研究生专题讲座，2012.05.21

流域生态水文过程观测与模拟

楊 大 文
(yangdw@tsinghua.edu.cn)

清华大学水利系

报告提纲

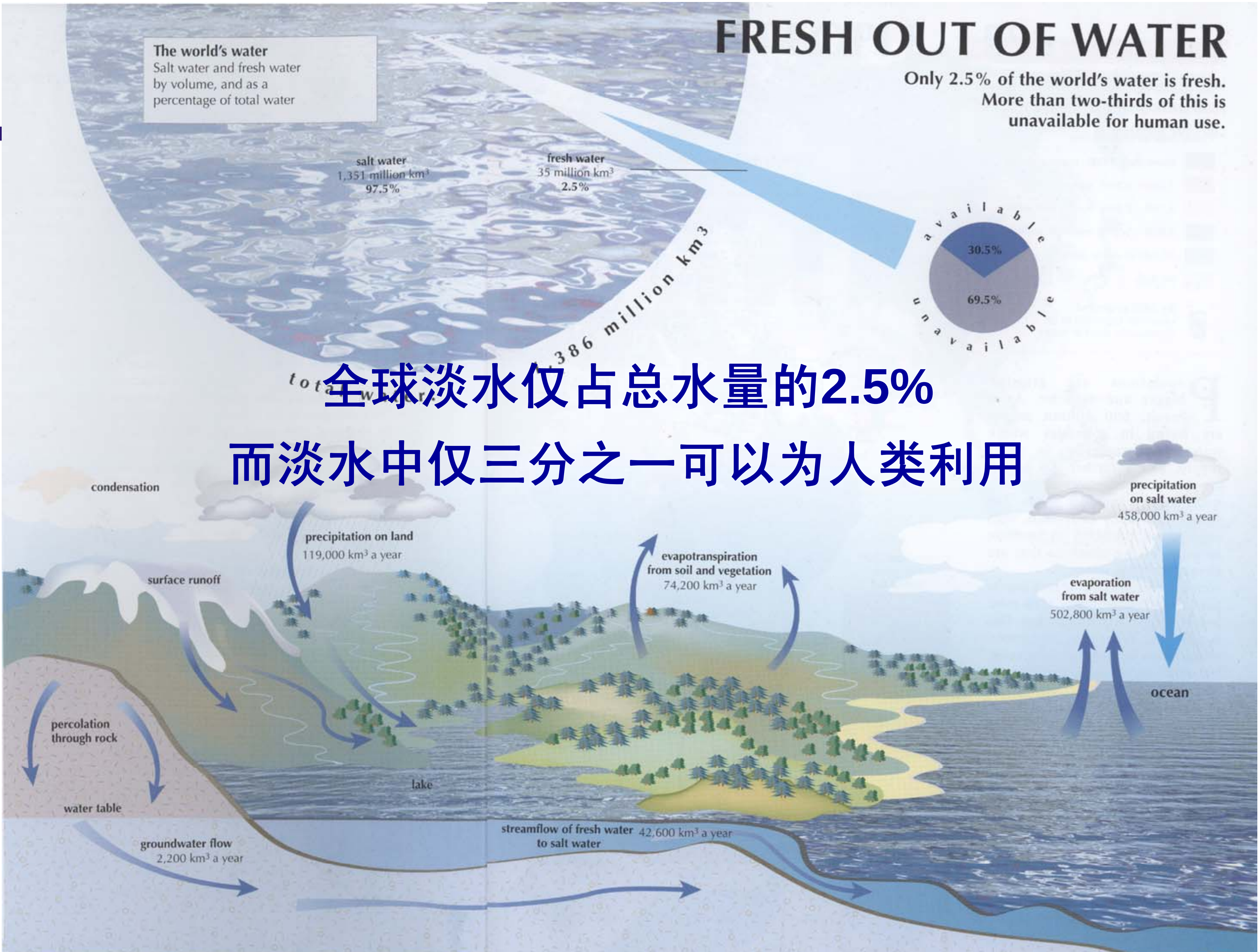
一、生态水文学的背景

二、生态水文过程观测及机理分析

三、生态水文模型构建及验证

四、气候变化的生态水文响应分析

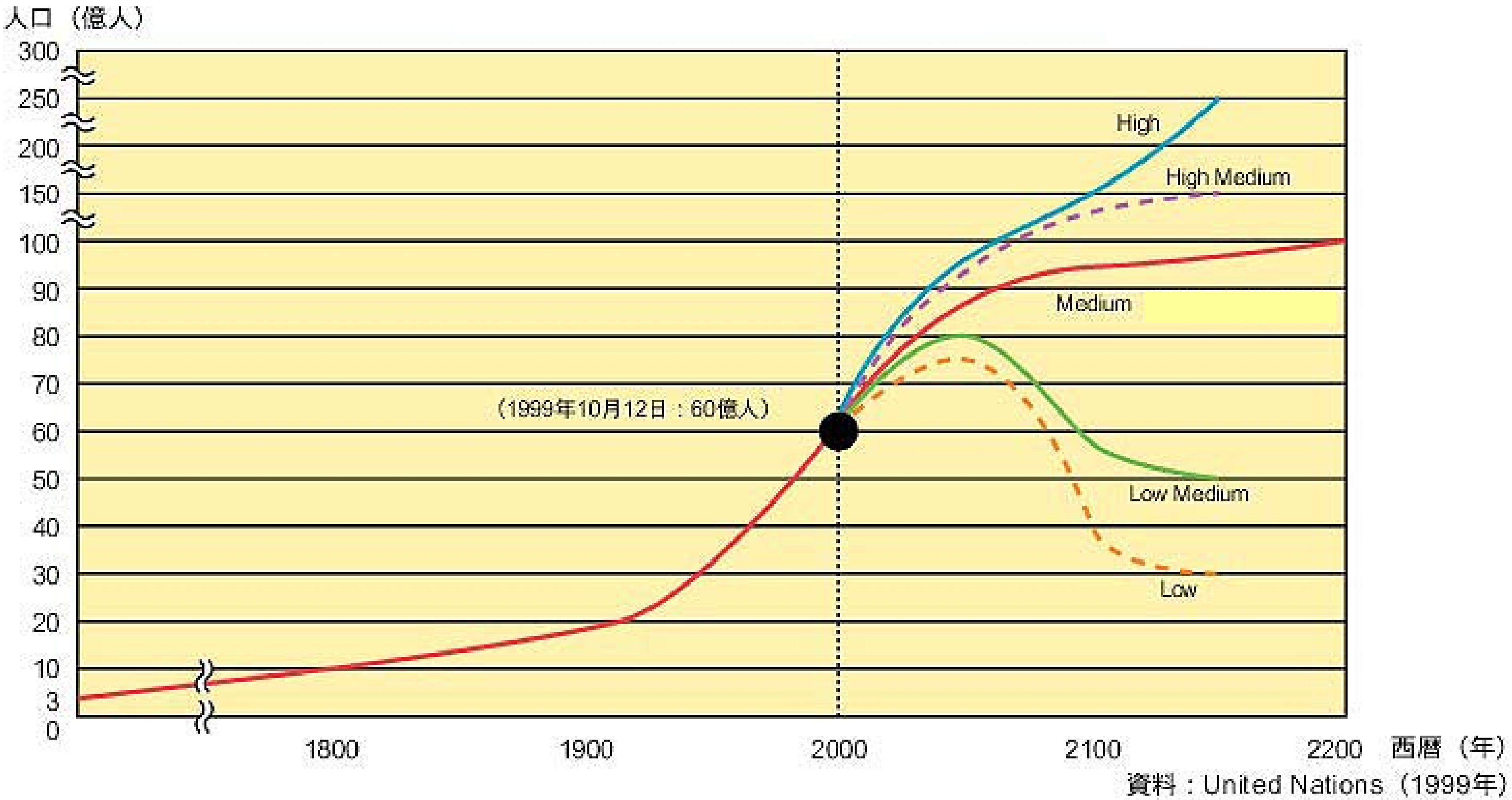
五、生态水文学的研究思路



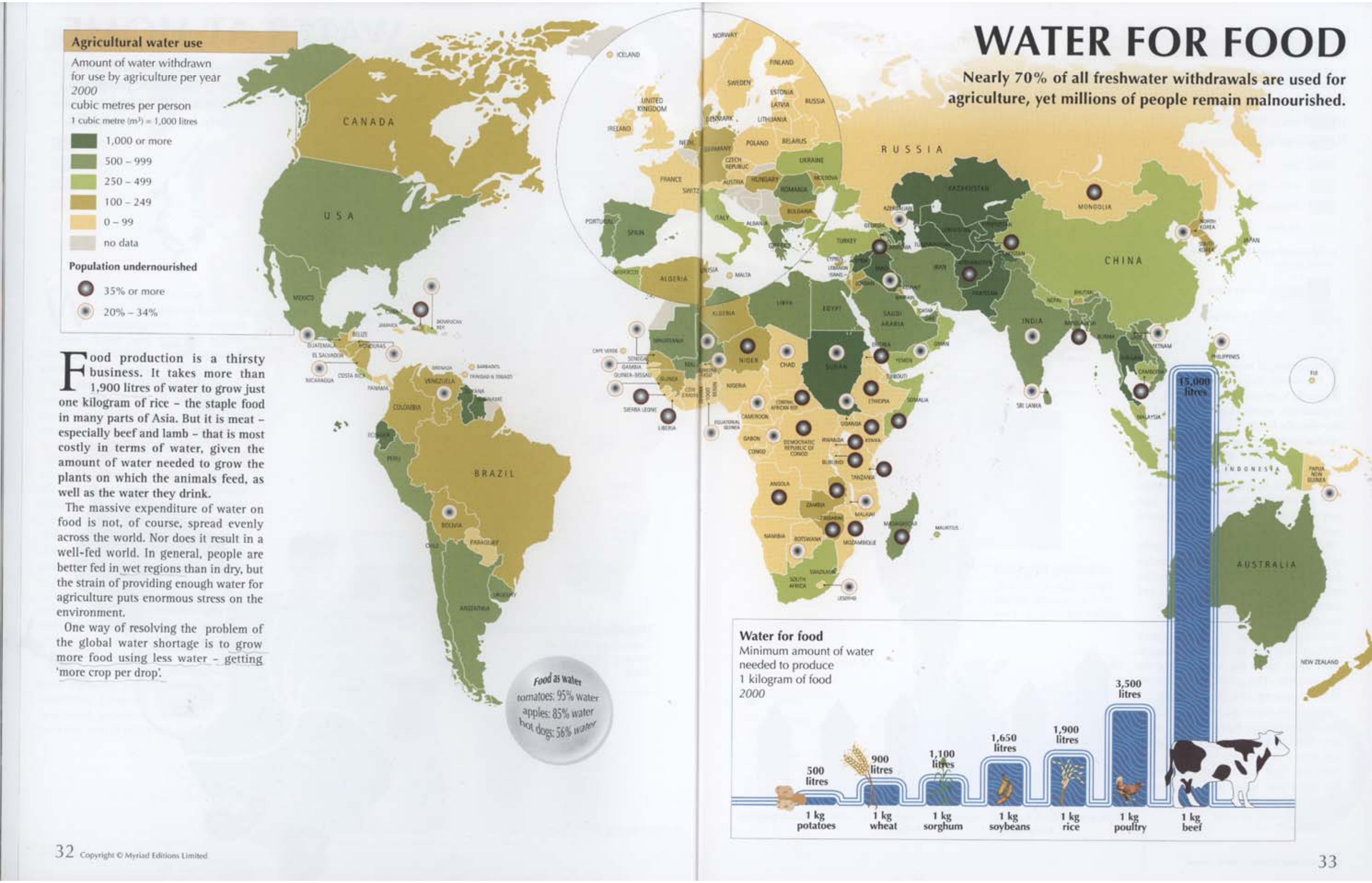
全球淡水仅占总水量的2.5%

而淡水中仅三分之一可以为人类利用

世界人口变化和预测


人口（億人）
300
250
200
150
100
90
80
70
60
50
40
30
20
10
3
0
High
High Medium
Medium
Low Medium
Low
（1999年10月12日：60億人）
1800
1900
2000
2100
2200
西暦（年）
資料：United Nations（1999年）

粮食生产需要大量水资源



WATER FOR FOOD

Nearly 70% of all freshwater withdrawals are used for agriculture, yet millions of people remain malnourished.

Food production is a thirsty business. It takes more than 1,900 litres of water to grow just one kilogram of rice – the staple food in many parts of Asia. But it is meat – especially beef and lamb – that is most costly in terms of water, given the amount of water needed to grow the plants on which the animals feed, as well as the water they drink.

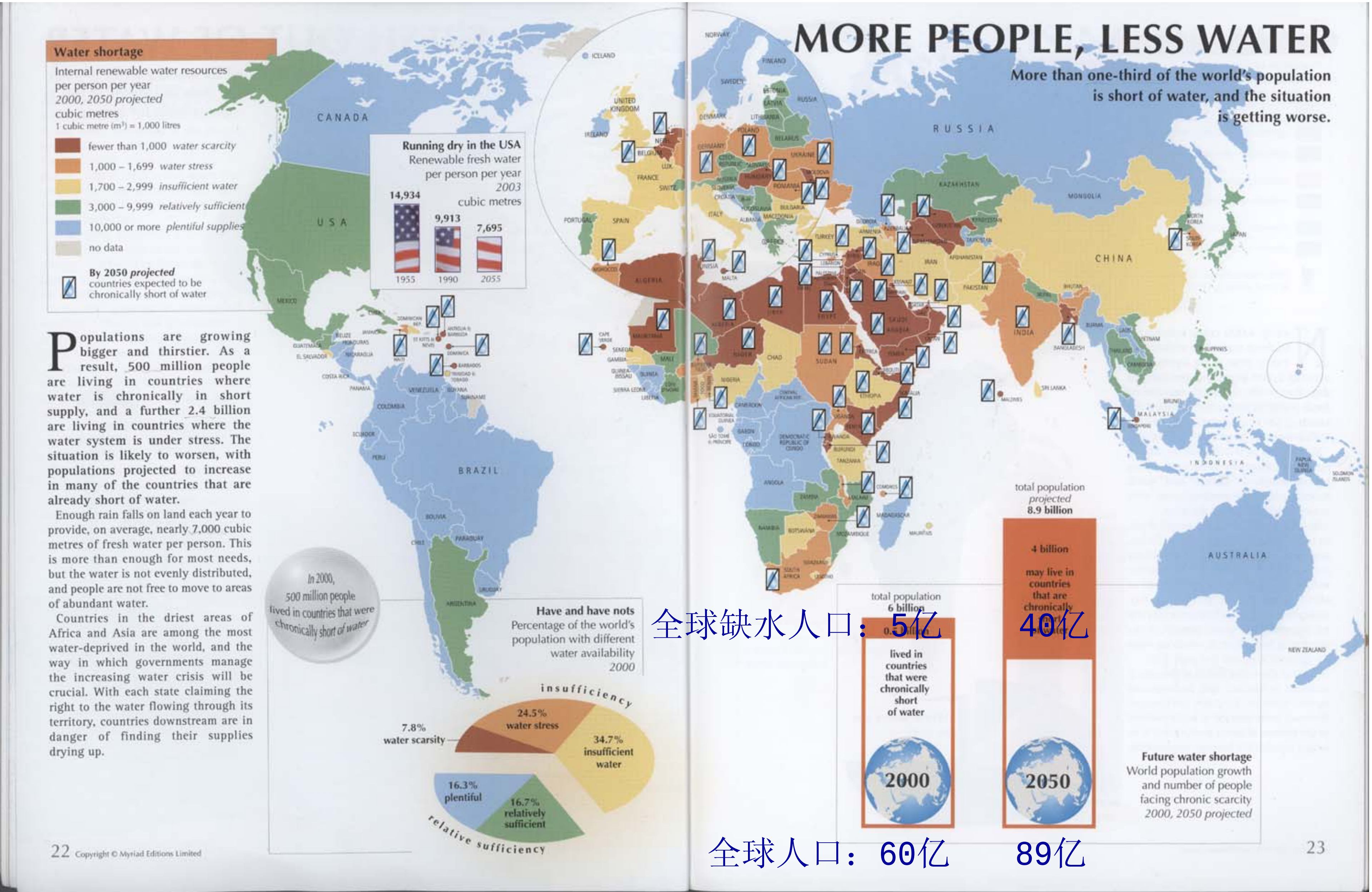
The massive expenditure of water on food is not, of course, spread evenly across the world. Nor does it result in a well-fed world. In general, people are better fed in wet regions than in dry, but the strain of providing enough water for agriculture puts enormous stress on the environment.

One way of resolving the problem of the global water shortage is to grow more food using less water – getting 'more crop per drop'.

32

33

人口增长导致水资源危机



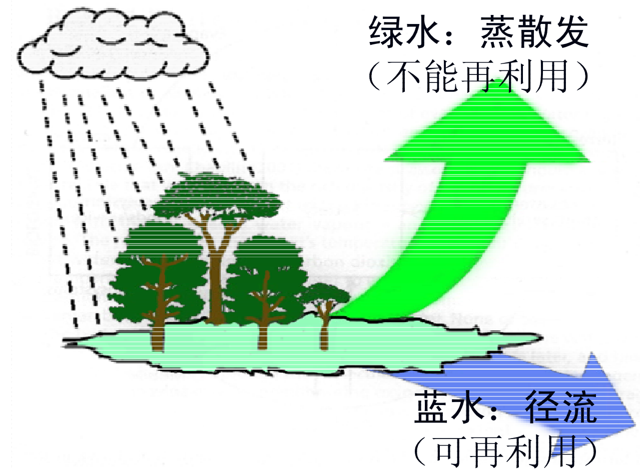
全球缺水人口：5亿　　40亿

全球人口：60亿　　89亿

一、研究背景

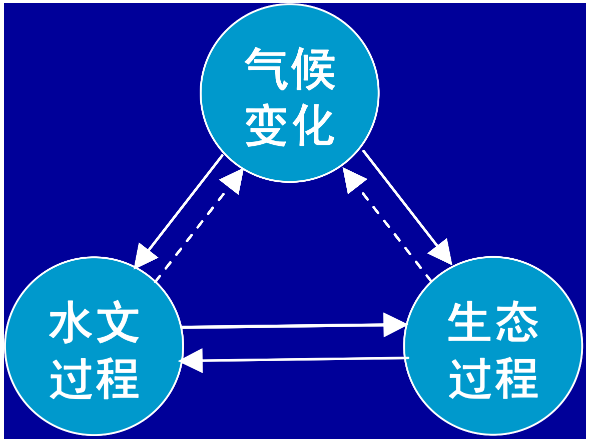
■ 水循环是一切水问题的科学基础，生态与水文过程相互作用是流域水循环的关键环节

- ❖ 流域水循环决定水资源，影响生态系统；
- ❖ 粮食生产和植被生态维持是水的主要社会与生态服务功能，也是“绿水”的主要消耗方式；
- ❖ 人类活动（如灌溉和水土保持等）直接影响生态、水文及水资源。



■ 气候变化的流域生态水文响应研究是水文学的前沿和热点

- ❖ 流域生态与水文过程之间存在着复杂的相互作用，气候是二者的主要驱动力之一；
- ❖ 气候变化下的流域水资源变化，要求我们必修研究生态过程与水文过程的耦合作用。



二、生态水文过程观测及机理分析

在哪里观测？

- 水资源消耗区
- 水资源形成区
- 水资源变化剧烈地区

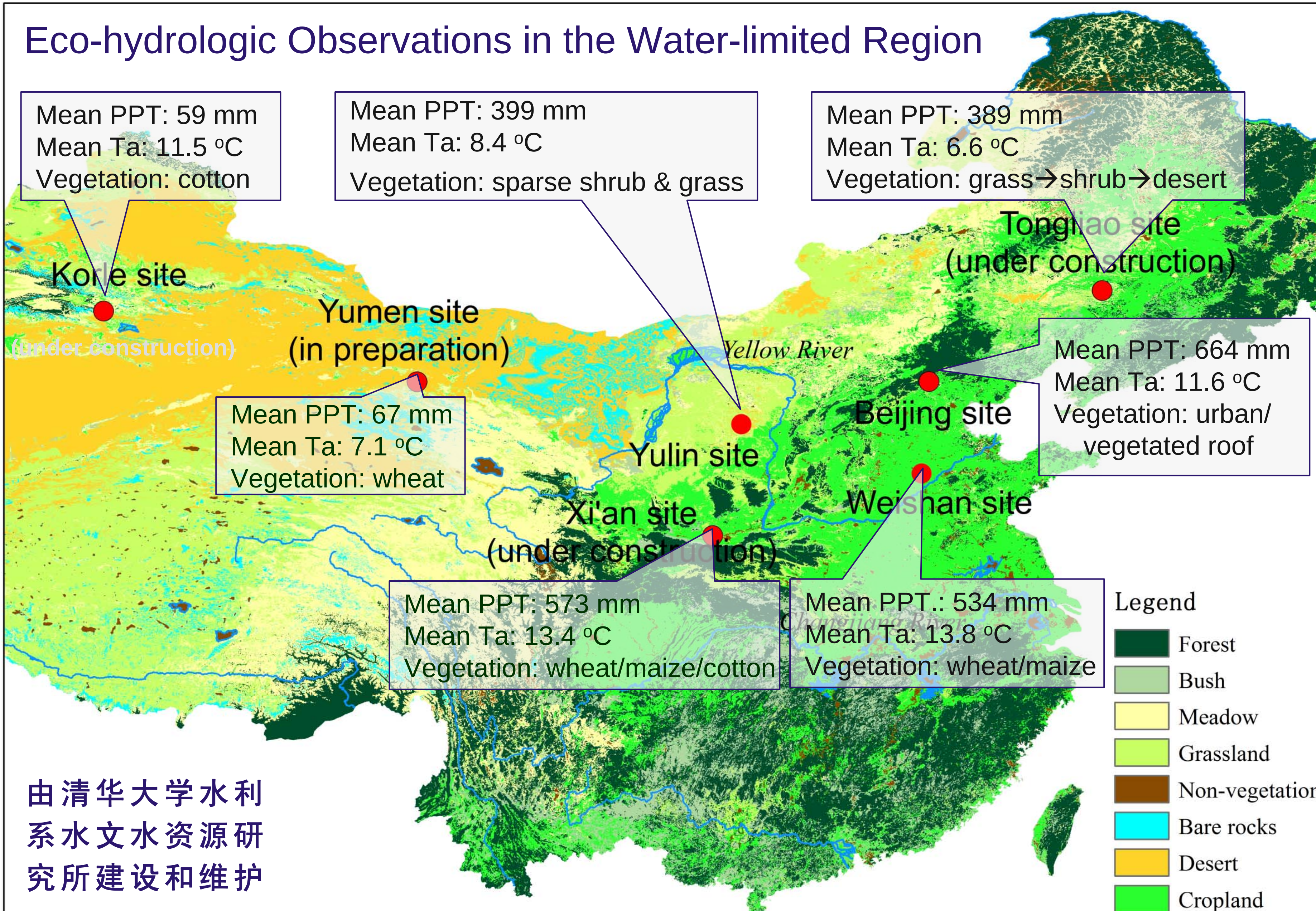
观测什么？

- 水、热、碳、氮等在土壤—植物—大气系统中的迁移和转化过程
- 土壤、植物、大气的状态变化过程

揭示什么机理？

- 各种通量的变化特征、他们之间的耦合关系
- 通量与状态之间的耦合关系

2.1 中国北方缺水地区生态水文观测网



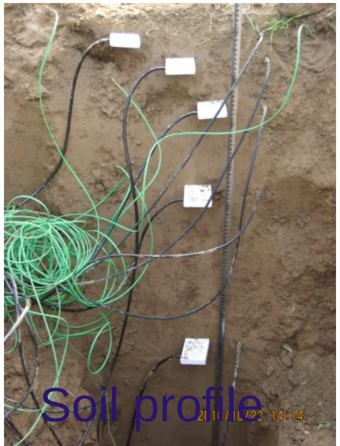
由清华大学水利系水文水资源研究所建设和维护

Plain cropland along the Downstream of Yellow River (Weishan site, 2005.03~)

(1) Instruments: Meteorological system, eddy covariance system, soil profiles, crop growth status, leaf-level gas exchange, water quality.

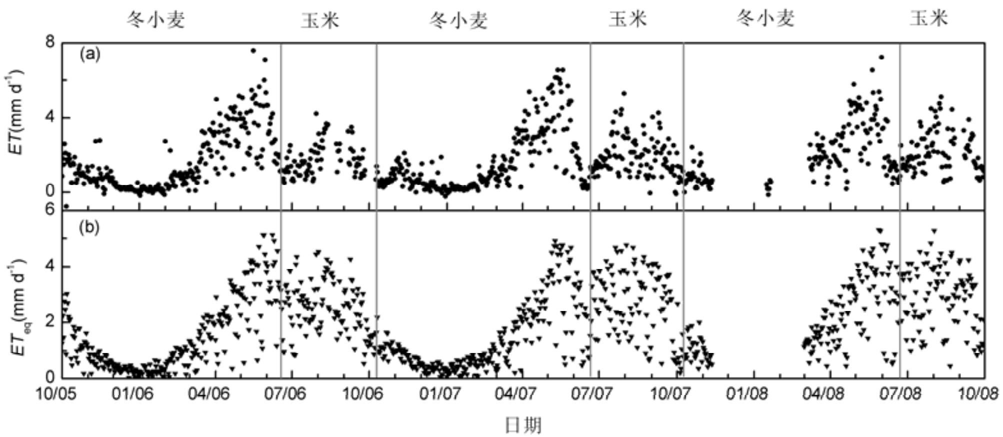
(2) Observation Items:

a. wind speed/direction, air temperature/humidity, air pressure, surface temperature, precipitation, radiation;
b. Latent/sensible heat flux, soil heat flux, carbon dioxide flux, soil evaporation, soil respiration;
c. Stomatal conductance, photosynthesis rate, transpiration;
d. Soil temperature, soil moisture, soil water potential, groundwater table;
e. Leaf area index, dry biomass, crop yield;
f. $N\text{-}NO_3$ and $N\text{-}NH_4$ concentrations in groundwater and soil water

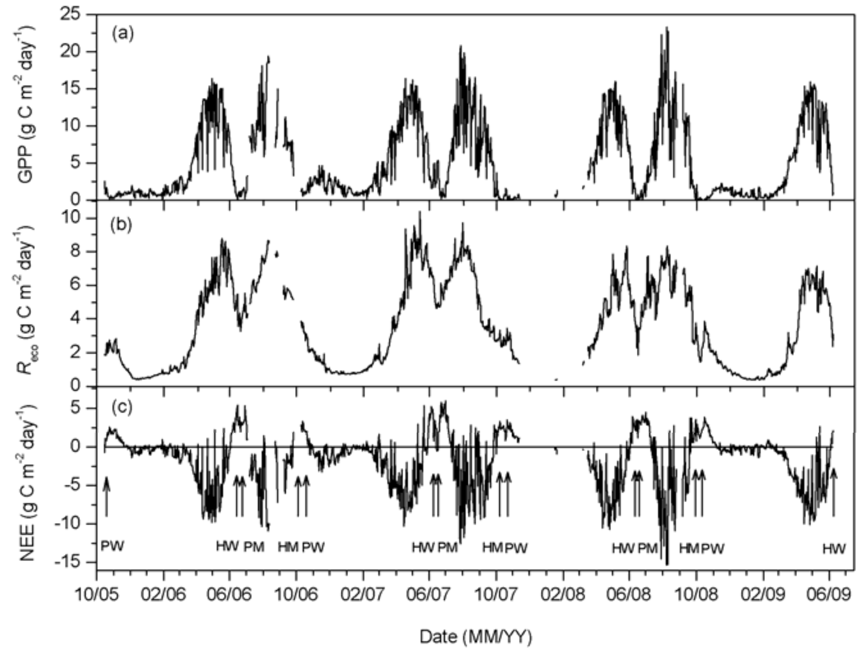


Plain cropland along the Downstream of Yellow River (Weishan site, 2005.03~)

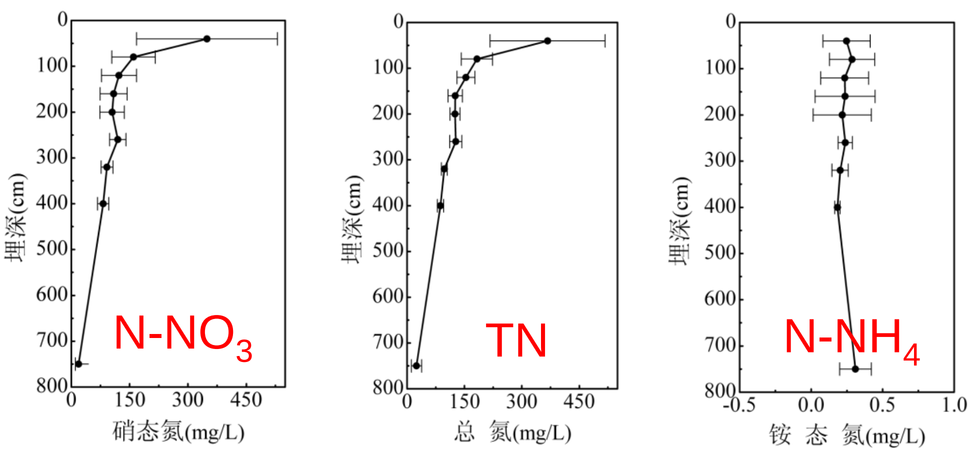
(3) Observation results



Long-term variability of ET



Long-term variability of CO_2 flux



Long-term variability of N concentration

Vegetated Roof in Beijing Urban Area
(Beijing site, 2009.06~)

(1) Instruments: Meteorological system, soil profiles, runoff flowmeter.
(2) Observation Items:

a. wind speed/direction, air temperature/humidity, air pressure, surface temperature, precipitation, radiation;
b. Soil temperature, soil moisture, soil water potential;
c. Precipitation, runoff
d. Indoor surface and air temperature;

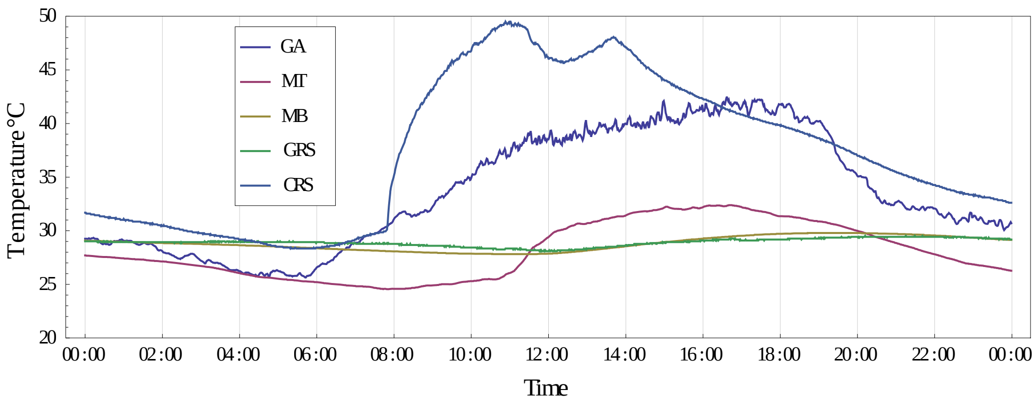
Meteorological Station

Four-Component Radiometer

Roof Vegetation: *Sedum*

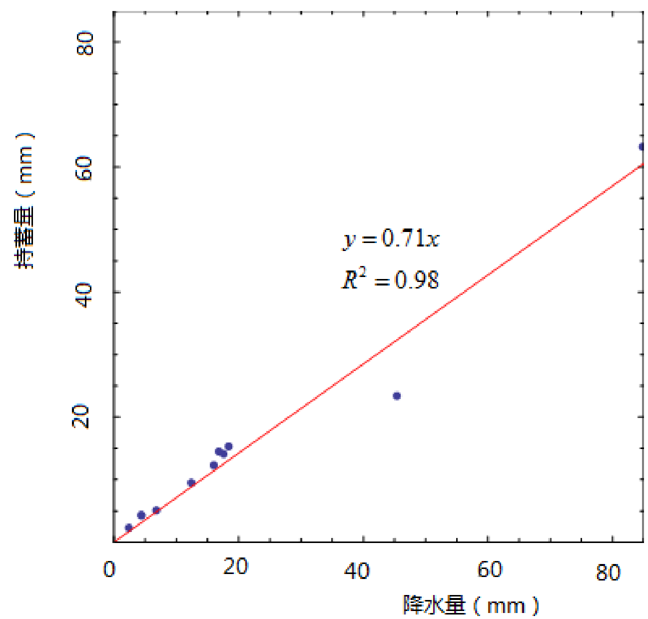
Vegetated Roof in Beijing Urban Area
(Beijing site, 2009.06~)

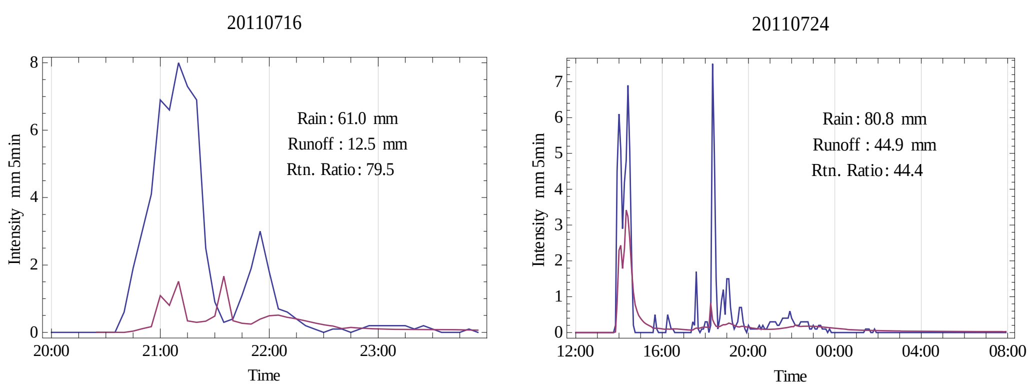
(3) Observation results



variability of roof surface temperature
on a typical summer day

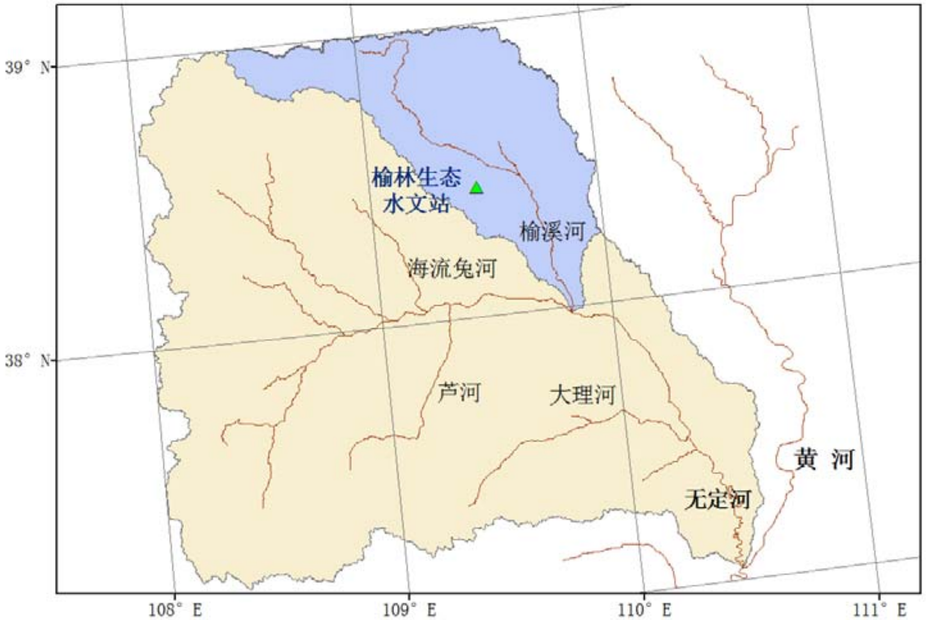
Overall Runoff Retention





Storm Water Hydrograph

陕西榆林自然流域水文过程观测



陕西榆林生态水文观测站位置

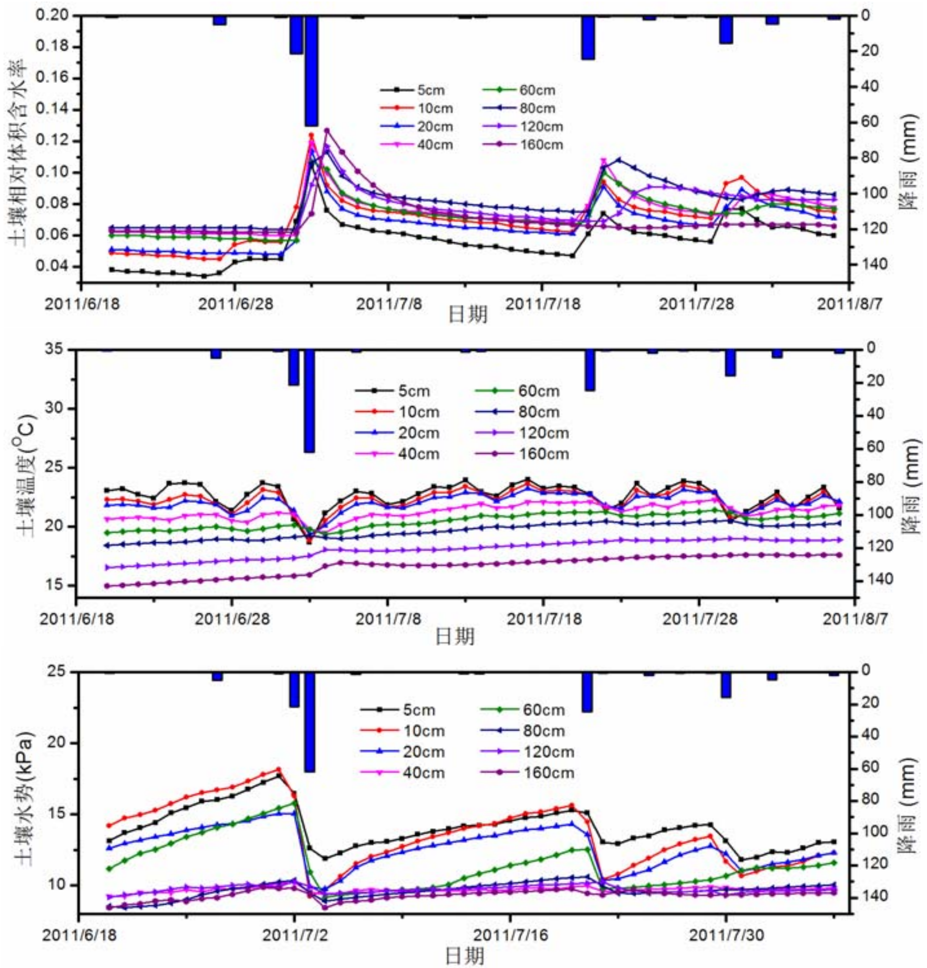
观测塔和涡度相关系统

榆林生态水文观测站下垫面情况

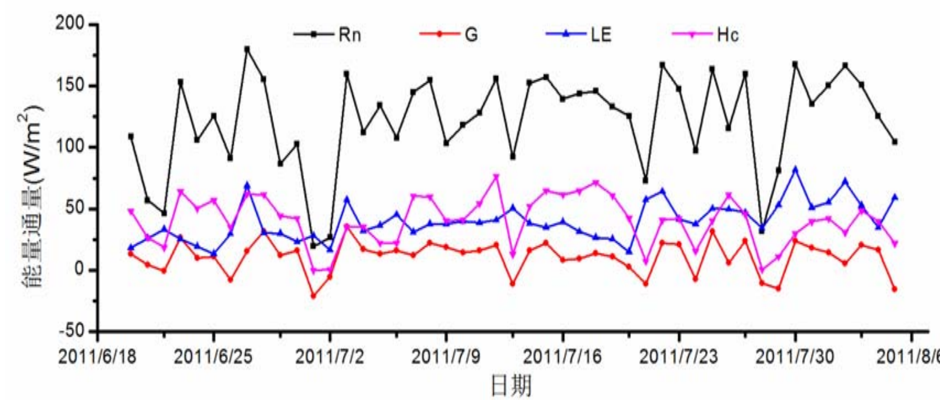
2010年开始建设，2011年6月正式开始连续观测。

陕西榆林自然流域水文过程观测

➤ 榆林生态水文过程的初步观测结果



不同深度土壤体积含水率、温度、水势变化



地表能量通量变化过程

沙柳（28.2%）

沙蒿（27.9%）

主要植物覆盖度调查结果

Oasis vegetation in the Northwest of China (Korle site, 2007.09~)

(1) Instruments: Meteorological system, soil profiles, eddy covariance system(under construction)

(2) Observation Items:

a. wind speed/direction, air temperature/relative humidity, air pressure, surface temperature, precipitation, radiation;
b. Latent/sensible heat flux, soil heat flux, carbon dioxide flux (under construction);
c. Soil salinity, soil temperature, soil moisture, water table depth;
d. Crop growing

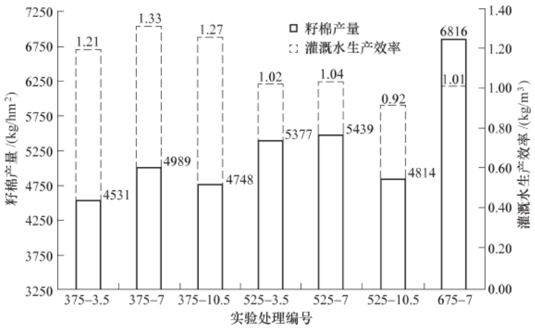
Soil profile

Laboratory

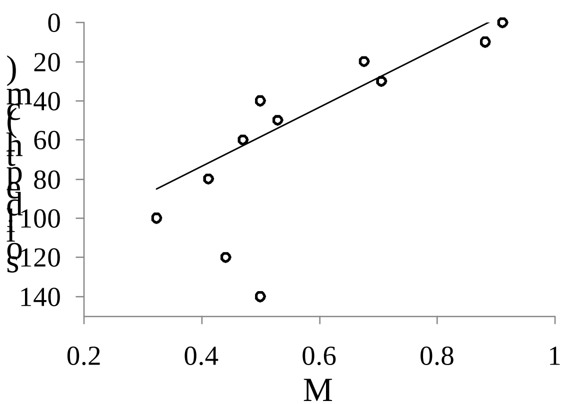
Cotton field

Oasis vegetation in the Northwest of China
(Korle site, 2007.09~)

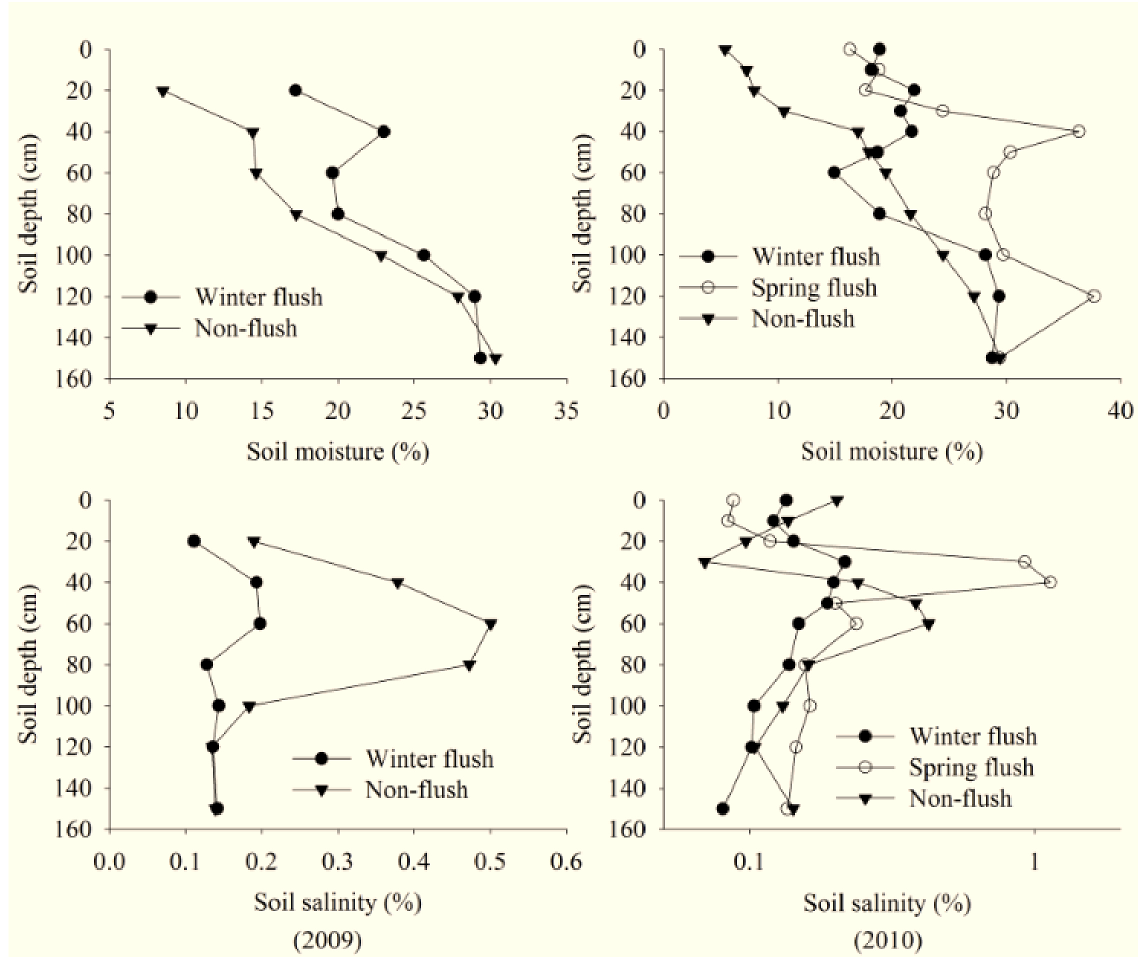
(3) Observation results



The cotton yield and water utilization efficiency under different treatments



The influential indices of mulched drip irrigation on soil salt



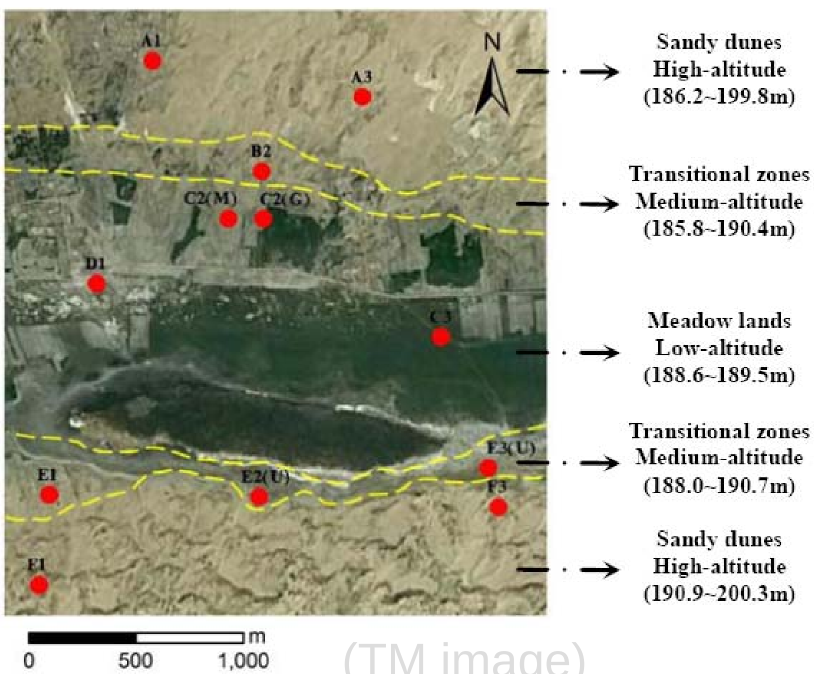
The soil water and salinity at the period of spring sowing (April 15th) under different non-growth flush styles

Agro-pastoral transitional zone in the Northeast of China (Tongliao site, 2012~)

(1) Instruments: Meteorological sites, two eddy covariance systems (one for grazed meadow, another for desert), soil profiles, LAS (Large Aperture Scintillometer).

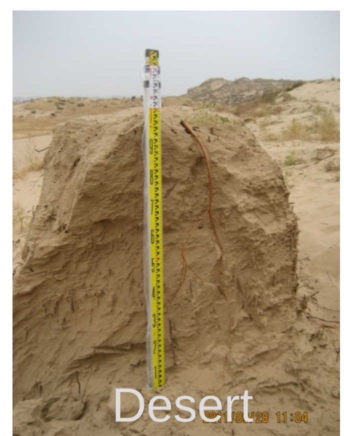
(2) Observation Items:

a. wind speed/direction, air temperature/relative humidity, air pressure, surface temperature, precipitation, radiation;
b. Latent/sensible heat flux, soil heat flux, carbon dioxide flux;
c. Soil temperature, soil moisture, soil water potential, water table depth;
d. Leaf area index.



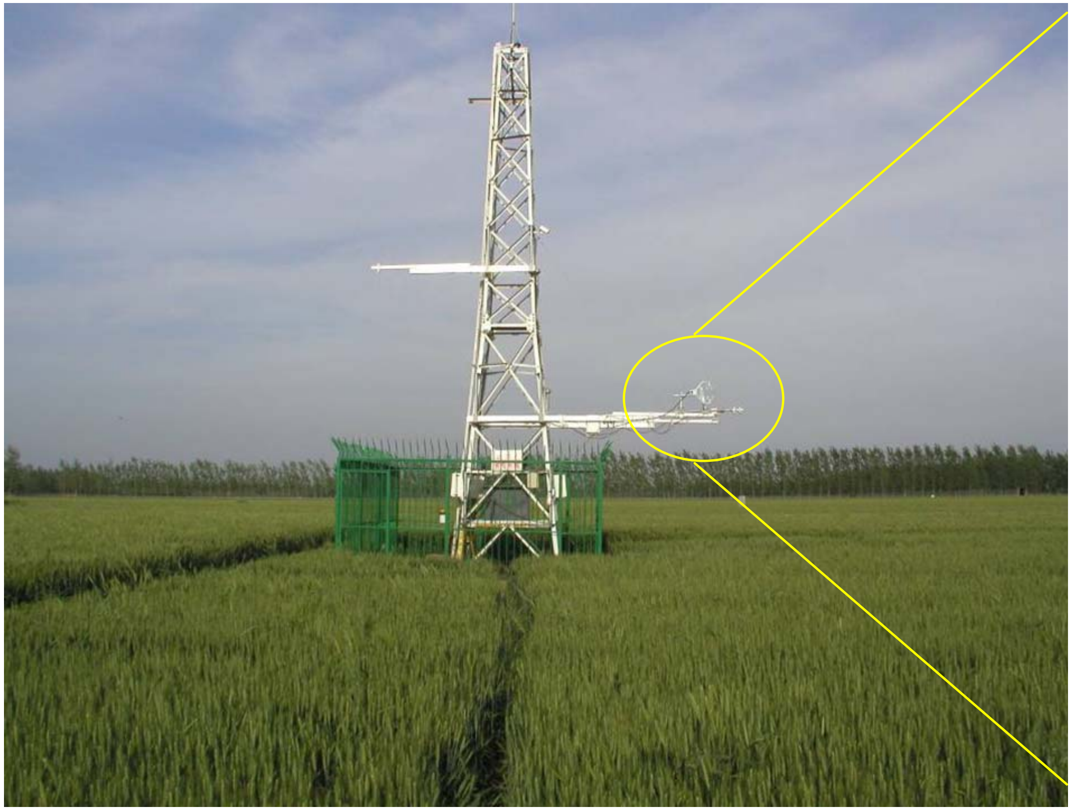
(TM image)

Meteorological Observation



2.2 基于观测的机理分析

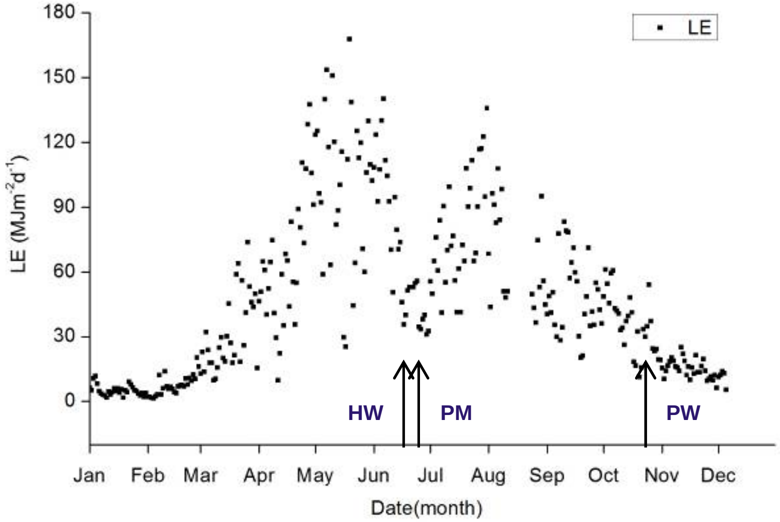
农田生态水文过程观测与机理研究



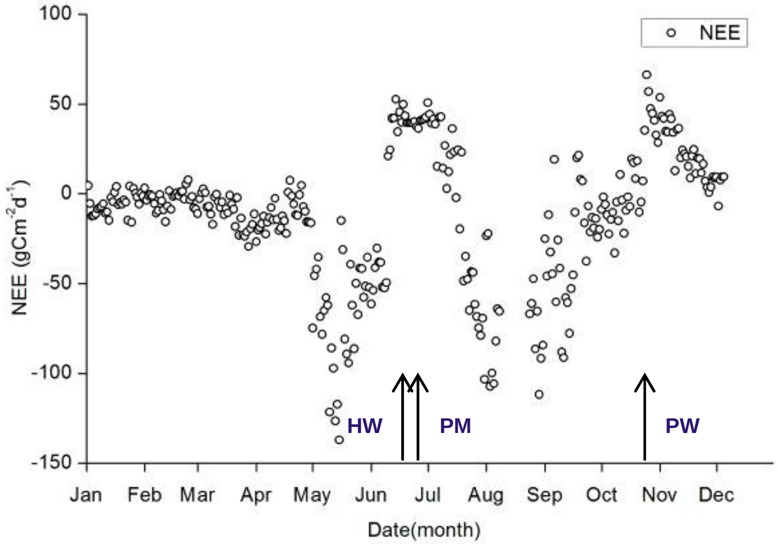
山东位山引黄灌区农田生态水文观测站

2005年开始水、热、CO_2通量观测，2011年更新了主要仪器，充实了生态观测内容

农田生态水文过程观测与机理研究



2010年潜热通量

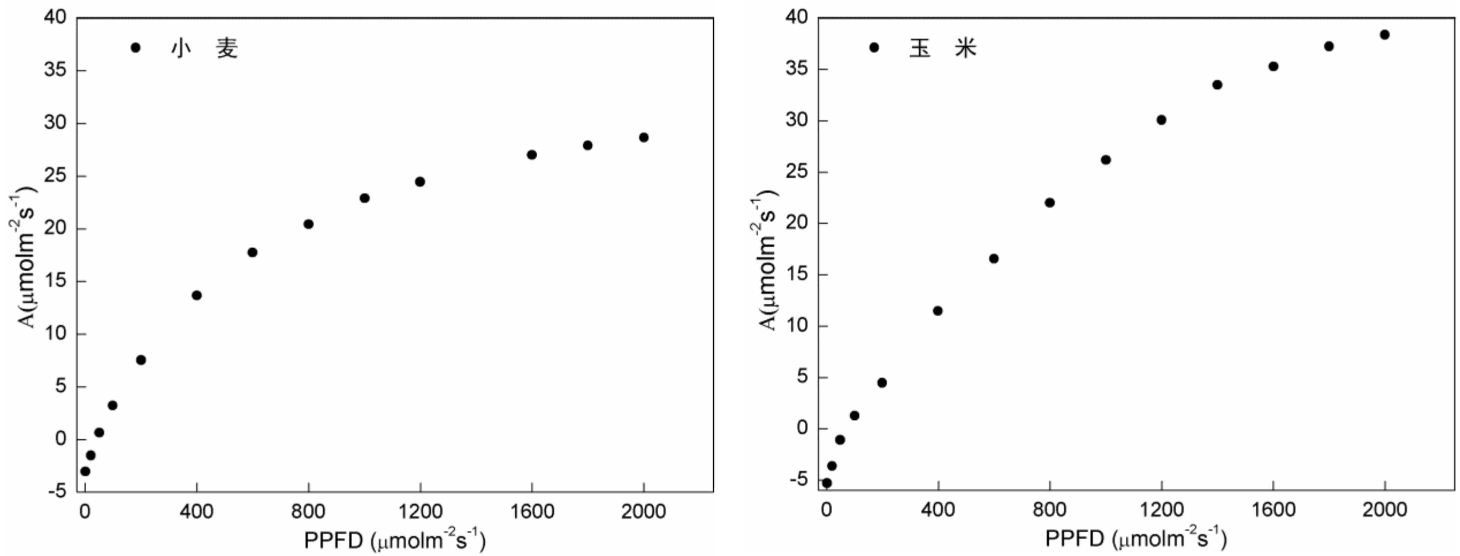


NEE(生态系统与大气碳交换量)

HW, 小麦收割; PM, 玉米种植; PW, 小麦种植

- 潜热通量和NEE季节变化与作物生长过程相吻合
- 秸秆还田后农田生态系统碳向大气释放有显著增加

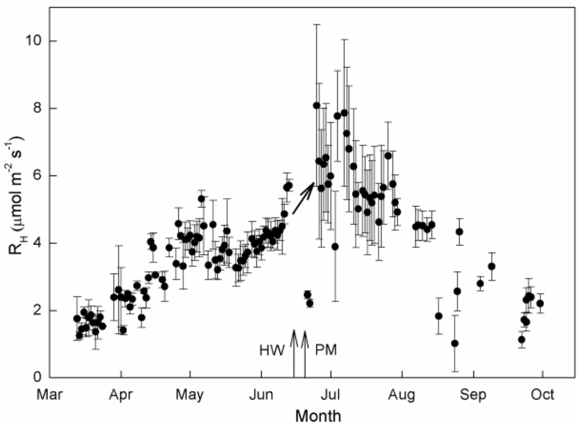
农田生态水文过程观测与机理研究

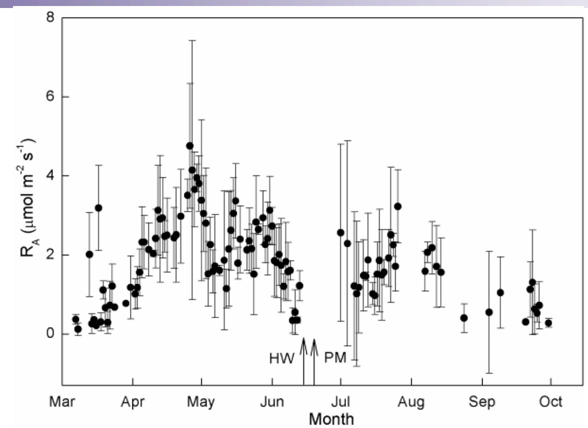


小麦和玉米光合作用的光响应曲线

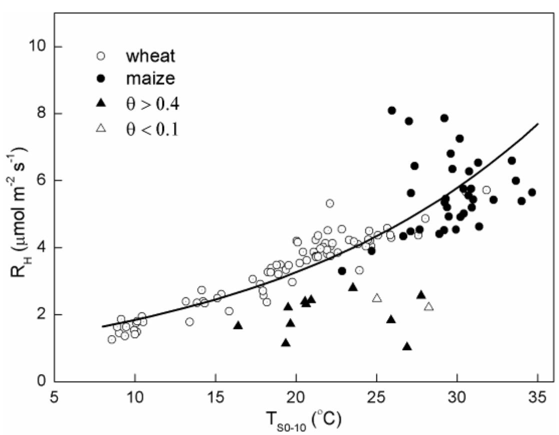
- 小麦饱和光强PPFD约为2000 μ mol m^{-2} s^{-1}，玉米饱和光强PPFD大于2000 μ mol m^{-2} s^{-1}
- 光强较低时，小麦光合作用较强；光强较高时，玉米光合作用较强；总体来看，玉米光合作用强度高于小麦

农田生态水文过程观测与机理研究

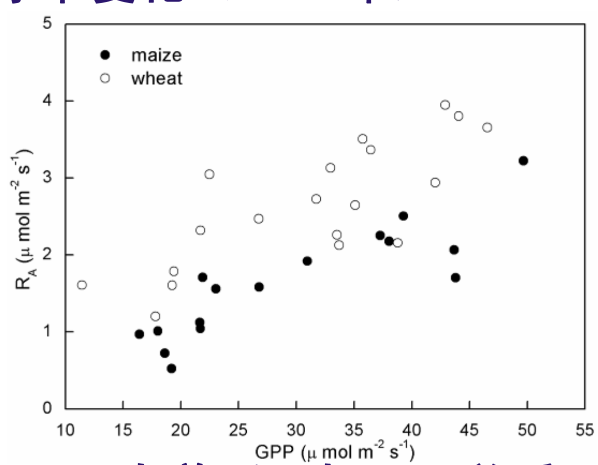




异养呼吸和自养呼吸季节变化（2011年）



异养呼吸与温度关系



自养呼吸与GPP关系

- 异养呼吸与土壤温度呈指数关系，土壤含水率过高/低均抑制异养呼吸
- 自养呼吸与GPP（gross primary productivity）具有较好的正相关关系

农田生态水文过程观测与机理研究

田间尺度能量平衡和碳平衡分析结果

(单位：MJ m^{-2} d^{-1})

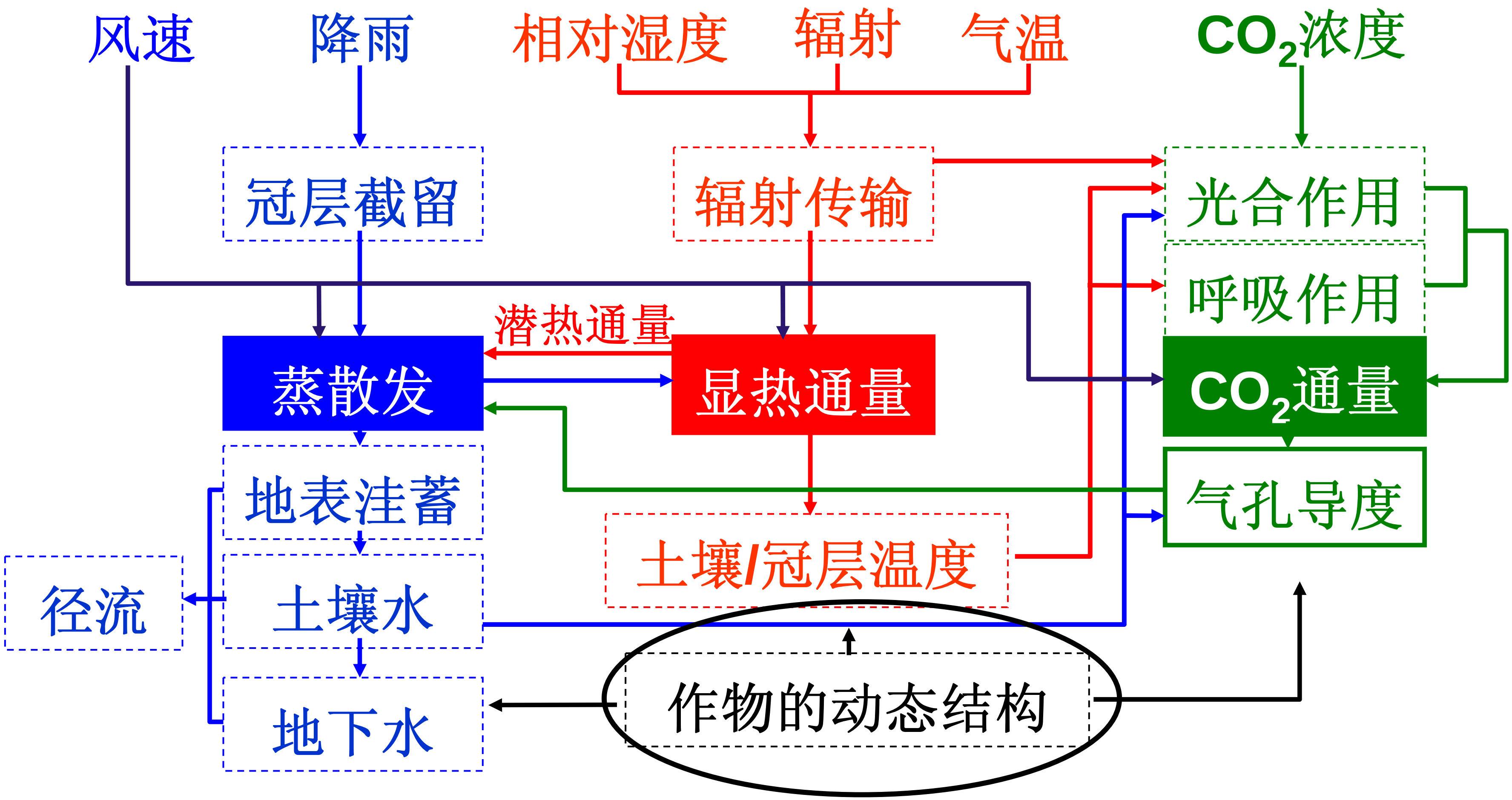
年	Rn	LE	Hs	G
05-06	6.2	4.1	1.0	0.0
06-07	6.2	3.9	1.1	0.0
07-08	8.0	5.0	1.0	0.2
平均	6.8	4.3	1.0	0.1

作物	Year	T_a	PPFD	SWC	*GPP*	R_{eco}	*NEE*	产量	C_{gr}	NEE+C_{gr}
		°C	mol m^{-2}	V/V	gC m^{-2}	gC m^{-2}	gC m^{-2}	g m^{-2}	gC m^{-2}	gC m^{-2}
年	2006-2007	13.74	7169	0.28	2008	1423	-585	--	--	--
	2007-2008*	13.16	7545	0.27	1668	1135	-533	--	615	82
冬小麦 (10.15-6.08)	2005-2006	8.14	4911	0.31	961	636	-326	645	250	-76
	2006-2007	8.88	4379	0.28	1114	720	-394	675	261	-133
	2007-2008	8.00	4810	0.28	782	479	-303	637	247	-56
	2008-2009	8.39	4109	0.27	967	572	-395	656	295	-100
夏玉米 (6.15-10.14)	2006	23.93	3272	0.27	--	--	--	706	267	--
	2007	22.62	2656	0.28	872	672	-201	--	--	--
	2008	22.69	2591	0.26	880	636	-244	975	368	124

三、生态水文模型构建及验证

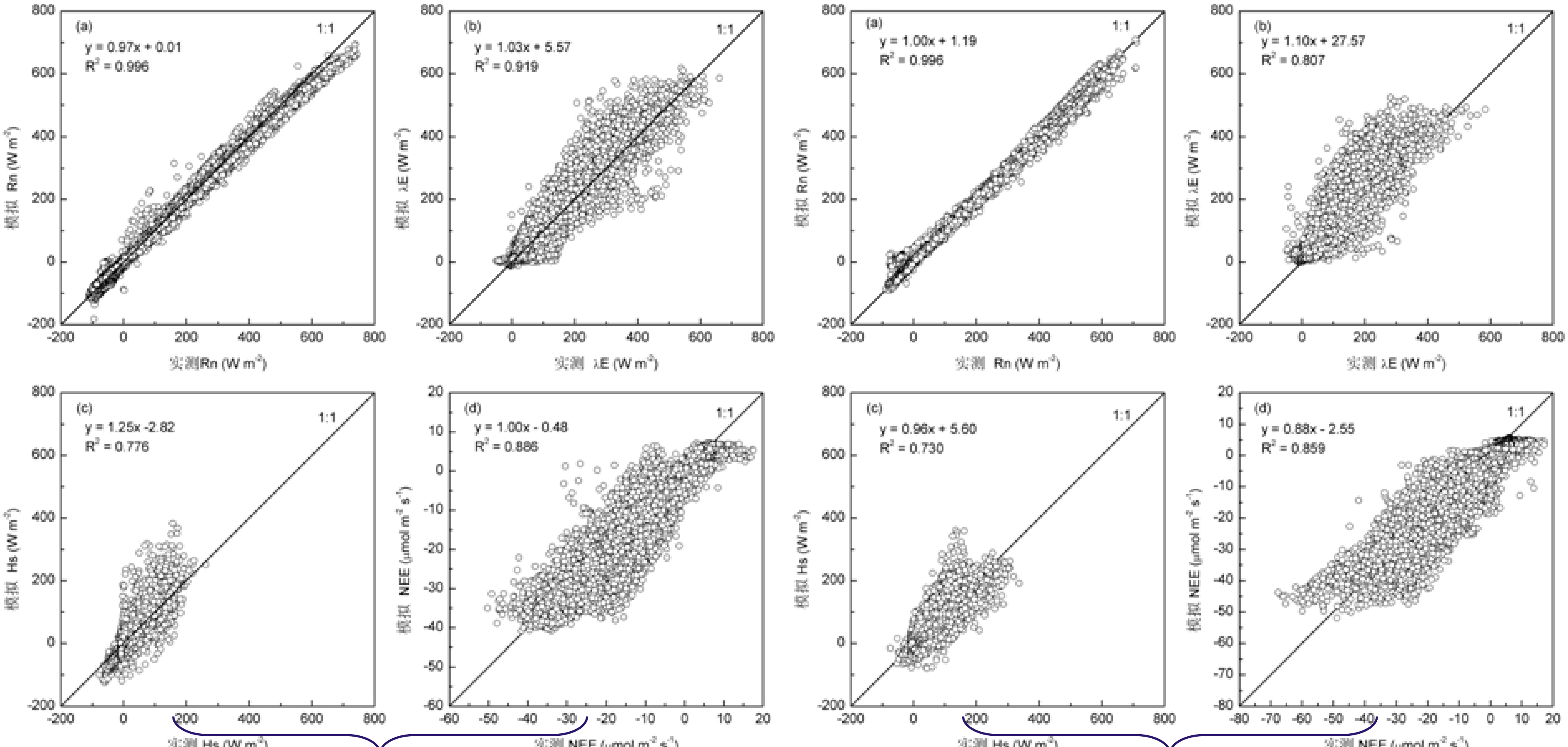
3.1 水文过程改进的陆面模型(HELP)

Hydrology Enhanced Land-surface Process model



蓝色：水循环；红色：能量传输；绿色：碳循环

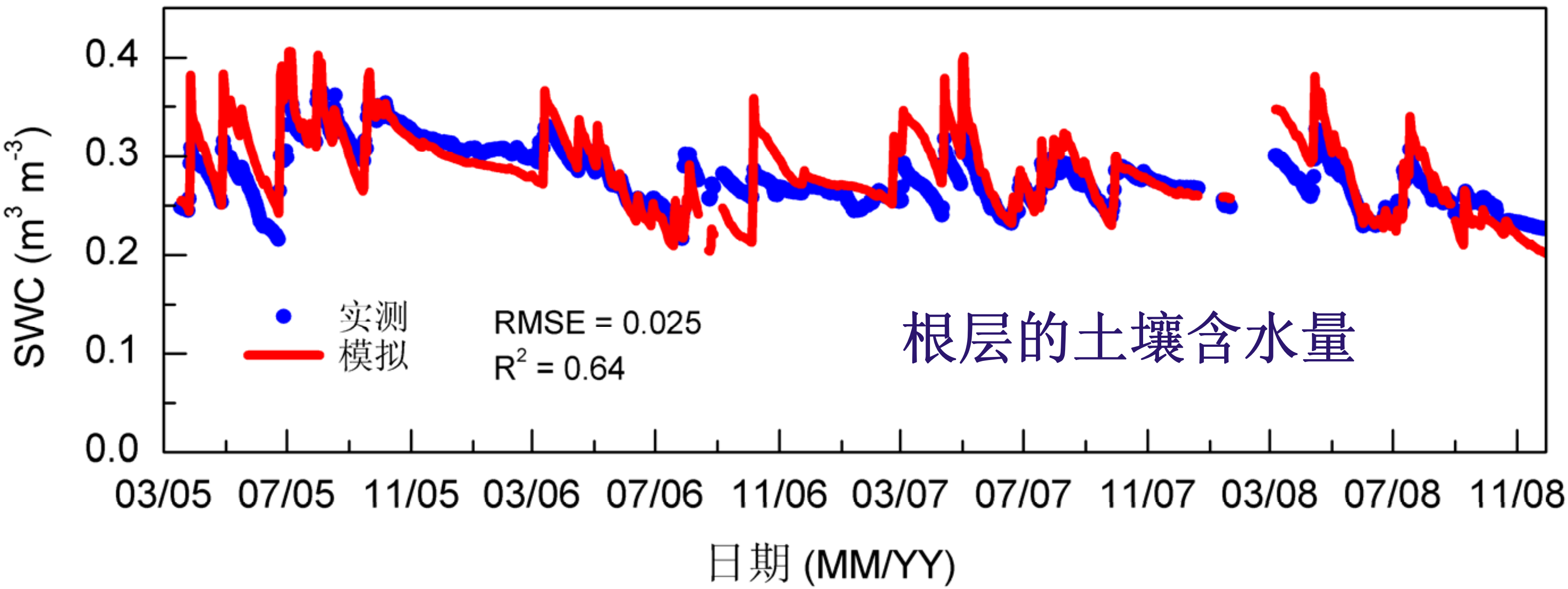
田间尺度生态水文模型(HELP)的验证



小麦 玉米

净辐射	潜 热
显 热	NEE

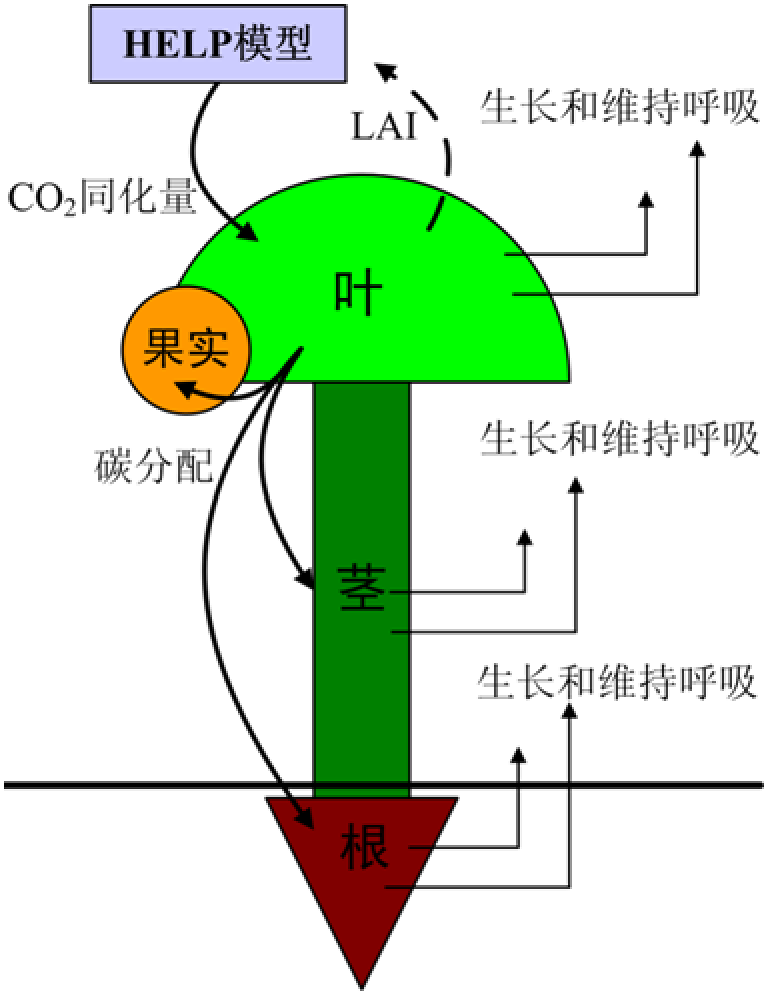
➢田间尺度生态水文模型(HELP)的验证

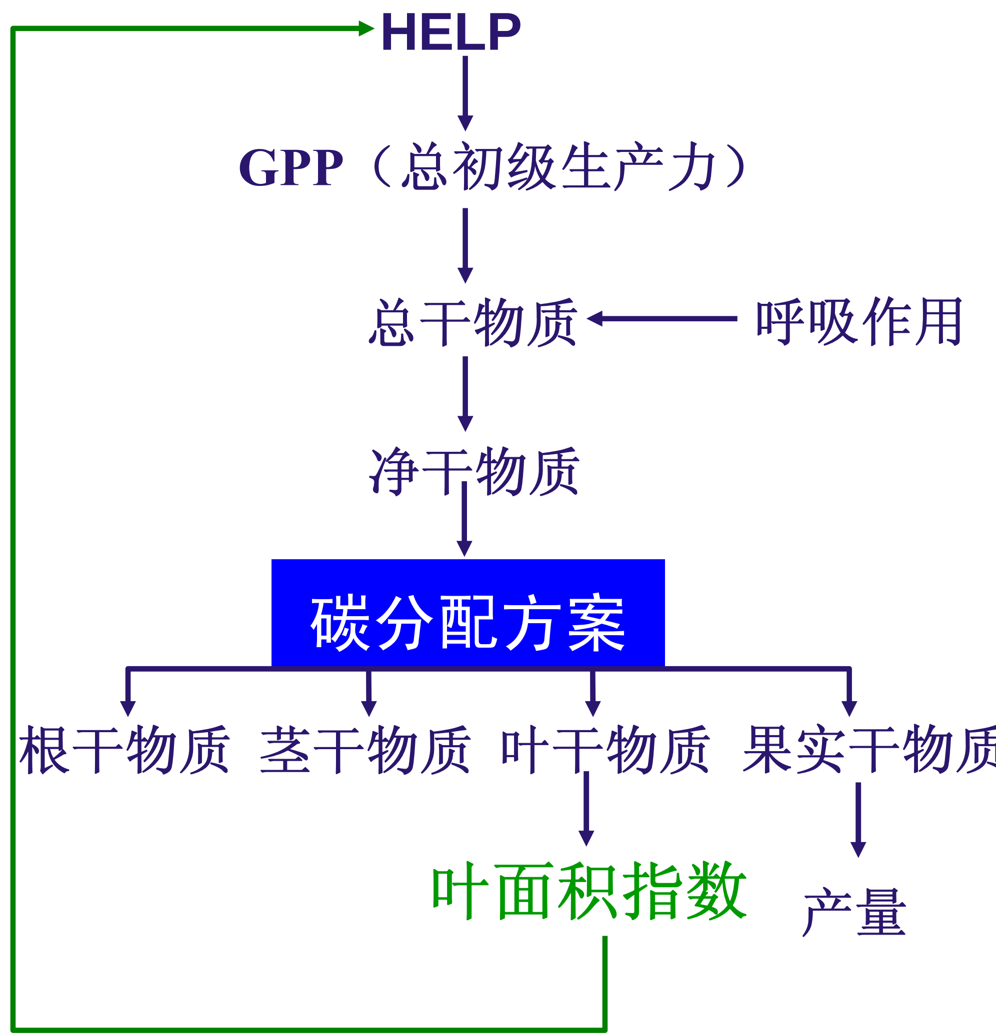


➢ 基于实测通量数据的验证表明，HELP能够准确模拟λE和*NEE*，为区域尺度水分及碳循环的模拟提供了可靠的工具。

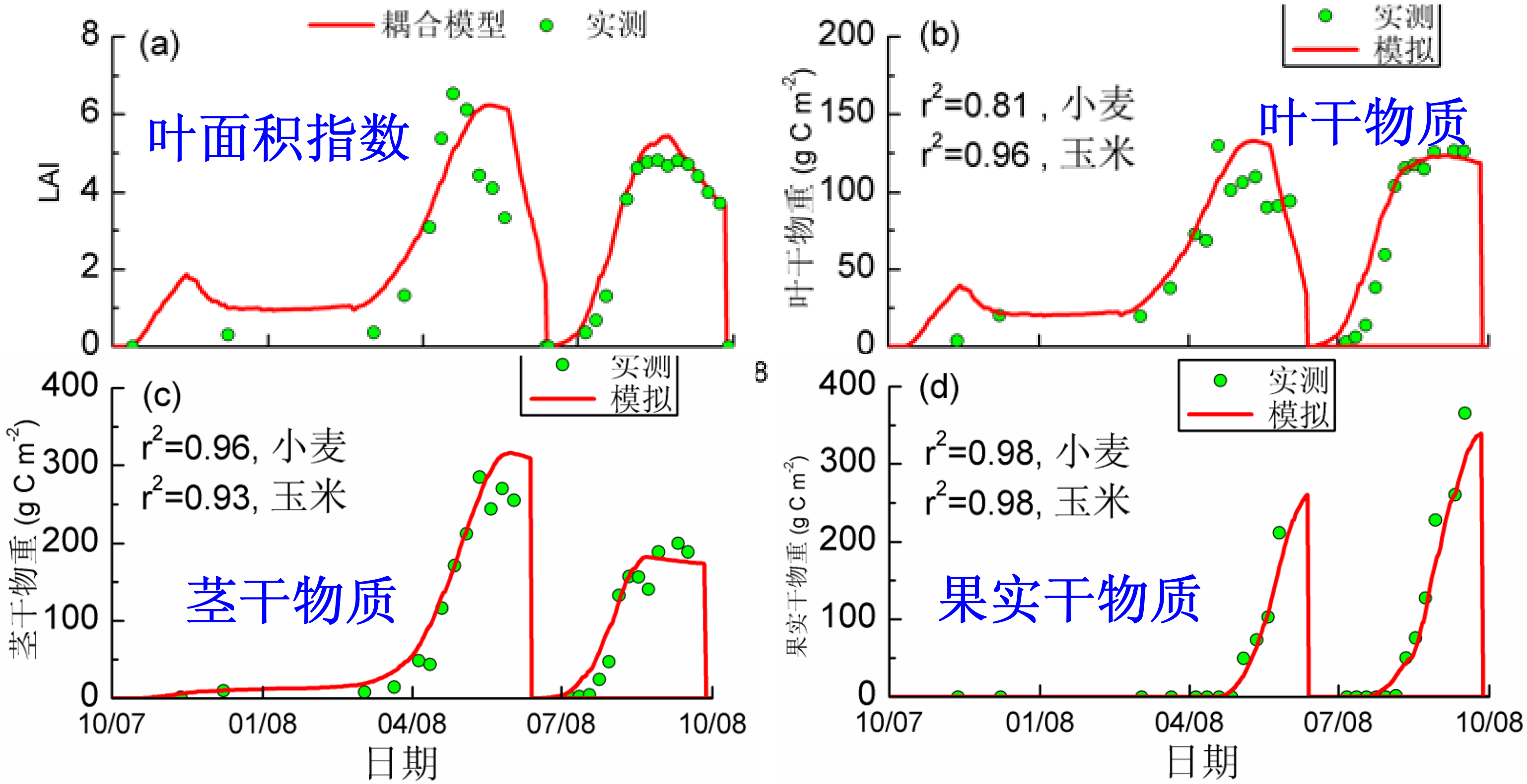
3.2 HELP与作物模型的耦合(HELP-C)

HELP-C (HELP coupled with Crop growth model)

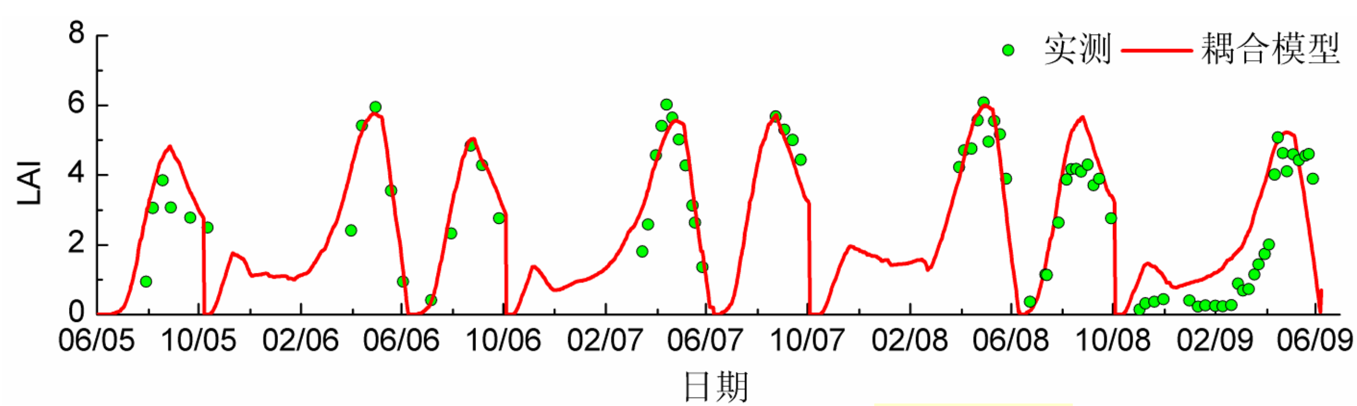




➤田间尺度生态水文模型(HELP-C)的验证

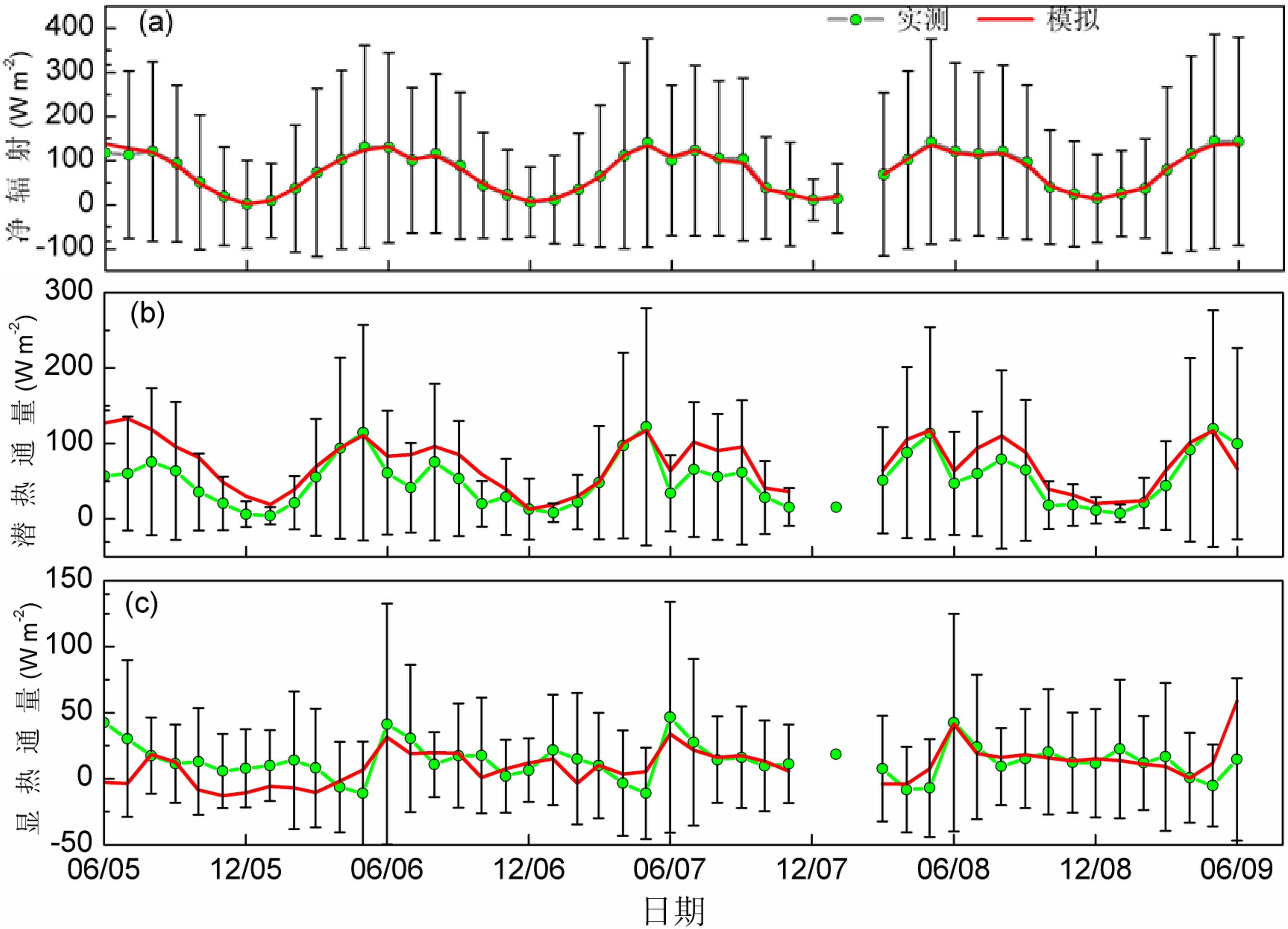


河北栾城

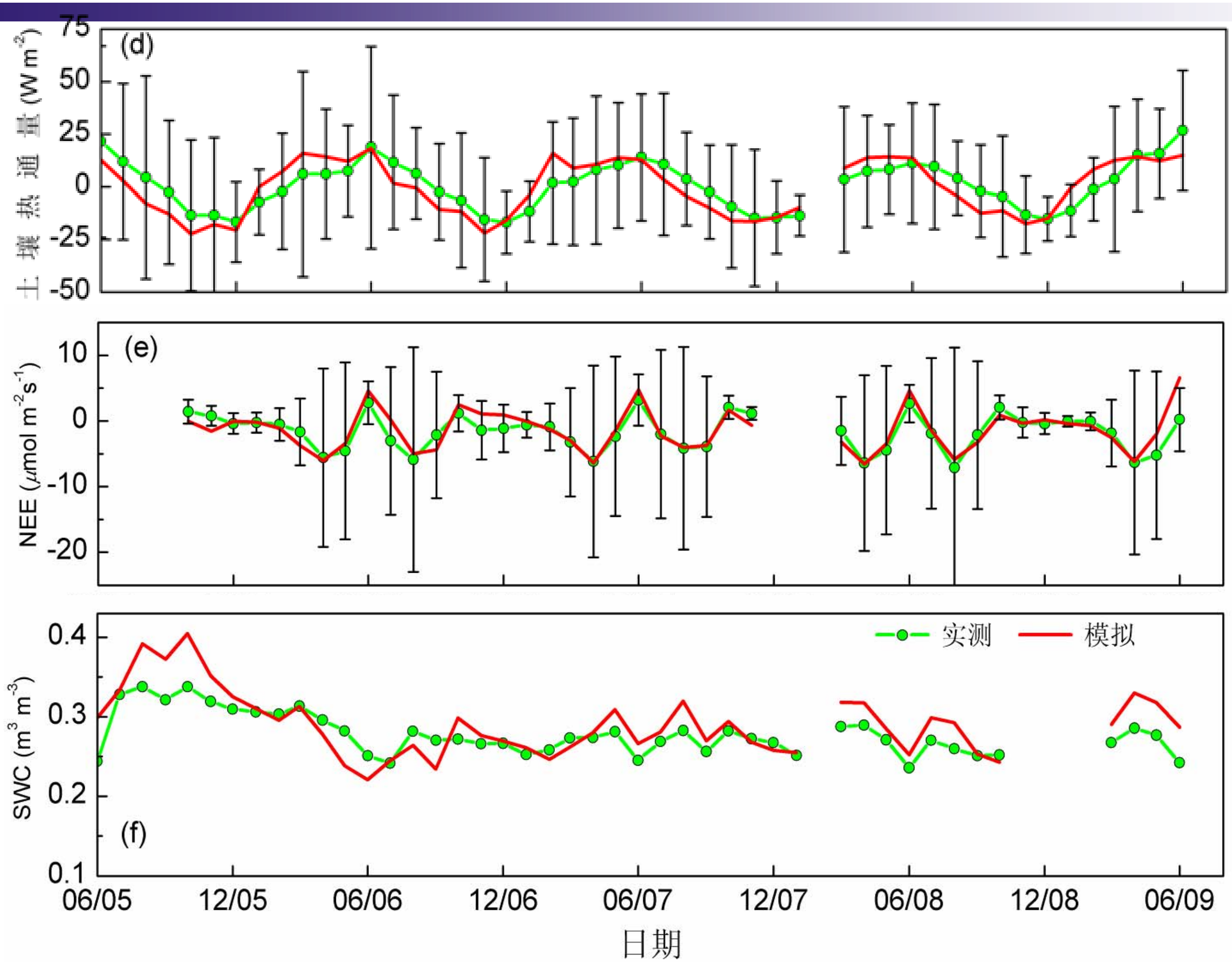


山东位山

➤田间尺度生态水文模型(HELP-C)的验证

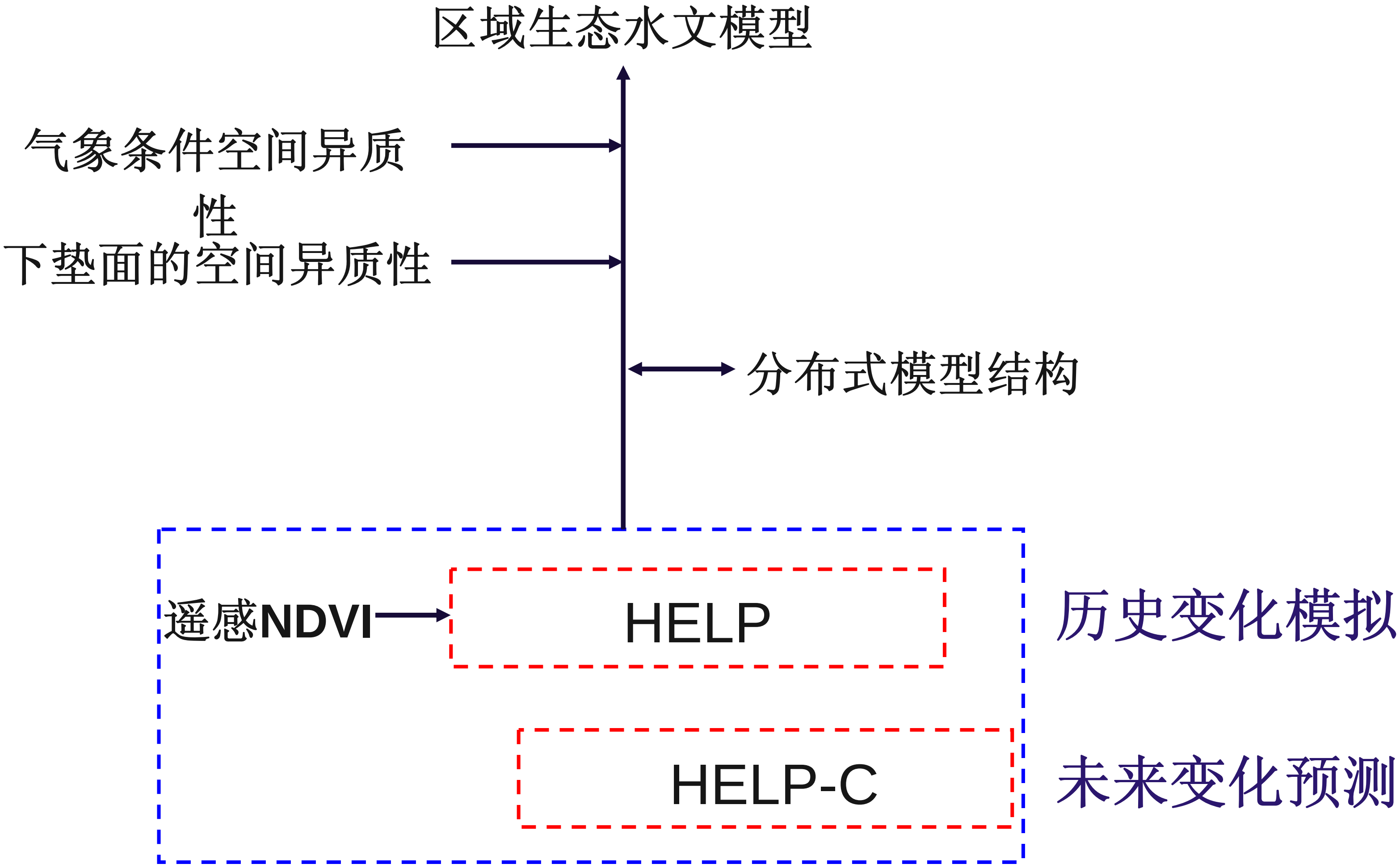


➢田间尺度生态水文模型(HELP-C)的验证

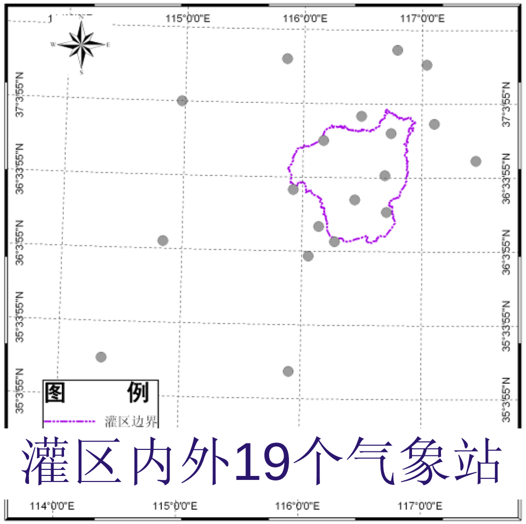


➢ HELP-C能较好模拟生物量和叶面积指数，能量通量、CO_2通量及土壤水分，为预测未来气候变化对灌区蒸散发及粮食产量的影响提供了工具。

3.3 区域尺度的生态水文模型

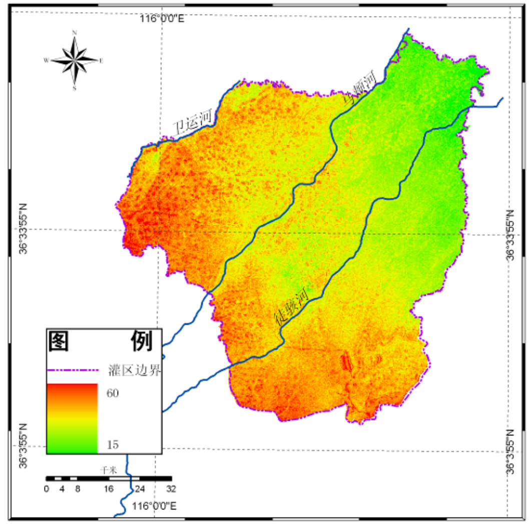


气象站网

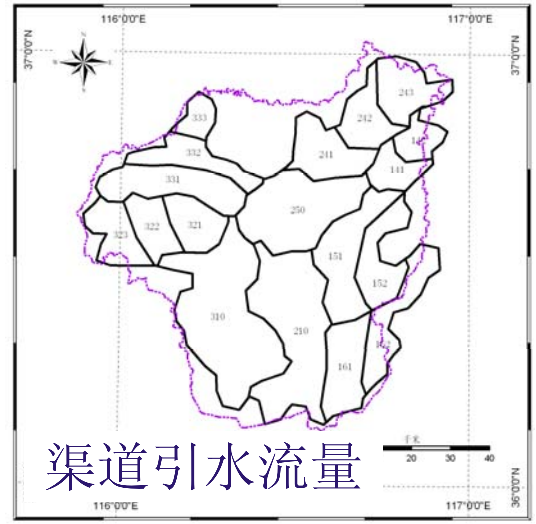


灌区内外19个气象站

DEM

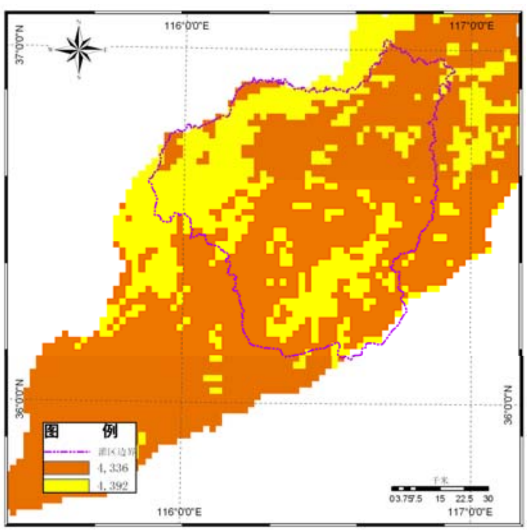


灌域分区



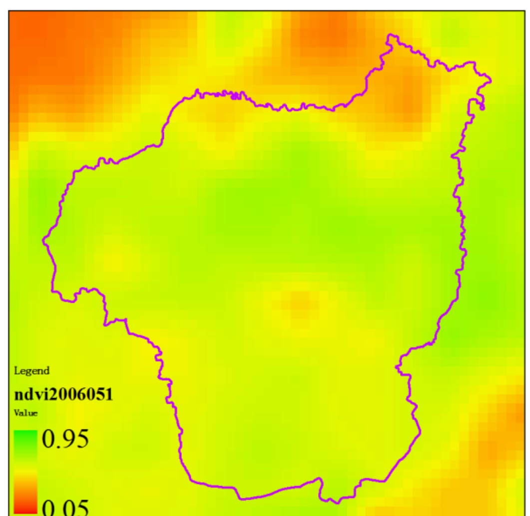
渠道引水流量

土壤类型分布

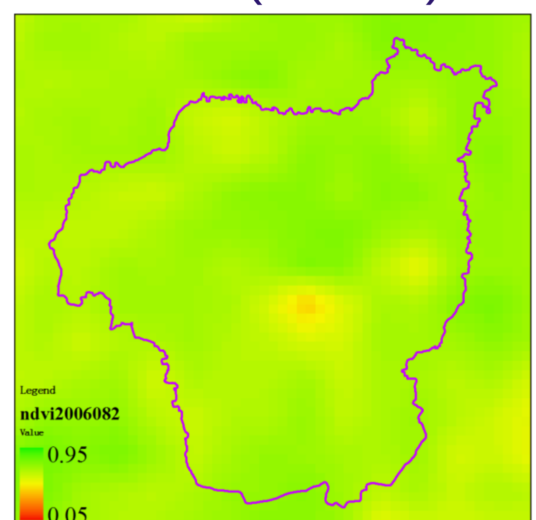


（1985,1995及2000年）

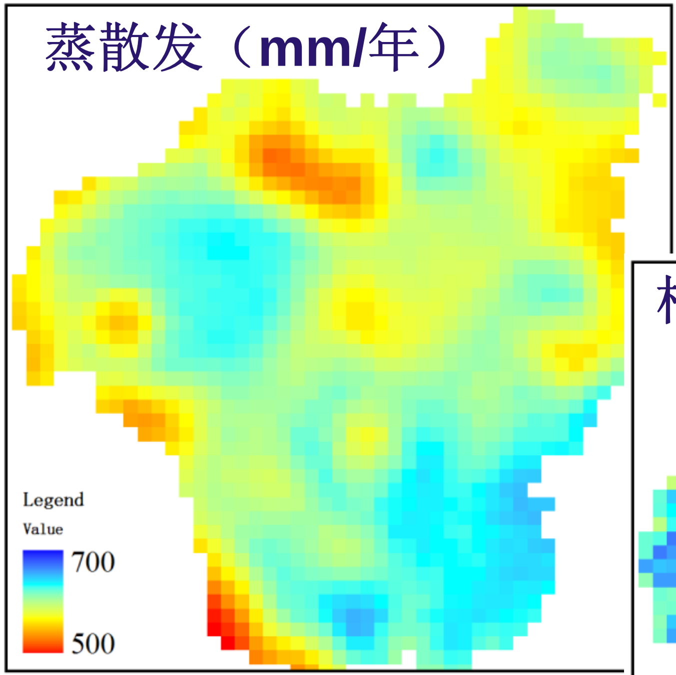
NDVI(2006.5)

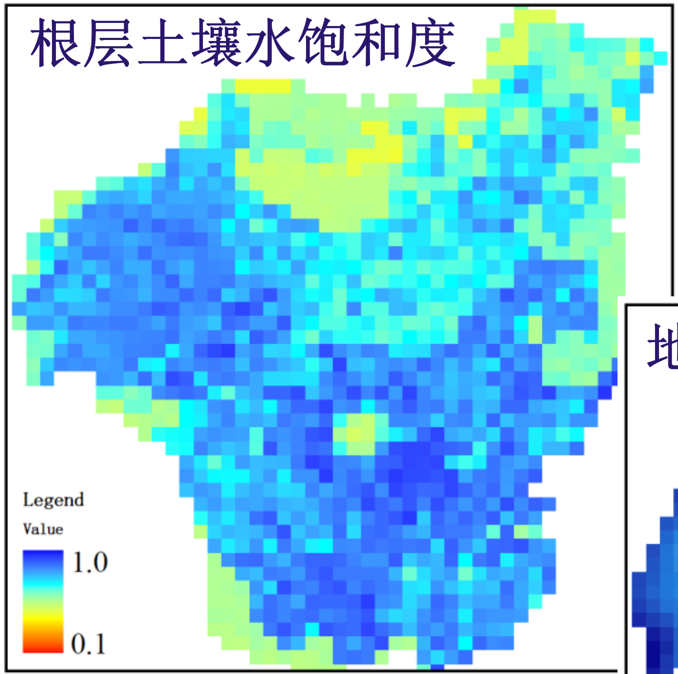


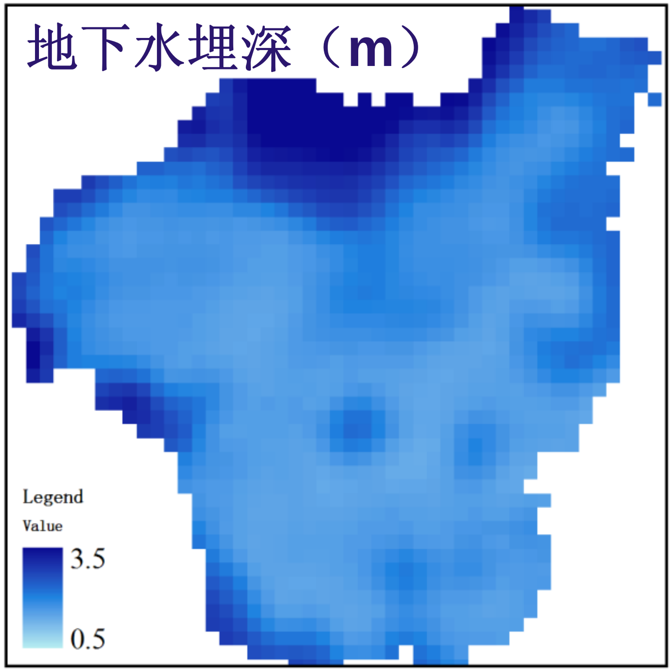
NDVI(2006.8)



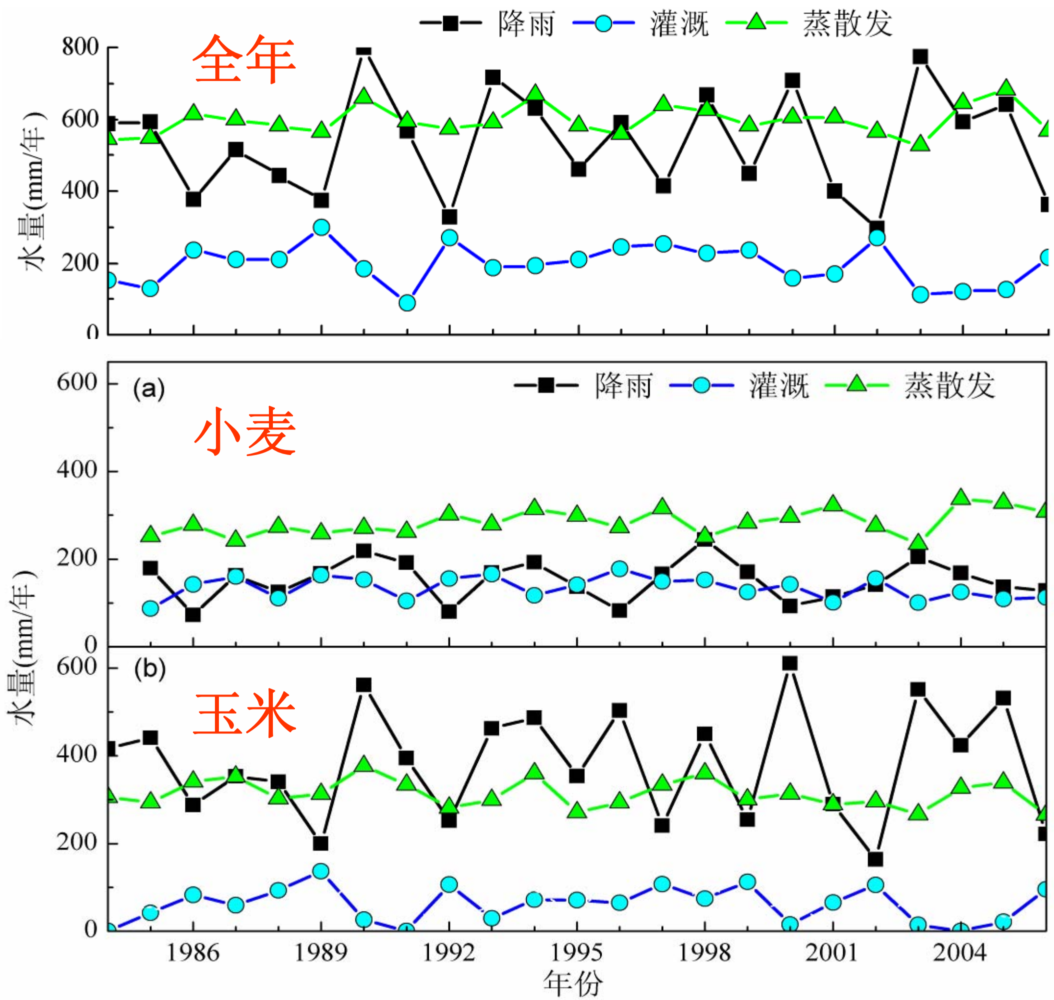
➢多年平均的水量平衡要素







➢ 灌区蒸散发变化过程



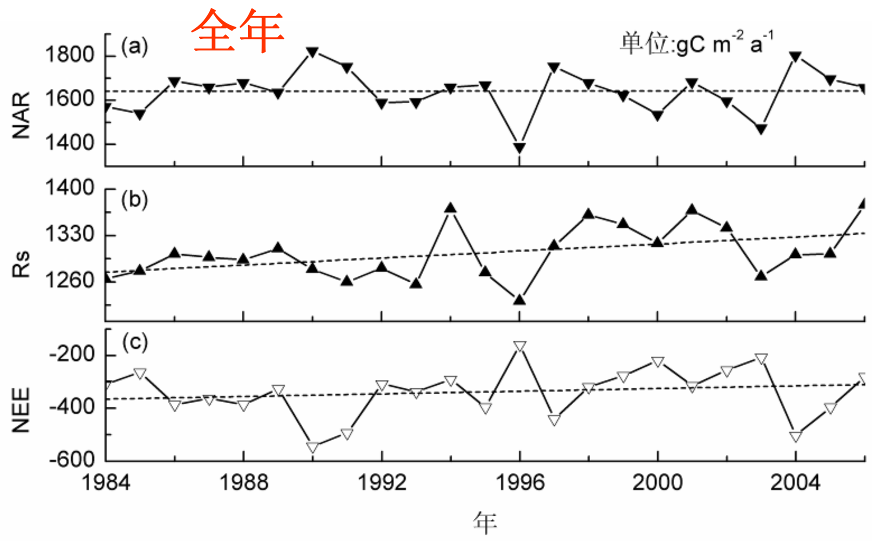
（1984~2006年）

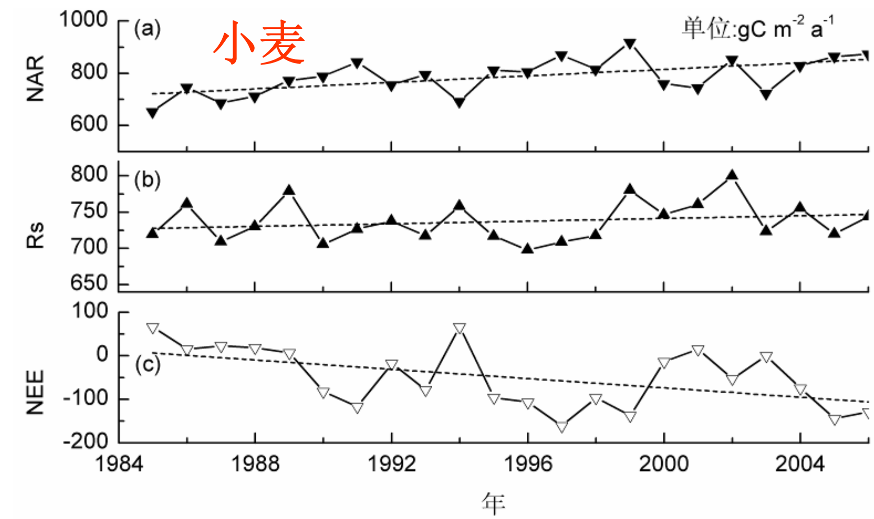
- 多年平均降雨和灌溉分别为534和196 mm；多年平均蒸散发为596 mm
- 降雨年际变异性大，蒸散发量年际变异性小
- 小麦季节的蒸散发量有升高趋势

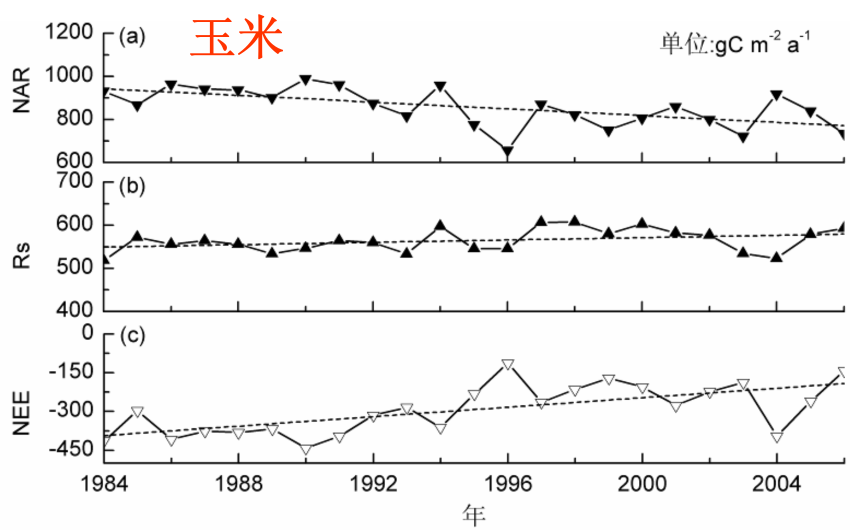
➢ 灌区不同年代的水量平衡特征

时 期	降雨量（mm）	灌溉量（mm）	总供水量 (mm)	蒸散发量（mm）	灌溉量/供水量	蒸散发量/供水量
1984-1989	482	**206**	688	**574**	30%	83%
1990-1999	562	**210**	772	**607**	27%	79%
2000-2006	539	**167**	706	**599**	24%	85%
23年的平均值	534	196	730	596	27%	82%

➤碳平衡要素的年际变化



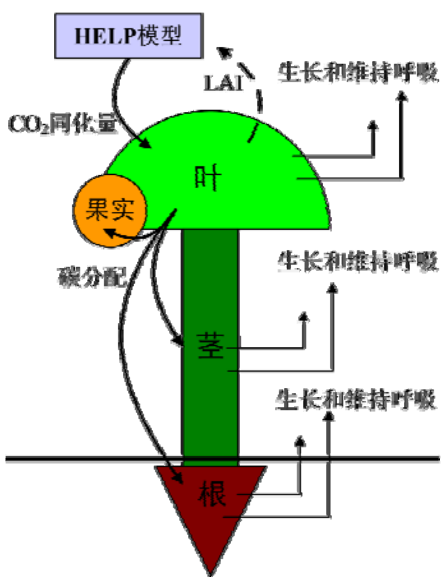


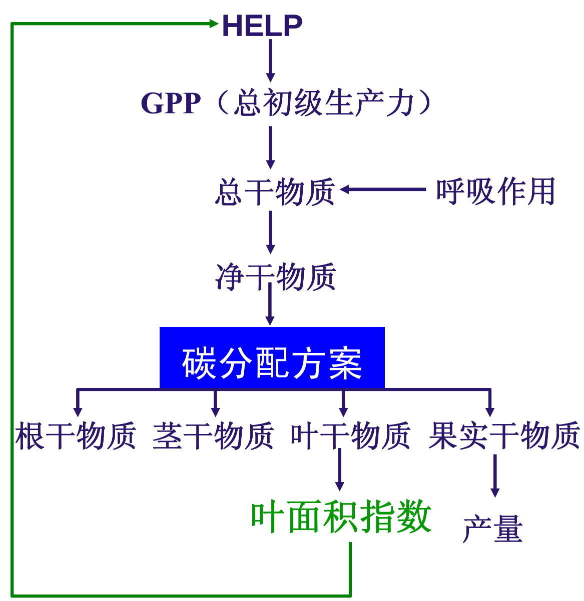


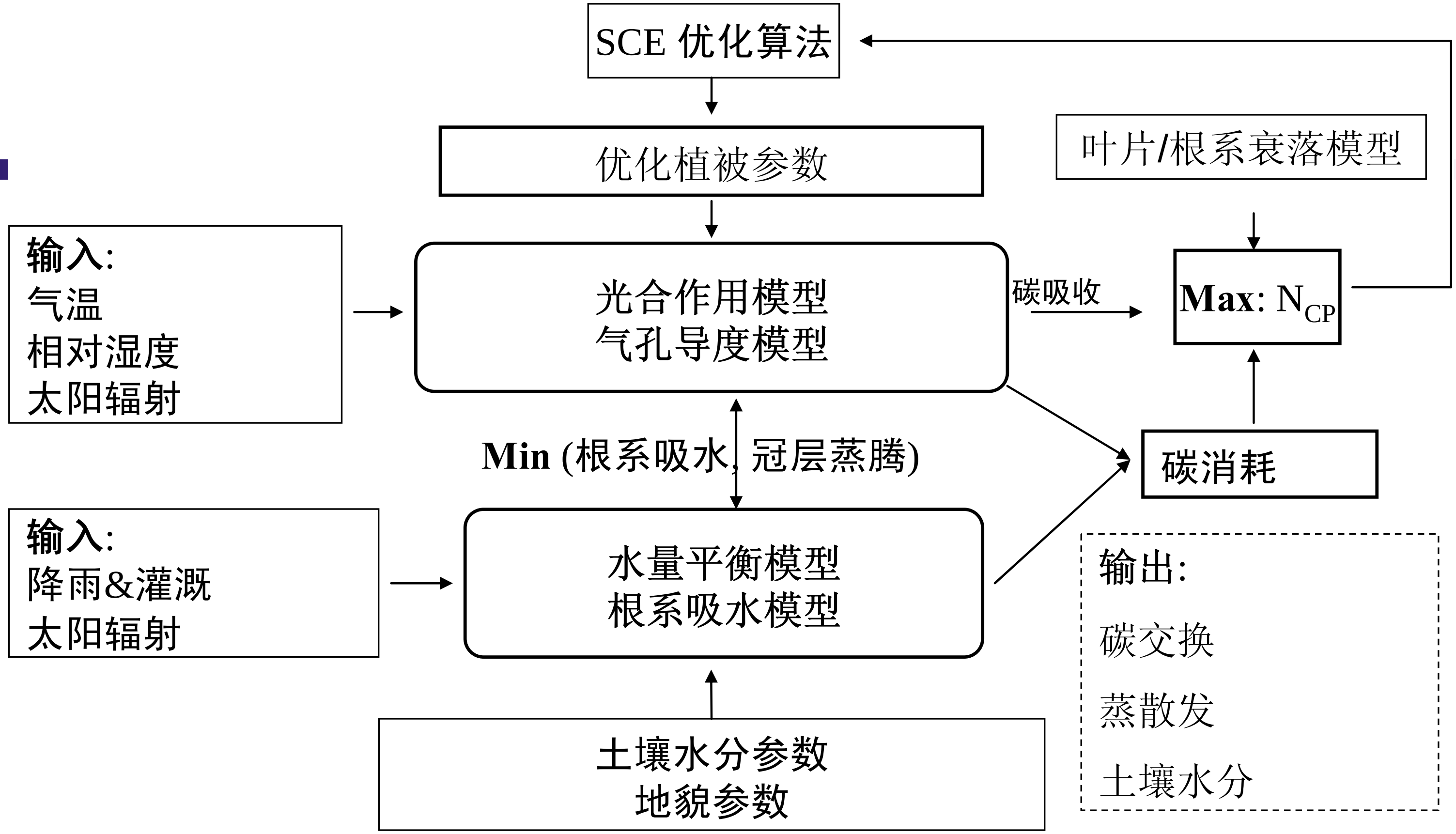
- 年净同化速率NAR、土壤呼吸Rs及碳交换量NEE均无显著变化趋势
- 小麦NAR显著增长，Rs无显著变化，NEE显著下降（碳汇变强）
- 玉米NAR显著下降，Rs无显著变化，NEE显著升高（碳汇变弱）
- 仅考虑气象因素时，冬小麦和夏玉米的NAR均呈下降趋势
- 作物品种的改良、施肥增加能够抵消气候变化对NAR的负面影响

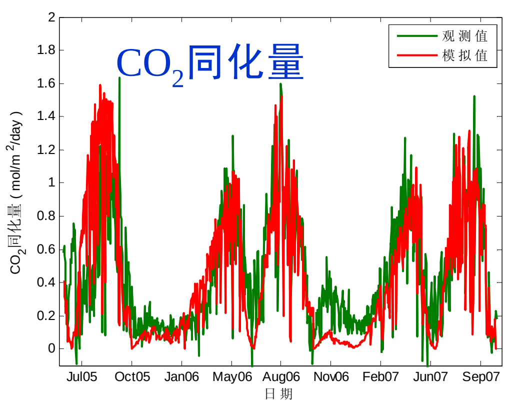
3.4 基于生态最适性假设的流域生态水文模型

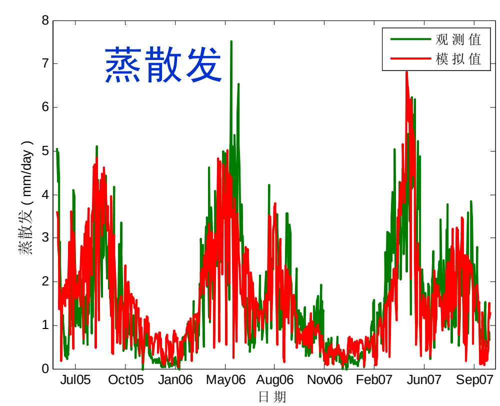
- **生态最适性：**自然选择和生存竞争导致植物对资源（水分、阳光和CO_2）的最佳利用
- **可调节的因子：**如气孔导度，冠层覆盖率，根深等
- **目标函数：**如光合作用最大化，胁迫最小化等
- **约束条件：**水量、能量平衡，生物化学和生物物理约束等

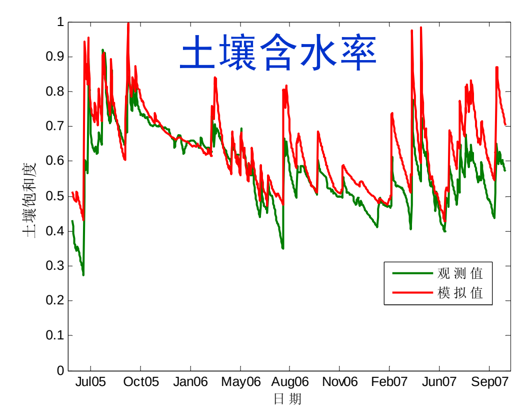





SCE 优化算法
优化植被参数
叶片/根系衰落模型
输入:
气温
相对湿度
太阳辐射
光合作用模型
气孔导度模型
碳吸收
Max: N_{CP}
Min (根系吸水, 冠层蒸腾)
碳消耗
输入:
降雨&灌溉
太阳辐射
水量平衡模型
根系吸水模型
输出:
碳交换
蒸散发
土壤水分
土壤水分参数
地貌参数

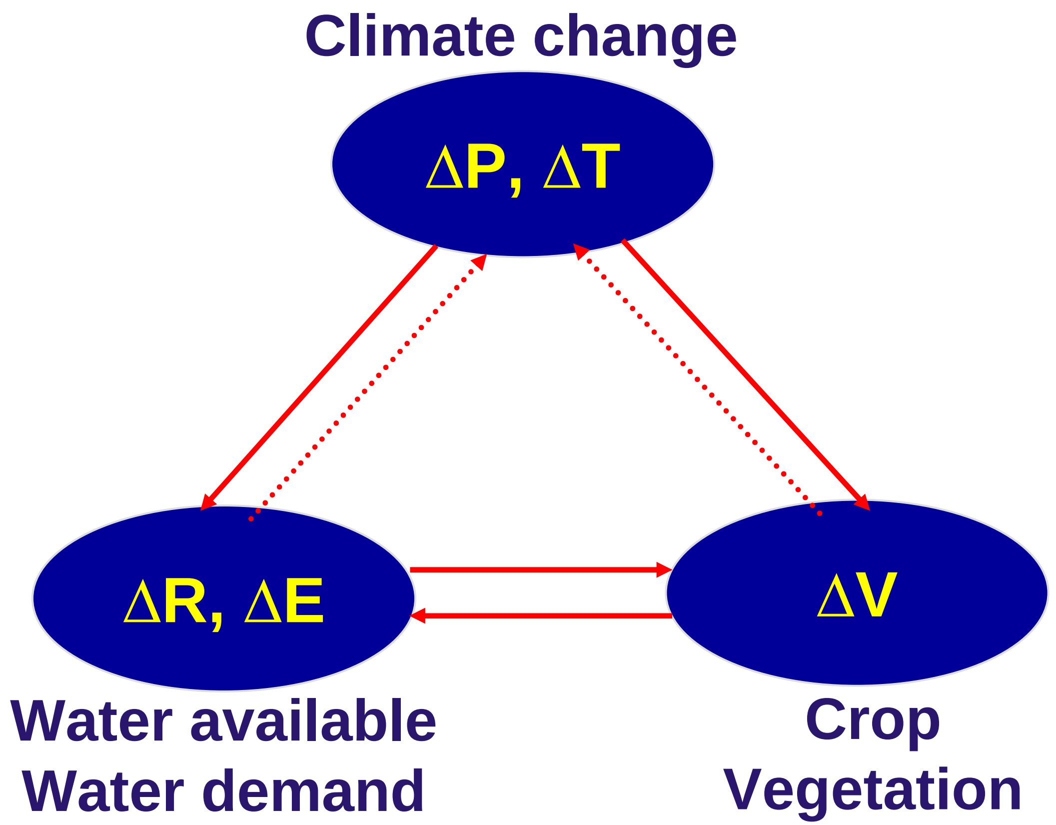

CO_2同化量
观测值
模拟值
CO_2同化量（mol/m ^{2}/day）
Jul05 Oct05 Jan06 May06 Aug06 Nov06 Feb07 Jun07 Sep07
日期


蒸散发
观测值
模拟值
蒸散发（mm/day）
Jul05 Oct05 Jan06 May06 Aug06 Nov06 Feb07 Jun07 Sep07
日期


土壤含水率
观测值
模拟值
土壤饱和度
Jul05 Oct05 Jan06 May06 Aug06 Nov06 Feb07 Jun07 Sep07
日期

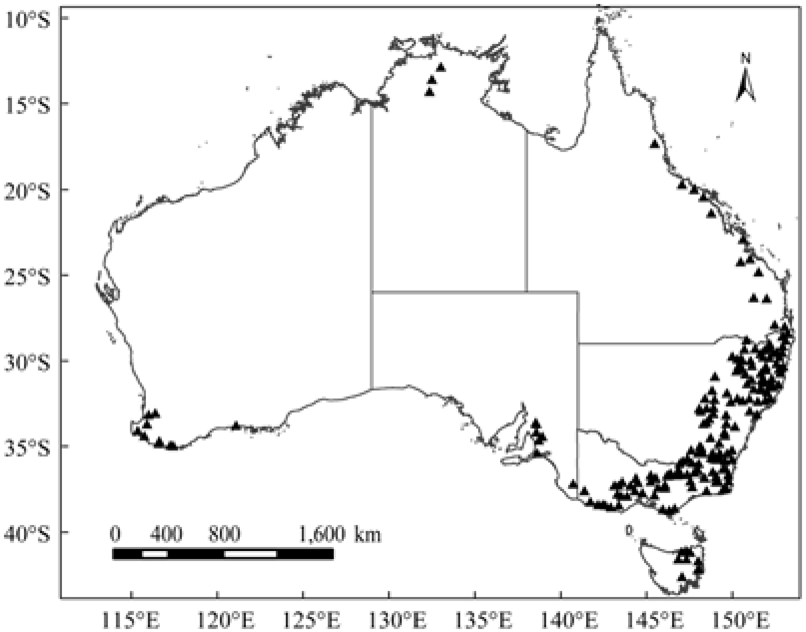
四、气候变化的生态水文响应

- **To assess/predict impacts of the climate change**
  - ❖ Understanding the eco-hydrological processes
  - ❖ Effective model to simulate the soil-vegetation-atmosphere interaction



4.1 基于统计回归方法的气候弹性分析

1. 澳洲193个典型流域分析



核心问题：气候、水文(总径流、地表和地下径流)、植被覆盖(总植被、森林和非森林覆盖)之间的关系。

(1) 径流变化与降雨、气温、土壤水(前期降雨)变化的定量关系

$$\frac{\Delta R_i}{\overline{R}} = \varepsilon_R^P \frac{\Delta P_i}{\overline{P}} + \varepsilon_R^{P_{-1}} \frac{\Delta P_{-1}}{\overline{P}} + \cdots + \varepsilon_R^{P_{-n}} \frac{\Delta P_{-n}}{\overline{P}} + \varepsilon_R^T \Delta T_i$$

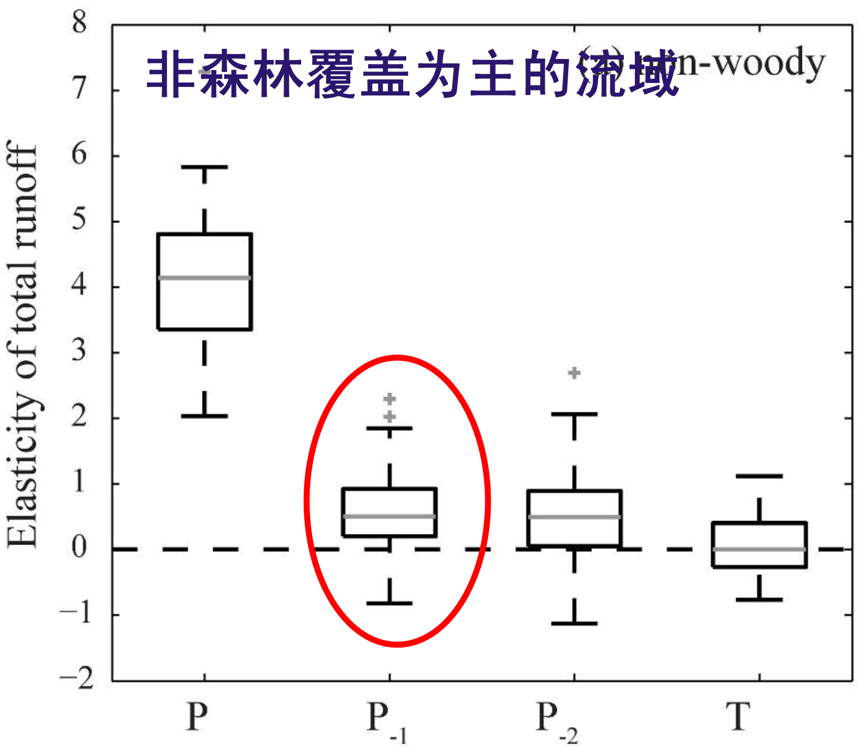
$$\frac{\Delta R_{s,i}}{\overline{R_s}} = \varepsilon_{R_s}^P \frac{\Delta P_i}{\overline{P}} + \varepsilon_{R_s}^{P_{-1}} \frac{\Delta P_{-1}}{\overline{P}} + \cdots + \varepsilon_{R_s}^{P_{-n}} \frac{\Delta P_{-n}}{\overline{P}} + \varepsilon_{R_s}^T \Delta T_i$$

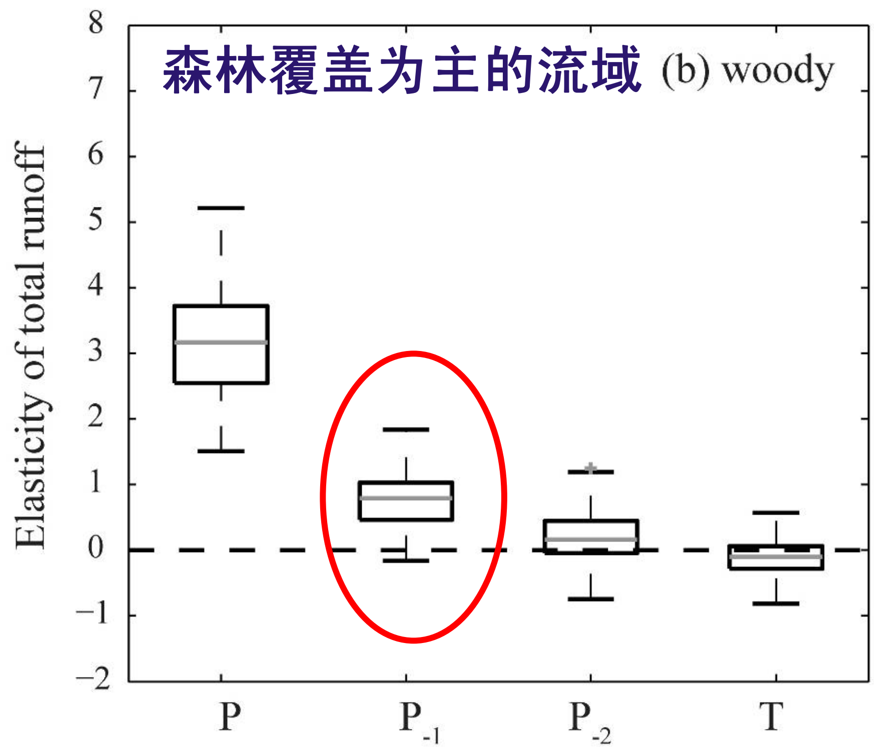
$$\frac{\Delta R_{g,i}}{\overline{R_g}} = \varepsilon_{R_g}^P \frac{\Delta P_i}{\overline{P}} + \varepsilon_{R_g}^{P_{-1}} \frac{\Delta P_{-1}}{\overline{P}} + \cdots + \varepsilon_{R_g}^{P_{-n}} \frac{\Delta P_{-n}}{\overline{P}} + \varepsilon_{R_g}^T \Delta T_i$$

↑ 总径流 地表/地下径流
↑ 降雨量
↑ 前期降雨(土壤水)
↑ 气温

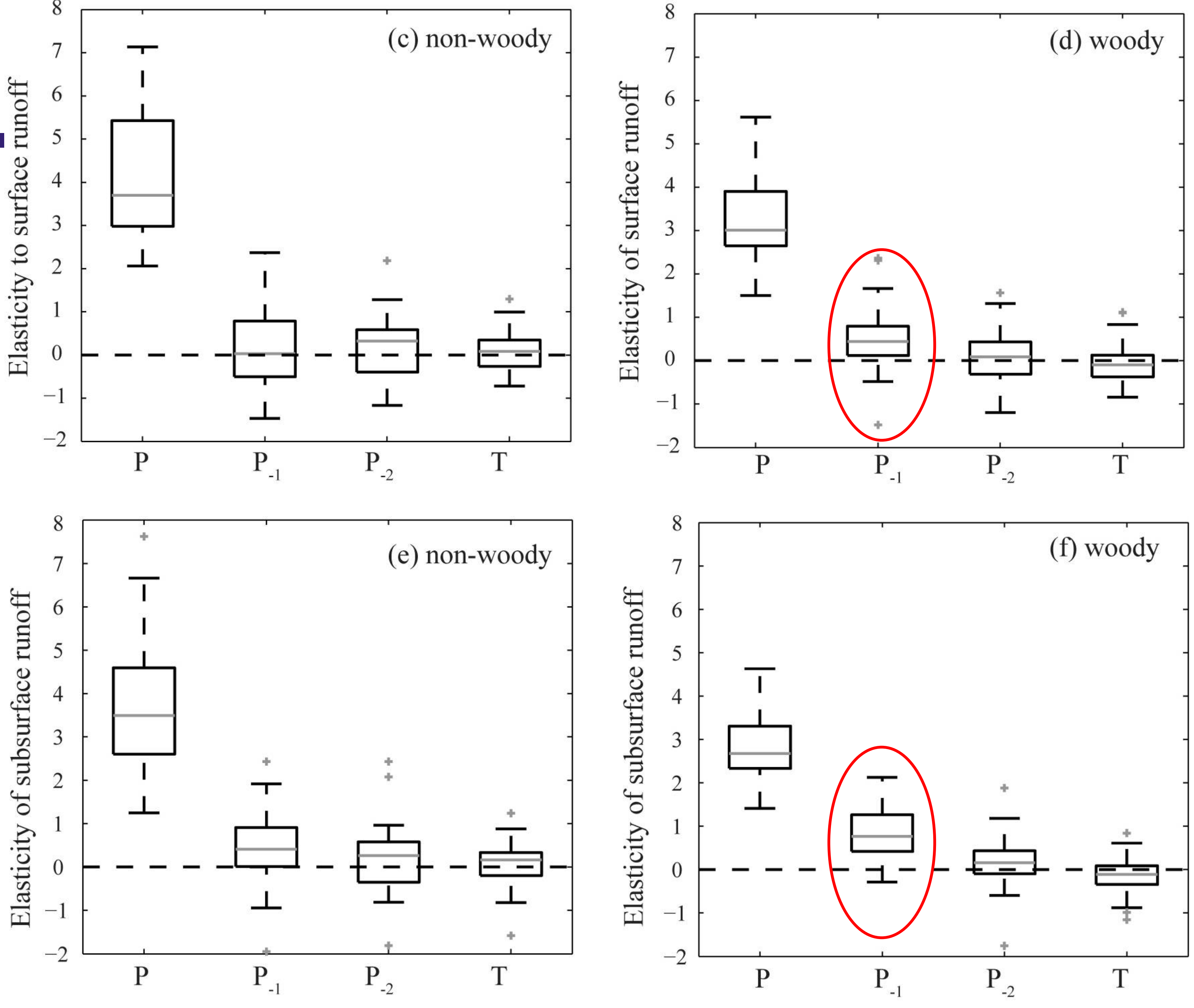
■气候因子变化对流域年总径流的影响程度

- ➢降水增加1%导致年径流量增加（+）或减少（-）的百分数
- ➢气温升高1℃导致年径流量增加（+）或减少（-）的百分数





地表径流



(c) non-woody
Elasticity to surface runoff
(d) woody
Elasticity of surface runoff
(e) non-woody
Elasticity of subsurface runoff
(f) woody
Elasticity of subsurface runoff
P
P-1
P-2
T

地下径流

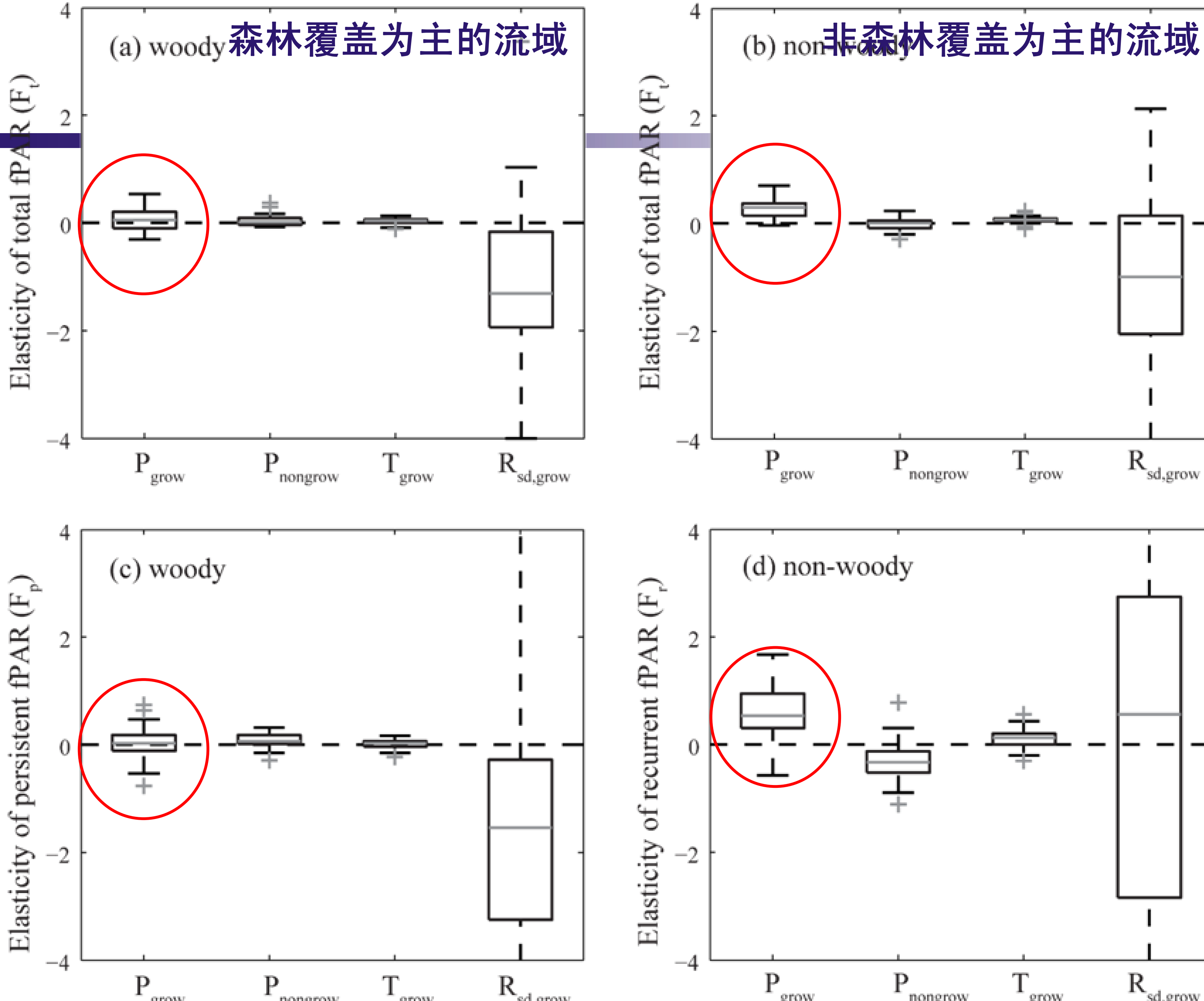
(2) 植被变化与降雨、日照、气温、土壤水变化的定量关系

$$\frac{\Delta F_{t,i}}{\overline{F_t}} = \varepsilon_{F_t}^{P_{grow}} \frac{\Delta P_{grow,i}}{\overline{P_{grow}}} + \varepsilon_{F_t}^{P_{nongrow}} \frac{\Delta P_{nongrow,i}}{\overline{P_{nongrow}}} + \varepsilon_{F_t}^{T_{grow}} \Delta T_{grow,i} + \varepsilon_{F_t}^{R_{sd,grow}} \frac{\Delta R_{sd,grow,i}}{\overline{R_{sd,grow}}}$$

$$\frac{\Delta F_{p,i}}{\overline{F_p}} = \varepsilon_{F_p}^{P_{grow}} \frac{\Delta P_{grow,i}}{\overline{P_{grow}}} + \varepsilon_{F_p}^{P_{nongrow}} \frac{\Delta P_{nongrow,i}}{\overline{P_{nongrow}}} + \varepsilon_{F_p}^{T_{grow}} \Delta T_{grow,i} + \varepsilon_{F_p}^{R_{sd,grow}} \frac{\Delta R_{sd,grow,i}}{\overline{R_{sd,grow}}}$$

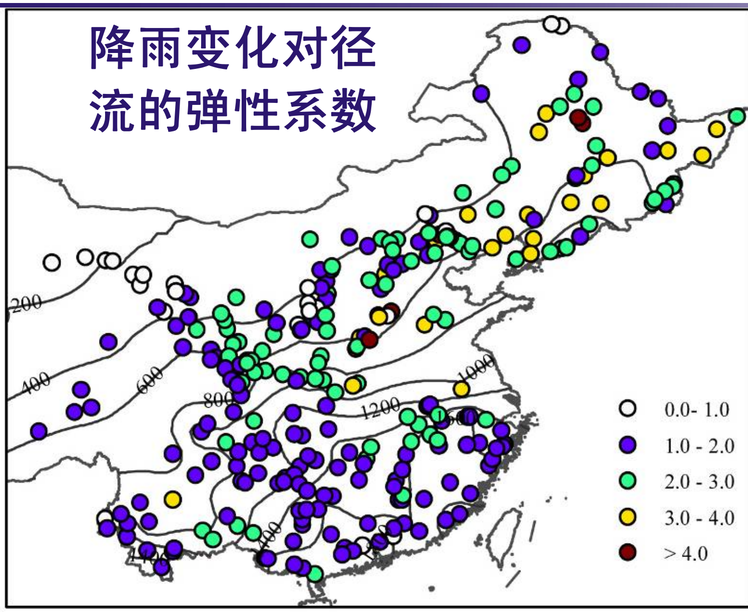
$$\frac{\Delta F_{r,i}}{\overline{F_r}} = \varepsilon_{F_r}^{P_{grow}} \frac{\Delta P_{grow,i}}{\overline{P_{grow}}} + \varepsilon_{F_p}^{P_{nongrow}} \frac{\Delta P_{nongrow,i}}{\overline{P_{nongrow}}} + \varepsilon_{F_r}^{T_{grow}} \Delta T_{grow,i} + \varepsilon_{F_r}^{R_{sd,grow}} \frac{\Delta R_{sd,grow,i}}{\overline{R_{sd,grow}}}$$

↑	↑	↑	↑	↑
总植被 森林 非森林	生长期 降雨量	土壤水 (非生长 期降雨)	生长期 气温	生长期 日照

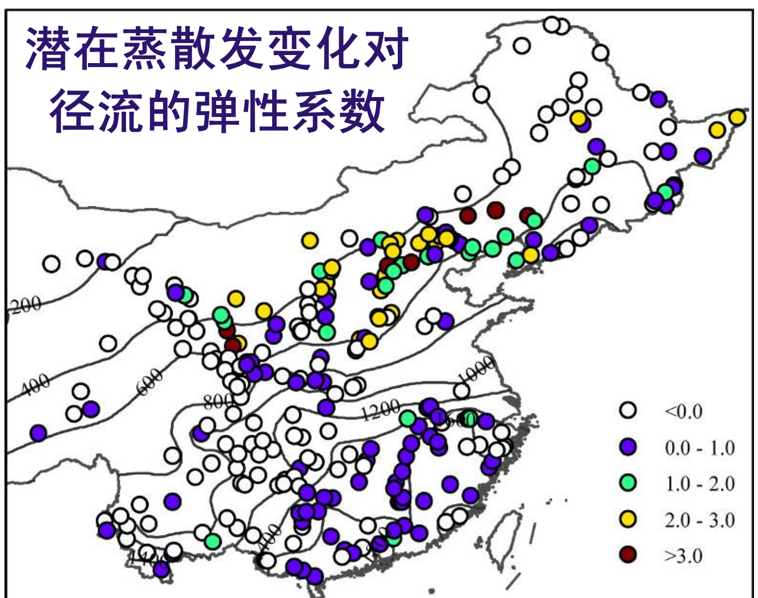


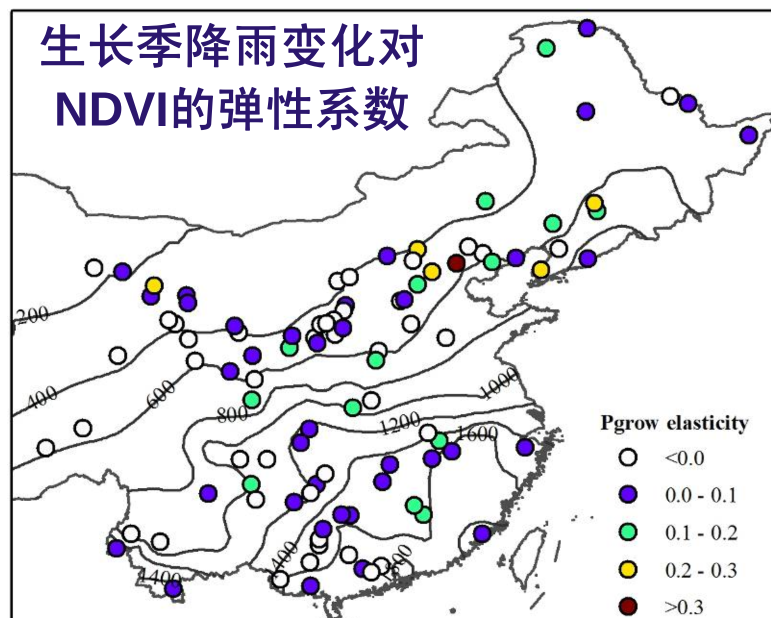
(a) woody
森林覆盖为主的流域
(b) non-woody
非森林覆盖为主的流域
(c) woody
(d) non-woody
Elasticity of total fPAR (F_t)
Elasticity of persistent fPAR (F_p)
Elasticity of recurrent fPAR (F_r)
P_{grow}
$P_{nongrow}$
T_{grow}
$R_{sd,grow}$
4
2
0
−2
−4

2. 中国296个典型流域分析



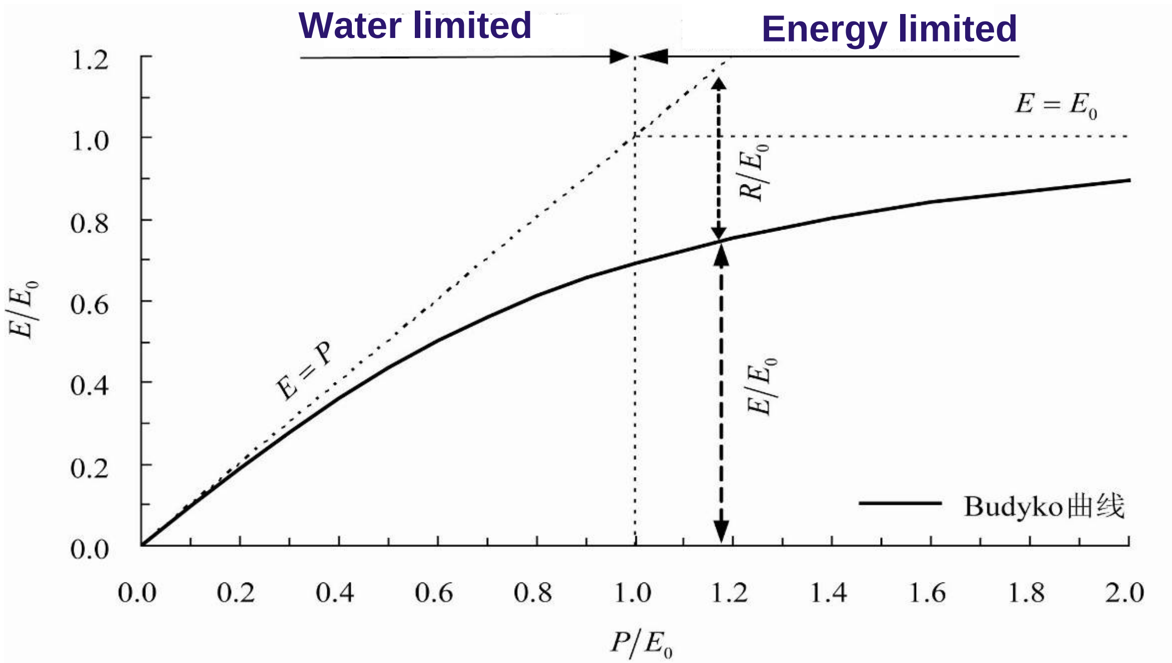
初步结论：北方流域生态水文(径流、蒸散发、NDVI) 对气候变化更为敏感。





4.2 基于流域水热耦合平衡方程的气候弹性分析

Budyko Hypothesis (1974): $E/P = f\left(E_0/P\right)$



- In dry climate, change of actual evapotranspiration (E) is dominated by change in precipitation (P) rather than in potential evaporation (E_0).
- In humid climate, the change of actual evapotranspiration (E) is controlled by change in potential evaporation (E_0) rather than precipitation (P).

Yang & Sun, et. al, Geophysical Research Letters, 2006

Elasticity of annual runoff to the climate change

$$E = \frac{E_0 P}{\left(P^n + E_0^n\right)^{1/n}}$$

Neglecting change of catchment storage →

$$R = P - \frac{E_0 P}{\left(P^n + E_0^n\right)^{1/n}}$$

By differentiating →

$$\frac{dR}{R} = \varepsilon_1 \cdot \frac{dP}{P} + \varepsilon_2 \cdot \frac{dE_0}{E_0}$$

$$\varepsilon_1 = \frac{\left(1 - \partial E / \partial P\right) P}{P - E}$$

Elasticity of runoff to change of P

$$\varepsilon_2 = -\frac{\partial E / \partial E_0 \cdot E_0}{P - E}$$

Elasticity of runoff to change of E_0

Yang, et al., Water resources Research, 2009.

Elasticity of annual runoff to the climate change

From Penman equation:

$$E_0 = \frac{\Delta}{\Delta + \gamma}(R_n - G)/\lambda + \frac{\gamma}{\Delta + \gamma} \cdot 6.43(1 + 0.536U_2)\left(1 - RH\right) e_s / \lambda$$

Differentiating →

$$dE_0 \approx \frac{\partial E_0}{\partial R_n} \cdot dR_n + \frac{\partial E_0}{\partial T} \cdot dT + \frac{\partial E_0}{\partial U_2} \cdot dU_2 + \frac{\partial E_0}{\partial RH} \cdot dRH$$

Substitution →

$$\frac{dR}{R} = \varepsilon_1 \cdot \frac{dP}{P} + \varepsilon_2 \cdot \frac{dE_0}{E_0}$$

$$\frac{dR}{R} = \varepsilon_1 \frac{dP}{P} + \varepsilon_2 \varepsilon_3 \frac{dR_n}{R_n} + \varepsilon_2 \varepsilon_4 dT + \varepsilon_2 \varepsilon_5 \frac{dU_2}{U_2} + \varepsilon_2 \varepsilon_6 \frac{dRH}{RH}$$

Elasticity of annual runoff to the climate change

$$\frac{dR}{R} = \varepsilon_1 \frac{dP}{P} + \varepsilon_2\varepsilon_3 \frac{dR_n}{R_n} + \varepsilon_2\varepsilon_4 dT + \varepsilon_2\varepsilon_5 \frac{dU_2}{U_2} + \varepsilon_2\varepsilon_6 \frac{dRH}{RH}$$

$$\varepsilon_1 = \frac{\bar{P}}{\bar{P} - \bar{E}} \left(1 - \left. \frac{\partial f}{\partial P} \right|_{P=\bar{P}, E_0=\bar{E}_0} \right)$$

$$\varepsilon_2 = -\frac{E_0}{P - E} \left(\left. \frac{\partial f}{\partial E_0} \right|_{P=\bar{P}, E_0=\bar{E}_0} \right)$$

$$\varepsilon_3 = \frac{\bar{R}_n}{\bar{E}_0} \cdot \left. \frac{\partial E_0}{\partial R_n} \right|_{R_n=\bar{R}_n, T=\bar{T}, U_2=\bar{U}_2, RH=\overline{RH}}$$

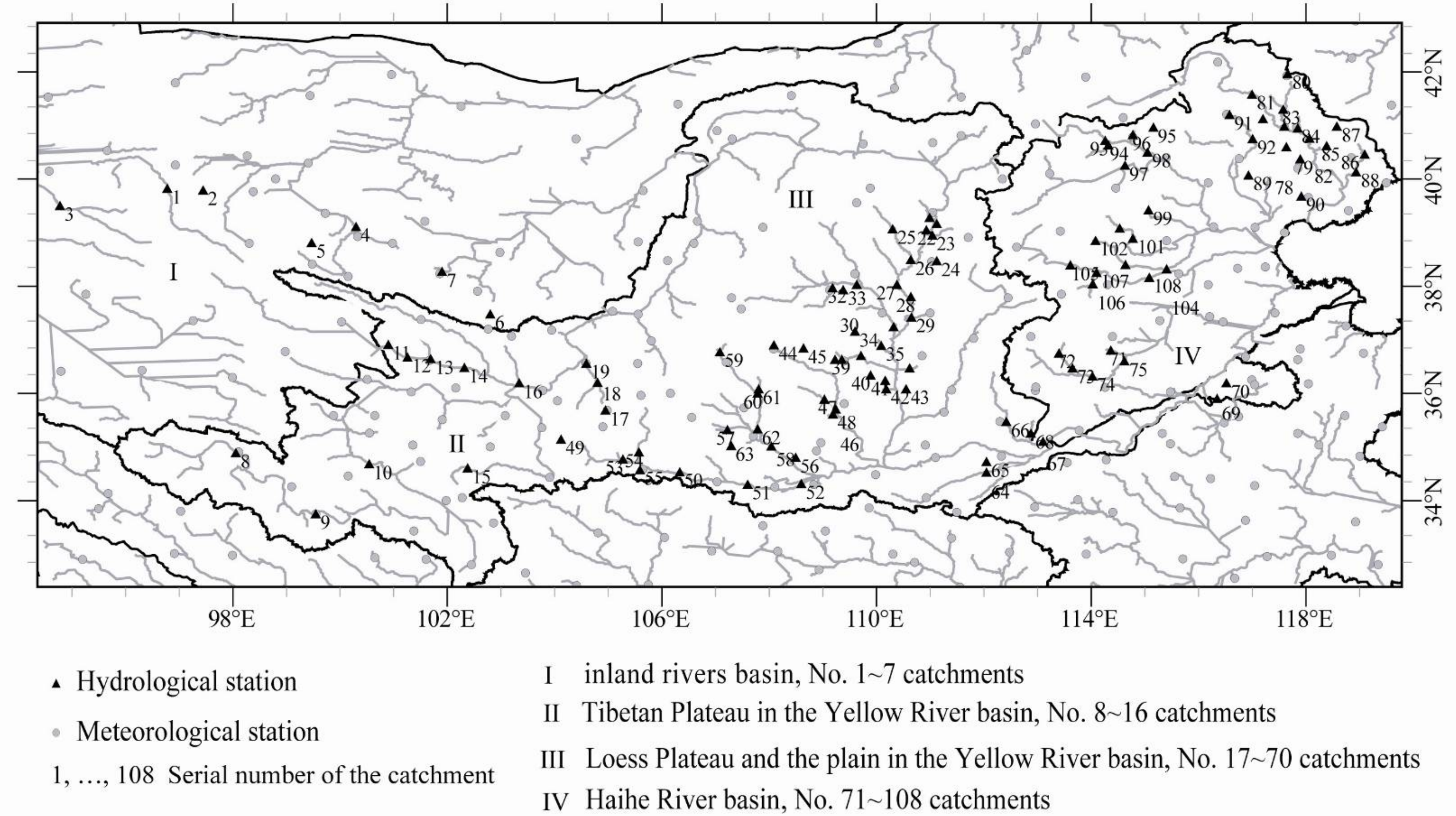
$$\varepsilon_4 = \frac{1}{\bar{E}_0} \cdot \left. \frac{\partial E_0}{\partial T} \right|_{R_n=\bar{R}_n, T=\bar{T}, U_2=\bar{U}_2, RH=\overline{RH}}$$

$$\varepsilon_5 = \frac{\bar{U}_2}{\bar{E}_0} \cdot \left. \frac{\partial E_0}{\partial U_2} \right|_{R_n=\bar{R}_n, T=\bar{T}, U_2=\bar{U}_2, RH=\overline{RH}}$$

$$\varepsilon_6 = \frac{\overline{RH}}{\bar{E}_0} \cdot \left. \frac{\partial E_0}{\partial RH} \right|_{R_n=\bar{R}_n, T=\bar{T}, U_2=\bar{U}_2, RH=\overline{RH}}$$

Yang, et al., Water resources Research, 2011.

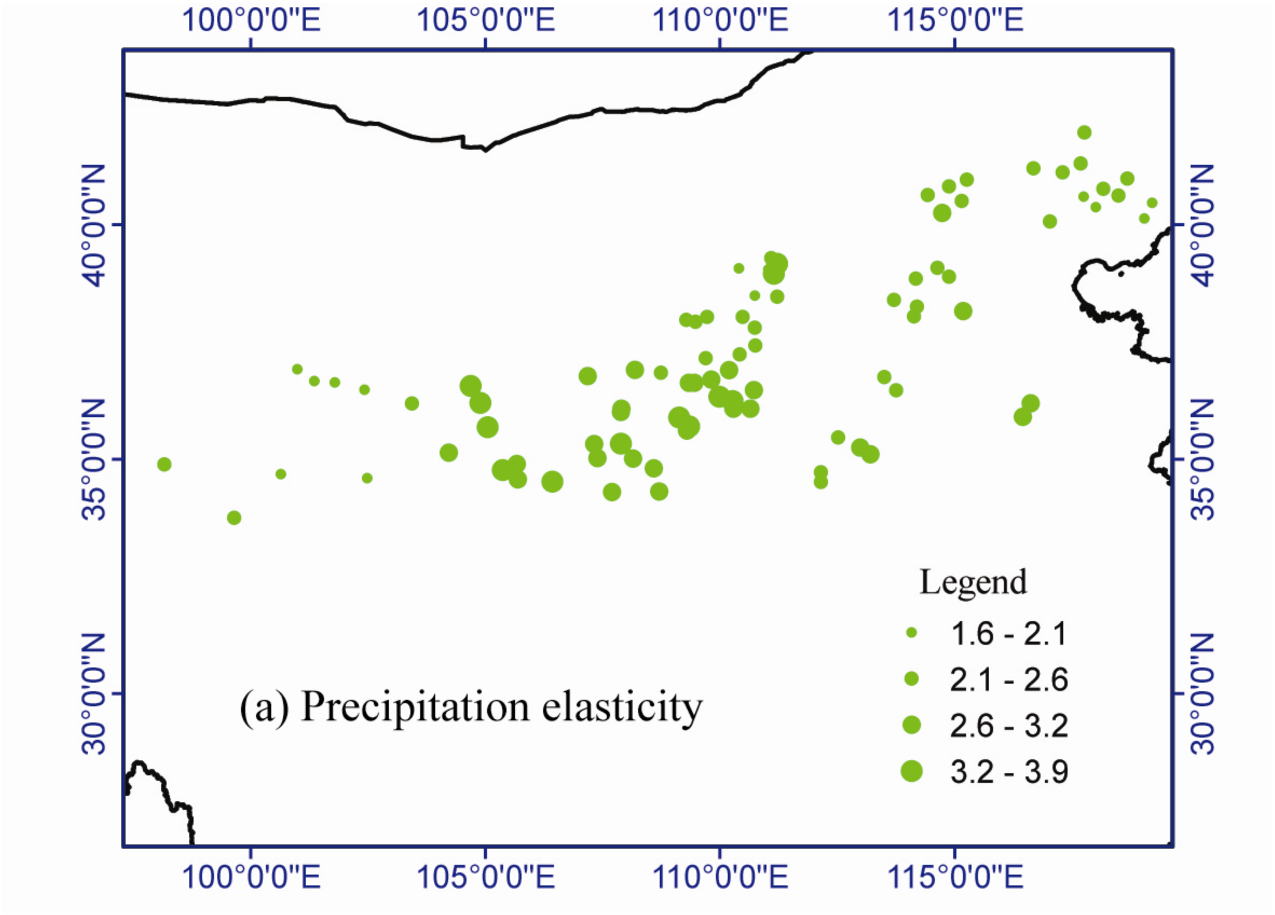
Predicting change of runoff due to the climate change



- Catchments have less human activity
- Drainage area varies 271~98414 km^2
- Dryness index (E_0/P) varies 1.16~6.80

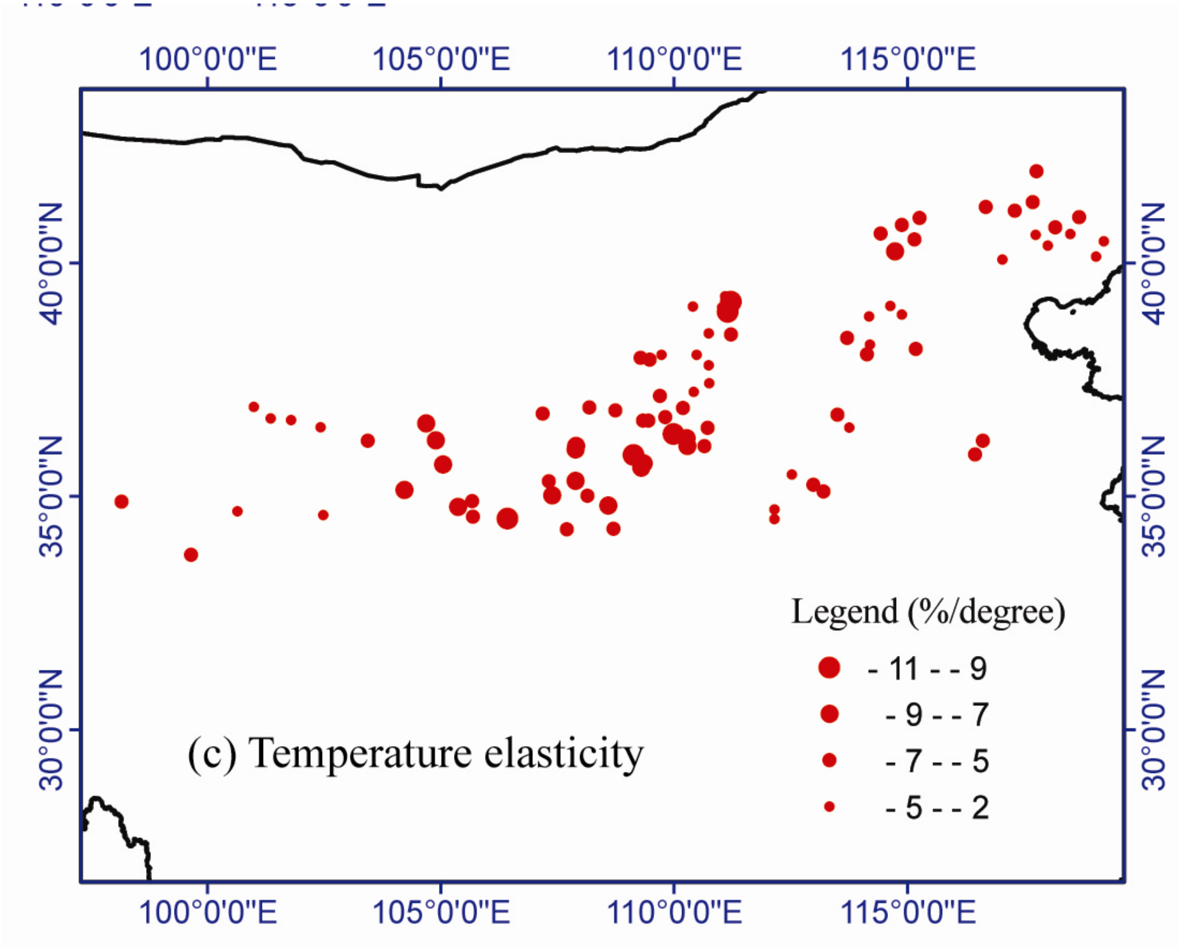
Predicting change of runoff due to the climate change

One percent change of annual precipitation will induce 1.6-3.9% annual runoff change: 1.6-2.1% in the upstream of Yellow river; 2.6-3.9% in the middle and lower reaches of Yellow River; 2.6-3.2% in the Haihe River.



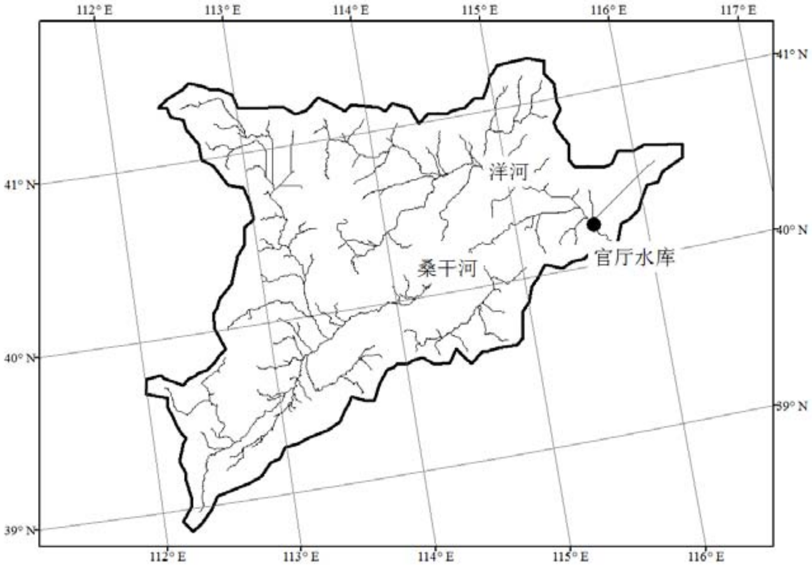
Predicting change of runoff due to the climate change

One ℃ increase of air temperature will induce -11~-2% annual runoff change: -5~-2% in the upstream of Yellow river; -11~-5% in the middle and lower reaches of Yellow River; -7~-2% in the Haihe River.

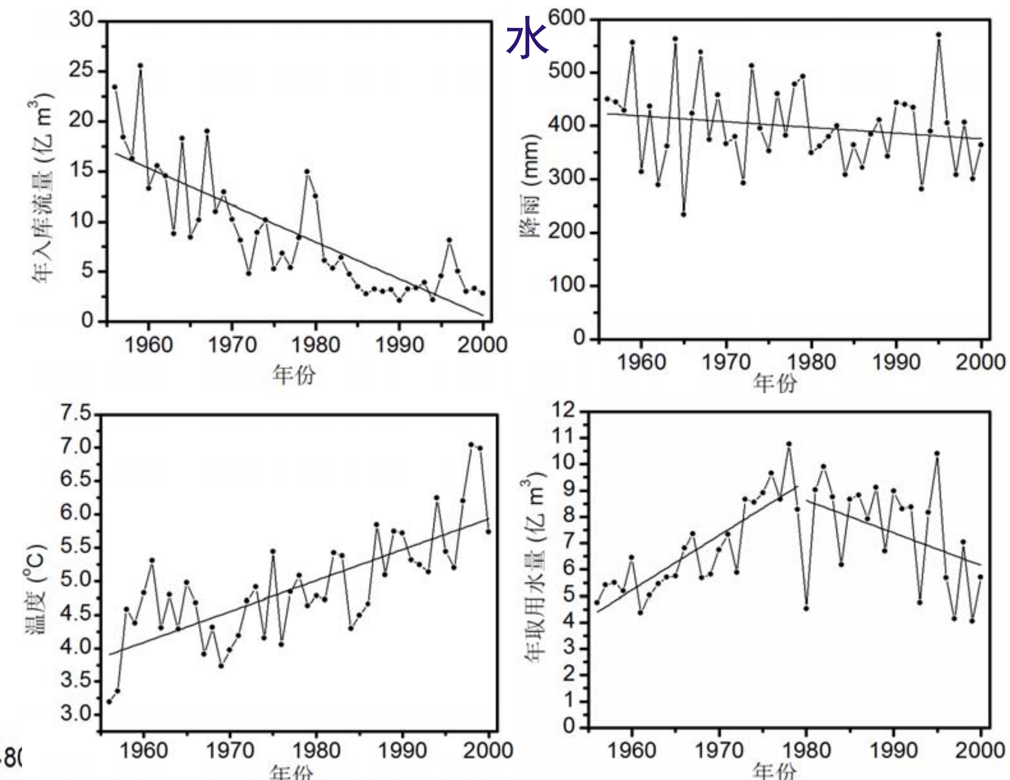


4.3 区分气候变化和人类活动对径流的影响

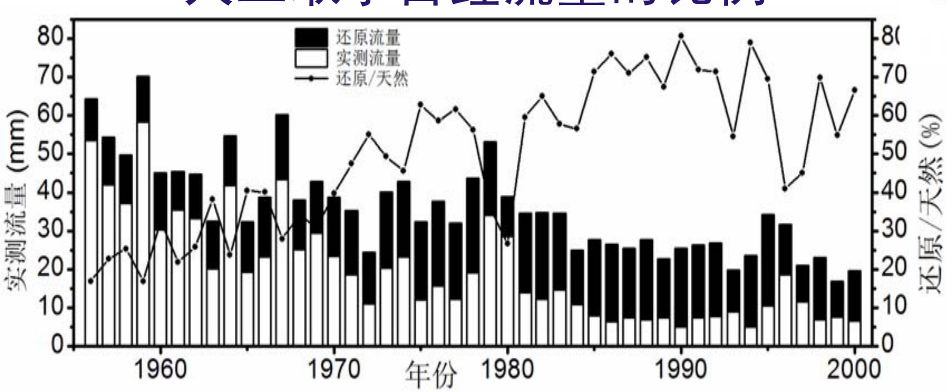
研究区域：官厅水库上游流域



年入库流量、降雨量、气温、人工取用水



人工取水占经流量的比例



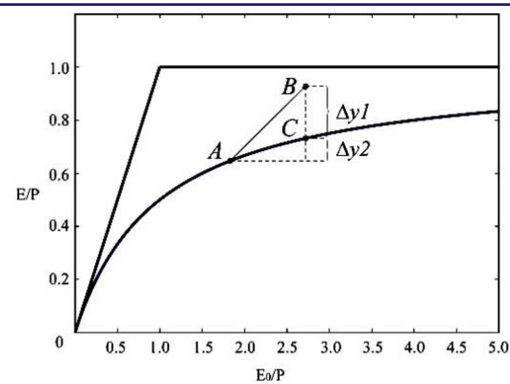
核心问题：径流量锐减的气候变化和人类活动贡献各有多大？

研究思路：

<table>
<tr><td rowspan="3">影响因素</td><td colspan="2">气候变化——(1)</td></tr>
<tr><td rowspan="2">人类活动</td><td>直接：人工取水——(2)</td></tr>
<tr><td>间接：下垫面变化——(3)</td></tr>
</table>

- ➢分前后两阶段 （1980年为界）
- ➢分析两阶段径流变化，求取气候、人工直接取水、下垫面的变化，再进行归因分析

研究方法：

模　型	基本内容	径流影响估计
分布式模型GBHM	分布式水文模拟	气候变化、下垫面变化影响
气候弹性模型	$\frac{\Delta R_i}{\overline{R}} = \varepsilon_P \cdot \frac{\Delta P_i}{\overline{P}} + \varepsilon_T \cdot \frac{\Delta T_i}{\overline{T}}$	气候变化影响
水热耦合平衡模型		气候变化：Δy2 人类活动影响：Δy1

各因素对官厅入库径流减少的影响

时段	实测径流 (mm)	人工取水 (mm)	（模拟）天然径流 (mm)			下垫面变化的影响 (mm)	
			气候弹性	GBHM	水热耦合	GBHM	水热耦合
1956~1979	28.4	15.6	43.9	48.6	46.1	34.6	37.0
1980~2000	10.1	16.8	34.5	34.6	37.0	32.3	28.3
径流变化	-18.3	1.4	-9.4	-14.0	-9.1	-2.3	-7.3 (除去人工取水1.4)
相对影响 (%)	100%	7.6%	51.4%	76.5%	49.7%	12.6%	39.9%

官厅水库入库径流减少归因分析

对径流减少的相对影响		气候弹性	GBHM	水热耦合
气候变化的影响		51.4%	76.5%	49.7%
人类活动的影响	人工取水		7.6%	
	下垫面变化	41.0%	12.6%	39.9%

4.4 气候变化情景下流域生态水文变化分析

GCMs

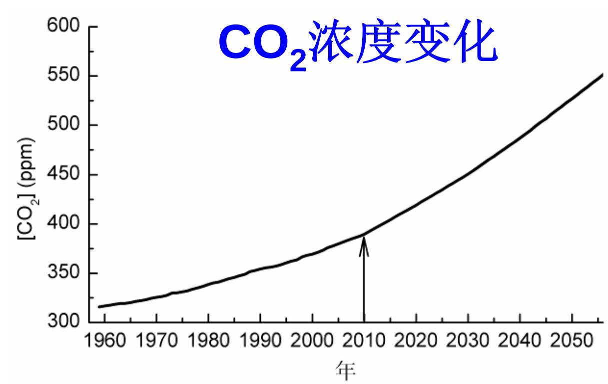
•MPI（Max-Planck-Institute for Meteorology, 德国）

•GFDL（Geophysical Fluid Dynamics Laboratory, 美国）

•MRI（Meteorological Research Institute, 日本）

•NCAR（National Centre for Atmospheric Research, 美国）

•HADCM3（UK Met. Office, 英国）



A1B情景：1.36倍

↓

辐射、气温、降雨

↓

空间降尺度：网格→站点

统计降尺度

↓

时间降尺度：月→日

天气发生器

基准年：1960~2009年

- 降雨：小麦季-46%，玉米季-8%
- 辐射：小麦季-2.3%，玉米季为-0.9%
- 气温：小麦季+0.24℃，玉米季-0.03℃

未来：2010~2059年

■未来气候情景下位山灌区的耗水变化

小麦： 太阳辐射（**-2.3%**）
- 作物耗水（−1.9%）
- 作物产量（−0.5%）

玉米： 太阳辐射（**-0.9%**）
- 作物耗水（−0.9%）
- 作物产量（−0.6%）

小麦： 降雨(−46%)/气温(+0.24℃)
- 作物耗水（−10%）
- 灌溉需水（+1.0%）
- 作物产量（+21%）

玉米： 降雨(−8%)/气温(−0.03℃)
- 作物耗水（−7%）
- 灌溉需水（−22%）
- 作物产量（−3.0%）

（充分灌溉）

小麦：充分灌溉　设定灌溉(240 mm yr^{-1})
- 灌溉需水（−26.0%）
- 作物产量（+6%）

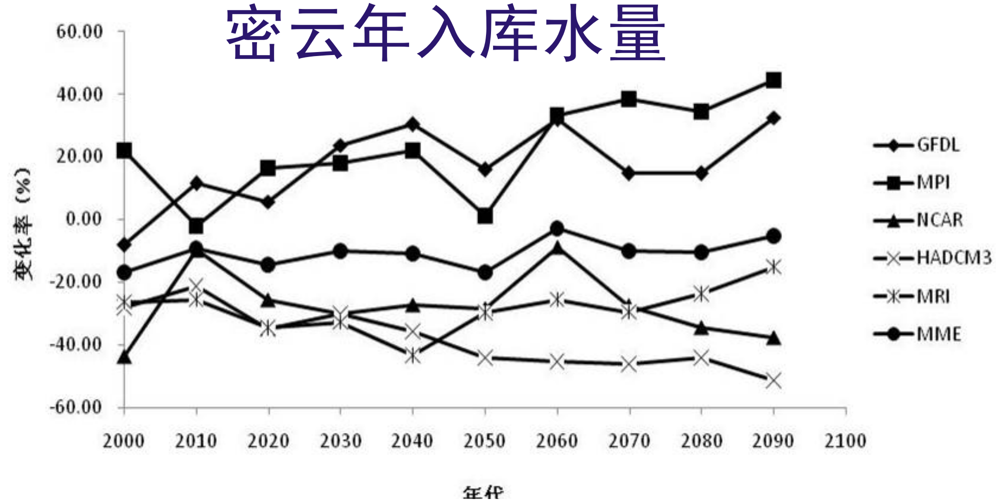
玉米：充分灌溉　设定灌溉(60 mm yr^{-1})
- 灌溉需水（−23%）
- 作物产量（−9.0%）

（过去）　**（未来）**

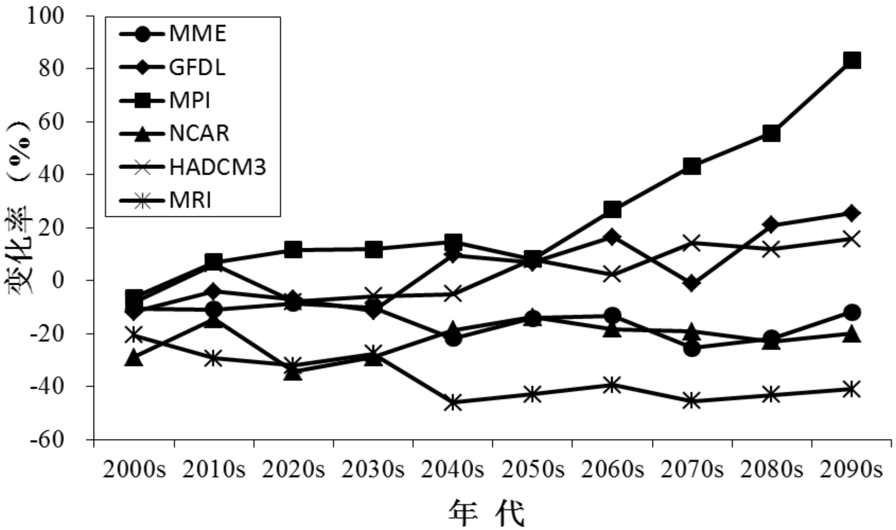
■未来气候情景下华北主要水库入库径流变化(不同GCM的比较)

- 密云入库水量减少幅度5~17%
- 官厅入库水量减少幅度约30%
- 潘家口入库水量减少幅度9~25%

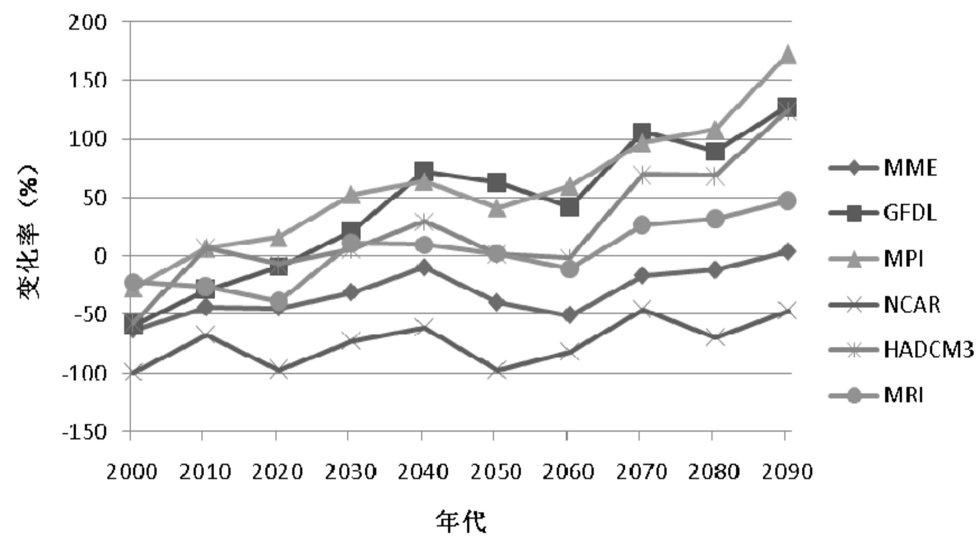
密云年入库水量



潘家口年入库水量

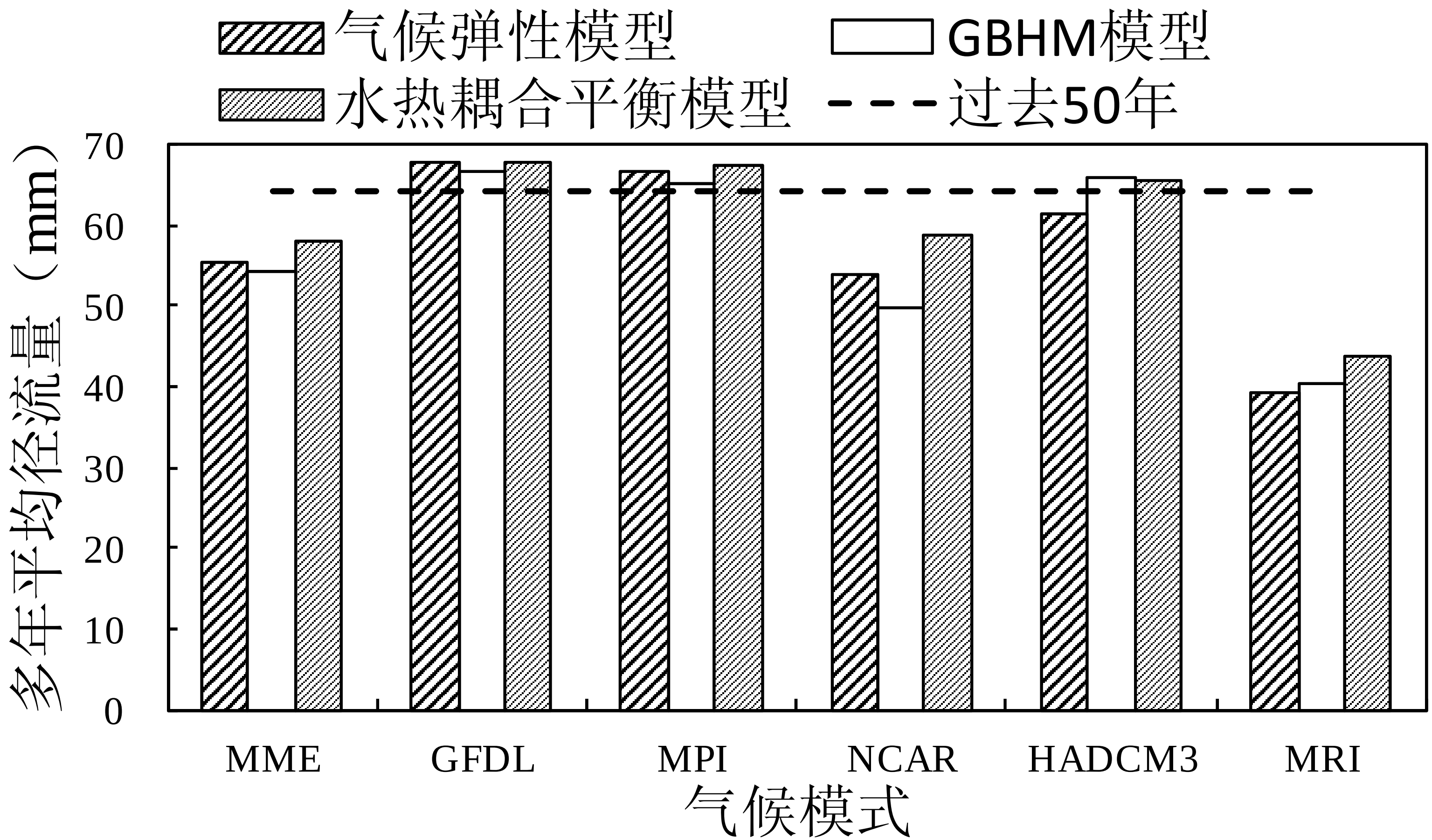


官厅年入库水量



■未来气候情景下华北主要水库入库径流变化 (不同水文模型的比较)

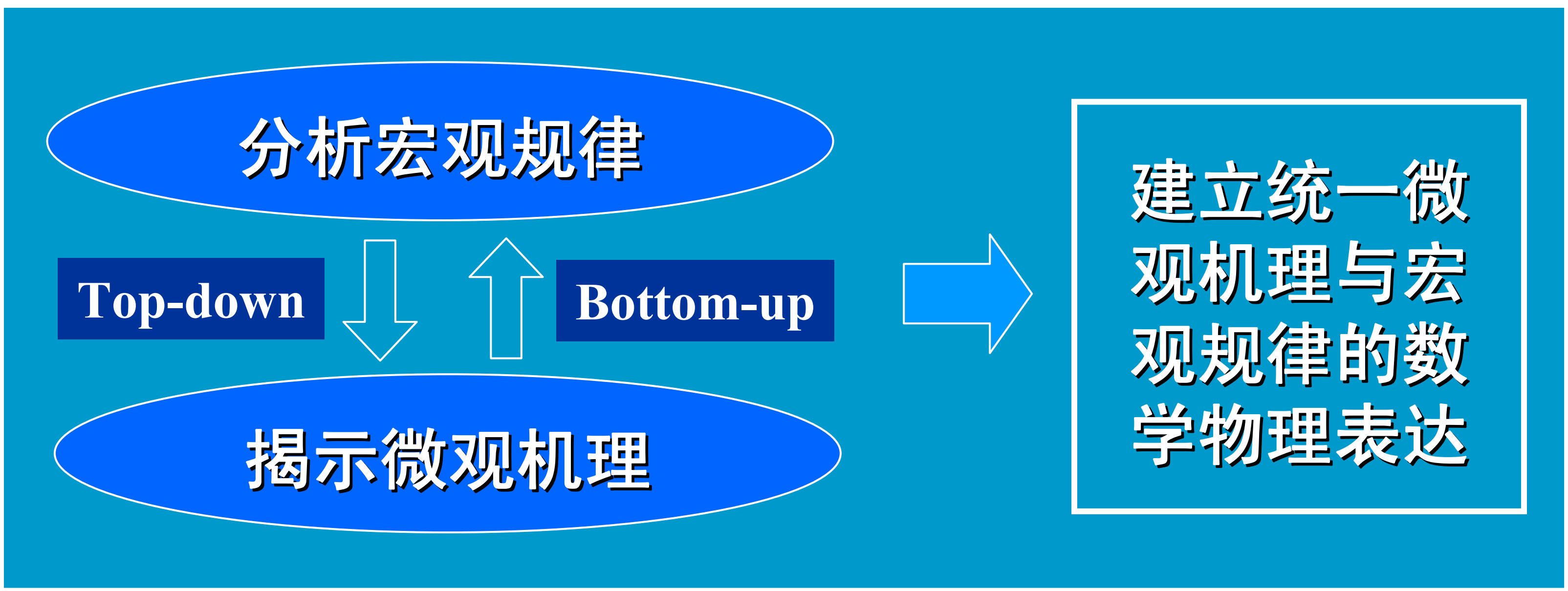
➢2090年潘家口入库水量



气候弹性模型、水热耦合平衡模型与GBHM模型计算结果相差10%以内。

五、流域生态水文学的研究思路

- 统计分析方法：从历史资料中探求宏观规律
- 现场观测手段：揭示生态水文过程机理
- 水文数值模拟：将理论与观测资料结合
- 可能的突破：建立统一微观机理与宏观规律的新理论



结　语

- 生态与水文过程相互作用是流域水循环的关键环节，生态水文学研究是21世纪的热点
  - 植被格局、植被结构变化对水文过程的影响
  - 揭示生态过程与水文过程的相互作用
  - 建立生态与水文耦合的流域水文模型
- 生态水文学研究中的不足
  - 植被格局与流域水文特征之间的关系认识不足
  - 植被动态过程与水文过程之间耦合模拟能力不足
  - 伴随水循环的物质（C、N）循环模拟能力不足
  - 缺乏对流域陆地生态与水生生态之间联系的认识

相关参考文献

(1) Lei Huimin, Dawen Yang, Yanjun Shen, et al. Simulation of evapotranspiration and carbon dioxide flux in the wheat-maize rotation croplands of the North China Plain using the Simple Biosphere Model. ***Hydrological Processes***, 2011, doi: 10.1002/hyp.8026.

(2) Lei Huimin, Dawen Yang, E. Lokupitiya, et al. Coupling land surface and crop growth models for predicting evapotranspiration and carbon exchange in wheat-maize rotation croplands. ***Biogeosciences***, 2010, 7: 3363-3375.

(3) Lei Huimin and Yang Dawen. Seasonal and interannual variations in carbon dioxide exchange over a cropland in the North China Plain. ***Global Change Biology***, 2010, 16: 2944-2957.

(4) Lei Huimin and Yang Dawen. Interannual and seasonal variability in evapotranspiration and energy partitioning over an irrigated cropland in the North China Plain. ***Agricultural and Forest Meteorology***, 2010, 150: 581-589.

(5) Lei Huimin, Yang Dawen, Stanislaus J. Schymanski, et al. Modeling the crop transpiration using an optimality-based approach. ***Science in China Series E***, 2008, 51, Supp. II: 60-75.

(6) Lei Huimin, Yang Dawen, Liu Xinbing, et al. Analysis of water resource variability over the irrigated area along the downstream reach of the yellow river. 2007, ***IAHS-AISH Publication***, 313. Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resources Management, p 286-293.

(7) 雷慧闽, 杨大文, 刘钰. 灌区不同空间尺度显热通量测定方法的对比分析. **水利学报**, 2011, 42(2): 136-142.

(8) 雷慧闽, 杨大文, 沈彦俊, 等. 黄河下游灌区水热通量的观测与分析. **清华大学学报**, 2007, 47(6): 801-804.

相关参考文献

(9) Xu, X., D. Yang and M. Sivapalan (2012). Assessing the impact of climate variability on catchment water balance and vegetation cover. ***Hydrol. Earth Syst. Sci.***, 16, 43–58, doi:10.5194/hess-16-43-2012.

(10) Yang HB and DW Yang (2012). Climatic factors influencing changing pan evaporation across China from 1961 to 2001. Journal of Hydrology, ***Journal of Hydrology***, 414–415:184–193, doi:10.1016/j.jhydrol.2011.10.043.

(11) Tang, LH, DW Yang, HP Hu, B Gao (2011), Detecting the effect of land-use change on streamflow, sediment and nutrient losses by distributed hydrological simulation. ***Journal of Hydrology***, 409:172-182.

(12) Yang, HB and DW Yang (2011), Derivation of climate elasticity of runoff to assess the effects of climate change on annual runoff. ***Water Resources Research***, 47, W07526, doi:10.1029/2010WR009287.

(13) Ma Huan, Dawen Yang, Soon Keat Tan, Bing Gao, Qingfang Hua (2010). Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment. ***Journal of Hydrology***, 389, 317–324.

(14) Yang, DW, WW Shao, PJF Yeh, HB Yang, S Kanae & T Oki (2009), Impact of vegetation coverage on regional water balance in the nonhumid regions of China. ***Water Resources Research***, 45, W00A14, doi:10.1029/2008WR006948. .

(15) Cong, ZT, DW Yang, B Gao, HB Yang, and HP Hu (2009), Hydrological trend analysis in the Yellow River basin using a distributed hydrological model, ***Water Resources Research***, 45, W00A13, doi:10.1029/2008WR006852.

Acknowledgements

This talk contains the research works by

Dr. Hanbo Yang,

Dr. Huimin Lei,

Dr. Xiangyu Xu,

and several other PhD students.

Prof. Sivapalan was kindly advised Drs Lei and Xu during their exchanges in UIUC.

谢谢大家！