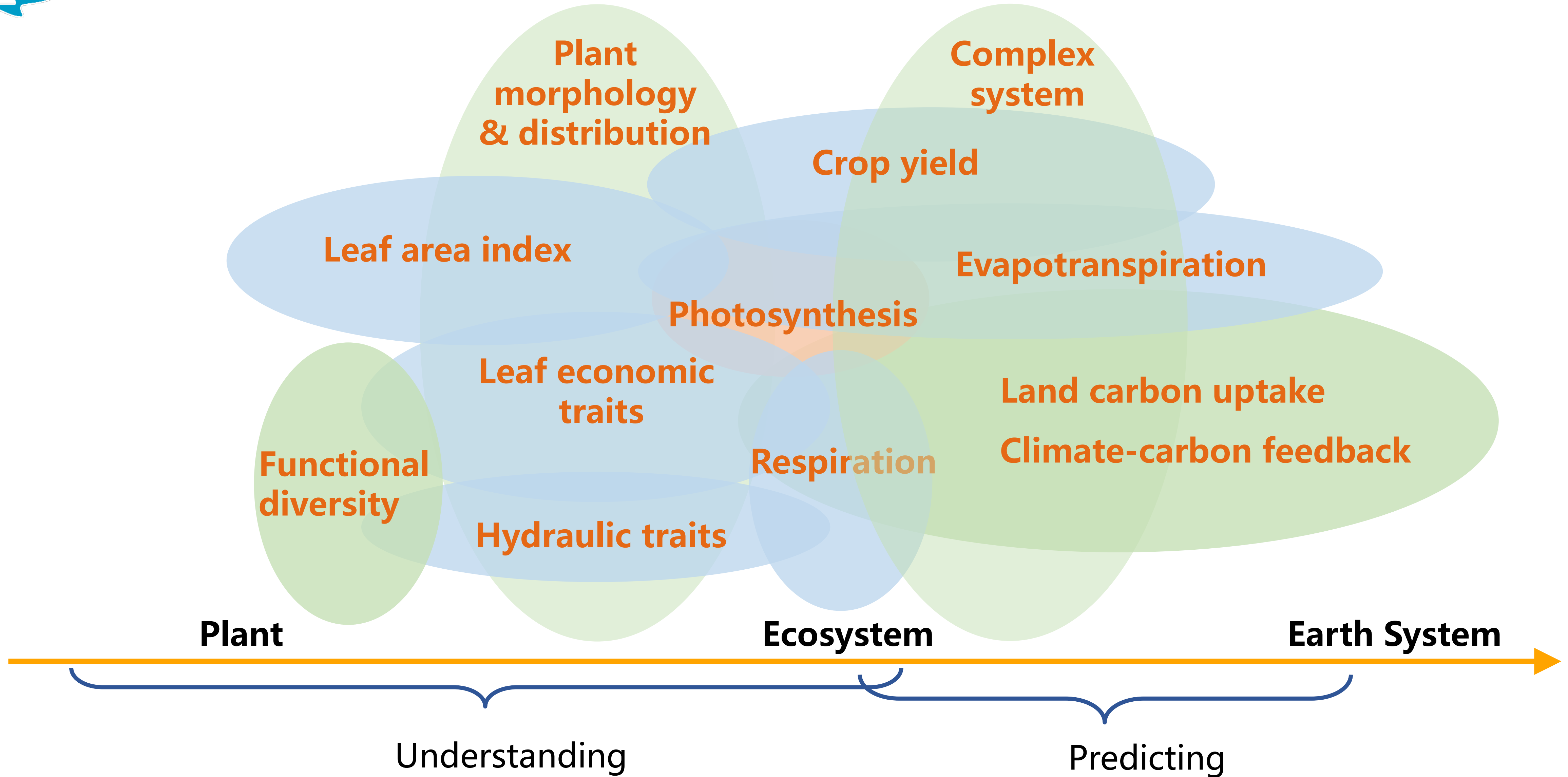
Research interest

- Understanding: environmental effects on plant respiration, leaf mass per area
- Applying: agriculture and hydrology
- **Predicting: carbon flux in Land Surface Models**



LPICEA | Lab of Plant Interactions: Climate, Ecosystem & Atmosphere

Department of Earth System Science | Tsinghua University



LPICEA | Lab of Plant Interactions: Climate, Ecosystem & Atmosphere

Department of Earth System Science | Tsinghua University