A discussion on the paper

"Mid-latitude freshwater availability reduced by projected vegetation responses to climate change"

by Justin S. Mankin et al., 2019

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Mid-latitude freshwater availability reduced by projected vegetation responses to climate change

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Main Scientific Problem → **Surface wetting** or **Surface drying** ?

What role does terrestrial vegetation play in shaping future water availability through its responses to climate change?

Outline

Background

- Precipitation Partitioning
- Vegetational Acclimation
- Plant Response Complexities

Methods

- Climate Model
- Climatological Analysis
- Blue Water Trade-Off (BWT)

Results

- Relative Hydrological Changes
- Absolute Hydrological Changes
- BWT Accounting for Runoff Changes
- Observationally Constraining BWT

Conclusions

- Freshwater Availability
- Significance of Terrestrial Vegetation

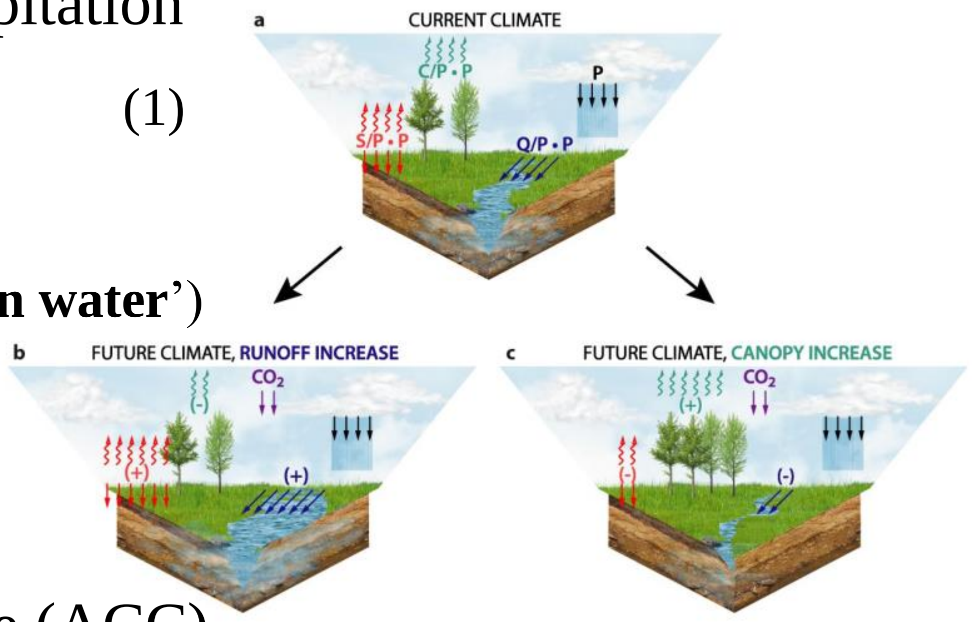
Background

Precipitation Partitioning and Freshwater Availability

- **Water budget of climatological Water-Year (WY) precipitation**

$$P = C + Q + S \quad \text{(Frank et al., 2015)} \qquad (1)$$

- *P*: WY total precipitation
- *C*: WY total canopy water flux (transpiration + interception, ‘**green water**’)
- *Q*: WY total runoff (‘**blue water**’)
- *S*: WY soil evaporation and multi-year storage (soil + storage)



- **Vegetation acclimation to anthropogenic climate change (ACC)**

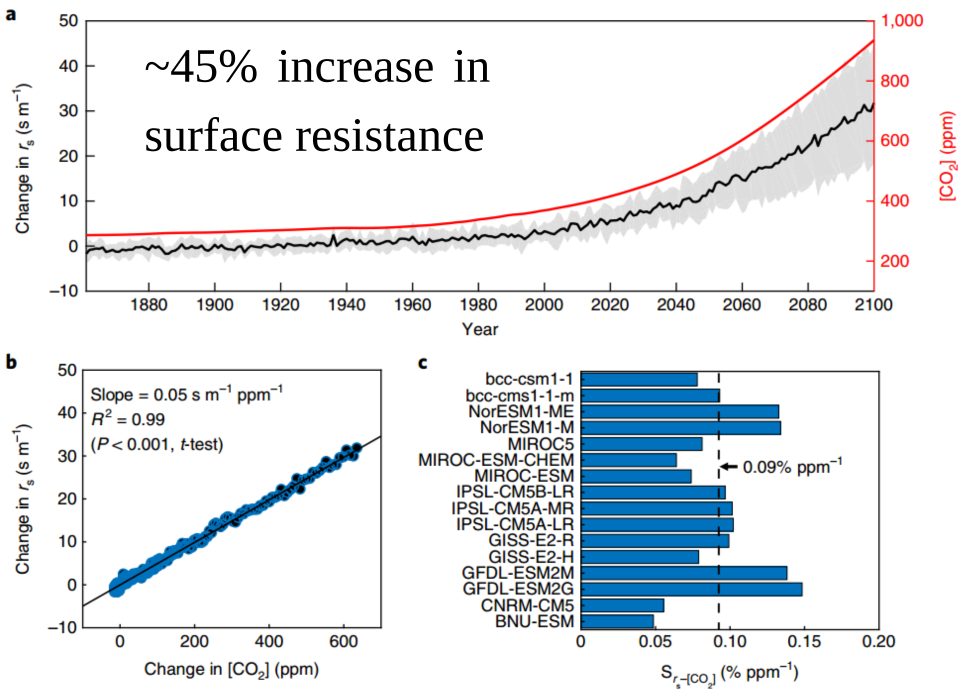
- Physiological responses of vegetation under ACC will lead to changes in ecosystem water consumption and by extension, the water available in soils and streams. Therefore, **how plants acclimate to elevated greenhouse gases (GHGs)** become central to future freshwater availability (Seager et al., 2010; Ciais et al., 2013).

Background

Vegetation Physiological Responses to Elevated GHGs

◻ Dominant view: ‘Plants Turn on the Tap’

- ➢ Atmospheric CO_2 enrichment tends to induce **partial stomatal closure** of plants, which increases surface resistance to evapotranspiration (ET), leading to conserved soil moisture and increased runoff, with expected potential to ameliorate hydrological drought risks from warming.
- ➢ Indirectly, the climate response to elevated [CO_2] could induce **higher vapour pressure deficit** (VPD) that also reduces the stomatal opening (Novick et al., 2016).
- ➢ This **anti-transpiration effect** was first accounted for by Idso and Brazel (1984) and has been reaffirmed recently with more sophisticated models and constraints (Swann et al., 2016; Milly and Dunne, 2016; Lian et al., 2018; Yang et al., 2019).

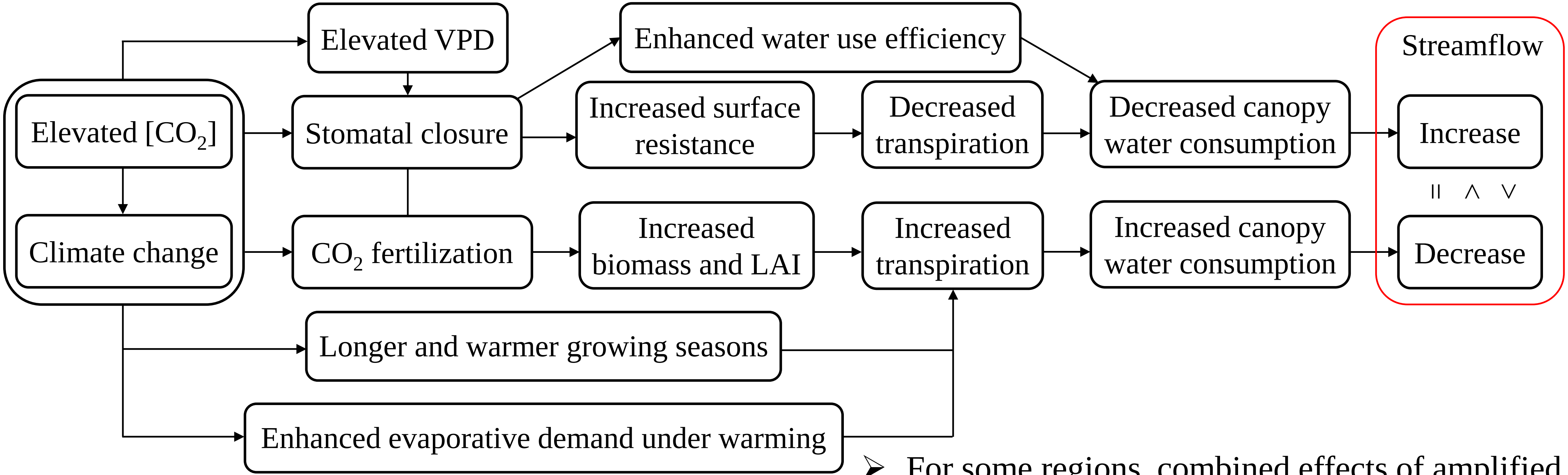


(Yang et al., 2019)

Background

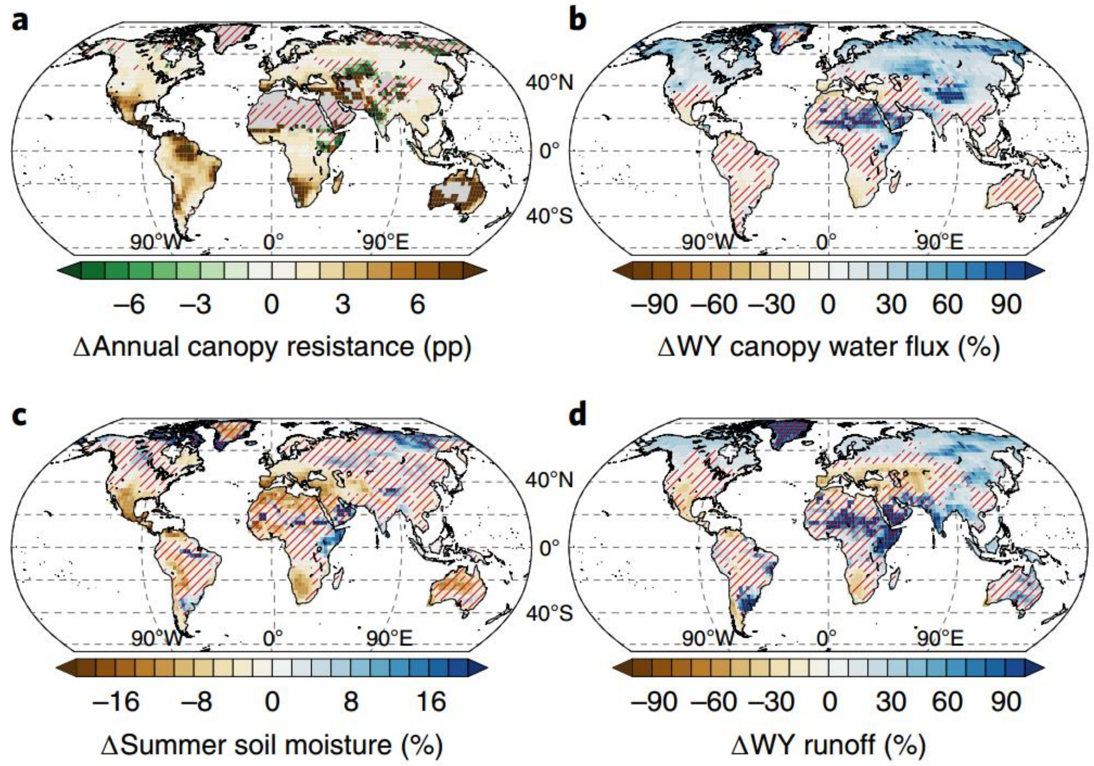
More Complexities on Vegetational Responses

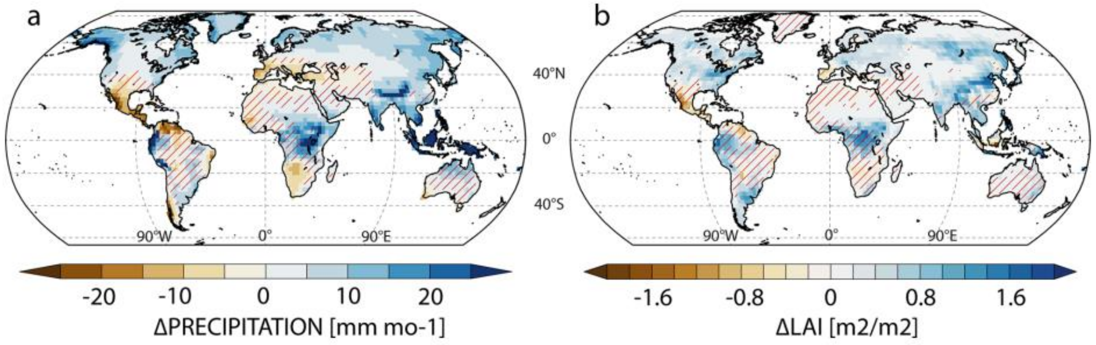
☐ Offset effect for streamflow



➢ For some regions, combined effects of amplified photosynthesis, higher evaporative demand and longer and warmer growing seasons increase ecosystem water use, **outpacing** decreases in transpiration from high [CO_2] (Frank et al., 2015; Ukkola et al., 2016; Mankin et al., 2018).

Evidence of Complexities on Region-Scale Responses





◻ Future hydrological responses

- Plants do increase surface resistance to ET, but their bulk water consumption also unexpectedly rises across 67% of the land surface. Summer soil moisture generally shows insignificant change in most land area.
- The conclusion that terrestrial vegetation responses under climate change will exclusively ameliorate surface drying does not capture the scope of **regional-scale hydrology**, because of regional differences in how vegetation alters the partitioning of precipitation at the land surface.

Methods

Climate Model and Output Variables

Models	
1: bcc-csm1-1-m	9: GFDL-ESM2M
2: bcc-csm1-1	10: inmcm4
3: CanESM2	11: IPSL-CM5A-LR
4: CCSM4	12: IPSL-CM5A-MR
5: CESM1-BGC	13: IPSL-CM5B-LR
6: CESM1-CAM5	14: MIROC-ESM-CHEM
7: CESM1-WACCM	15: MIROC-ESM
8: GFDL-ESM2G	16: NorESM1-ME
Variables	
precipitation, 'pr'	leaf area index, 'lai'
evapotranspiration, 'evspsbl'	total-column soil moisture, 'mrso'
transpiration, 'tran'	total runoff, 'mrro'
leaf evaporation, 'evspsblveg'	gross primary productivity, 'gpp'
soil evaporation, 'evspsblsoi'	surface air temperature, 'tas'

- Other output variables
  - Vapour pressure deficit (**VPD**) is calculated as saturation vapour pressure at 'tas' minus actual vapour pressure.
  - **Bulk canopy resistance (*R*$_s$)** is calculated as the inverse of canopy conductance (G_s) following the Community Land Model version 4 (CLM4) formulation:

$$R_s = \mathrm{VPD}/C.$$

  - Water use efficiency (**WUE**) is calculated as the ratio of annual average 'gpp' to 'tran'.

Methods

Temporal Scale of Climatological Analysis

Hemispheric definition

- *P*, *C*, ET and *Q* are analyzed in **WY totals** (sum of monthly fluxes, mm), where WY is defined as Oct-Sep in the Northern Hemisphere and Mar-Feb in the Southern Hemisphere (Mankin et al., 2018).
- Hemispheric definition of WYs can miss some regional differences in the timing of dry season termination; but ensures a hydrologically meaningful temporal aggregation considering models variation.
- Soil moisture is analyzed only **during the summer season**, taken as Jun-Aug in the Northern Hemisphere and Dec-Feb in the Southern Hemisphere.
- The future response is taken as the difference between the end-of-century (2070–2099, in RCP8.5) climatology and that for the late twentieth century (1976–2005, historical).

Methods

Derivation of Blue Water Trade-Off

1) Based on the water budget presented in Eq(1), the precipitation that is partitioned to the canopy and runoff can be written as:

$$\varphi = P - S = C + Q \quad (2)$$

2) The climatological change in the amount of φ between two time periods, f and h, is represented as:

$$\Delta\varphi = [P_f - S_f] - [P_h - S_h] = [C_f + Q_f] - [C_h + Q_h] \quad (3)$$

3) Since S changes only modestly relative to the other terms, if the partitioning ratio of precipitation among C and Q is stationary:

$$\beta_c = C_h / \varphi_h \quad (4)$$

$$\widehat{\Delta C} = \beta_c * \Delta\varphi \quad (5)$$

The historical partitioning ratio is same for Q, and: $\beta_c + \beta_q = 1$.

4) But in actual model simulations, they evolve with forcing. The difference between the predicted change in the canopy water flux based on a stationary partitioning ratio and its actual change is BWT:

$$\mathrm{BWT} = \Delta C - \widehat{\Delta C} \quad (6)$$

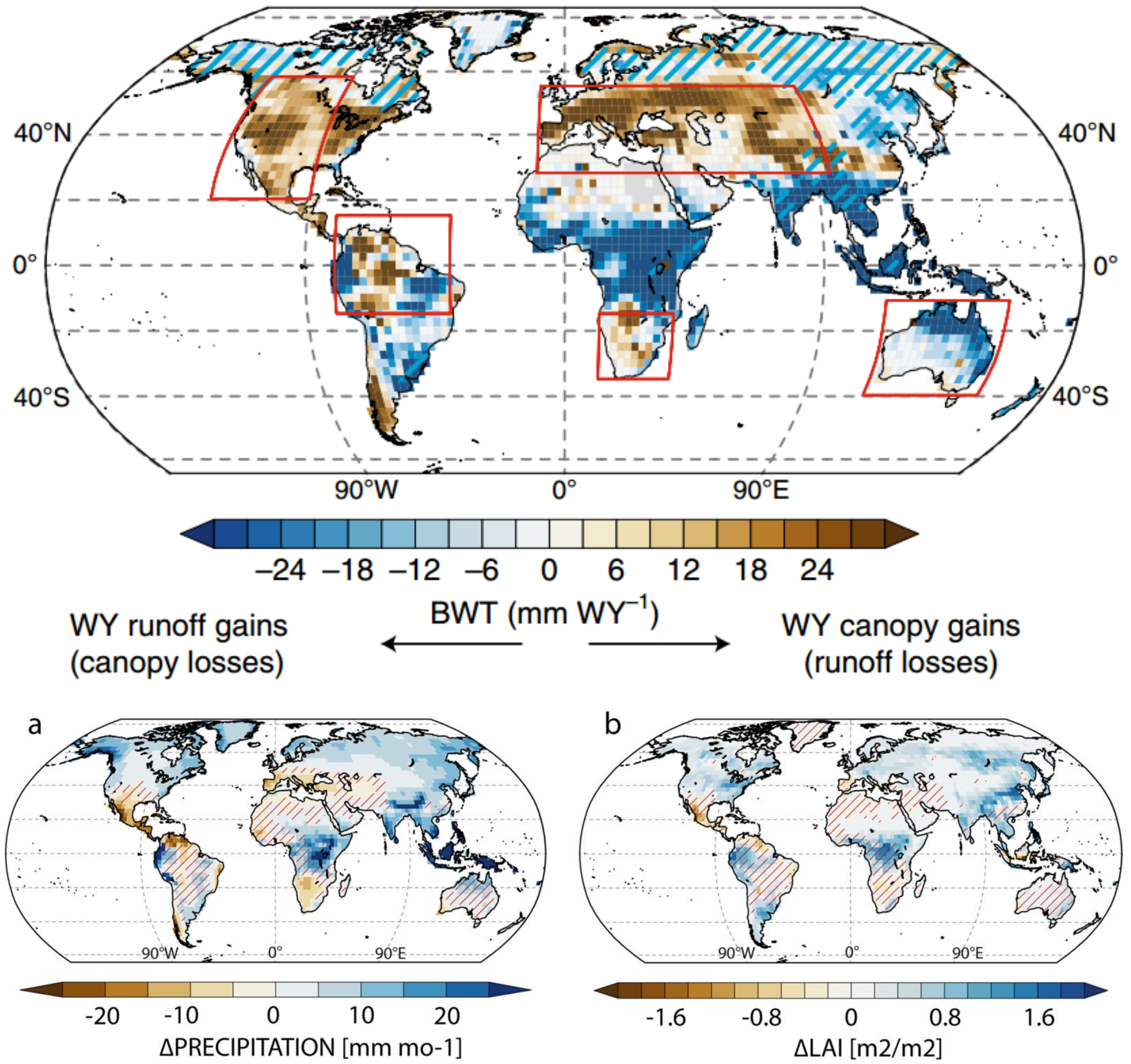
☐ Implications

BWT > (<) 0: canopy (runoff) are gaining water at the expense of runoff (canopy).

BWT = 0: partitioning ratio remains the same.

Results

Projected Changes in Precipitation Partitioning



◻ Global spatial pattern of BWT

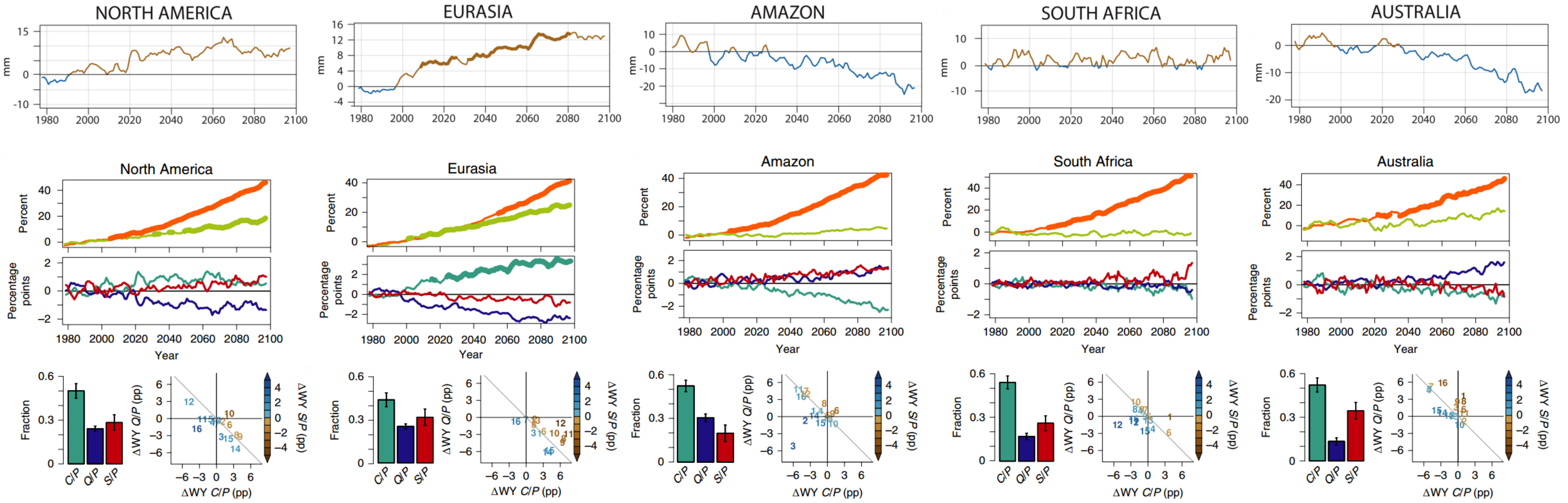
- ➢ The tropics generally have a relative increase of ~20 mm WY^{-1} in precipitation partitioning to runoff and away from plants, while most of North America and Eurasia show the opposite effect.
- ➢ Surface wetting generated from plants responses under high [CO_2] is driven almost entirely by the tropics, with high water availability already, or the very high latitudes, where human water demands are relatively low. By contrast, **the populous mid-latitudes** demand more precipitation at the direct sacrifice of runoff.

Results

Relative Changes in the Land Surface Hydrological Budget

1) BWT time series as an anomaly from the historical baseline; 2) WUE (orange) and LAI (green) changes;

3) Partitioning terms (C/P, Q/P, S/P) changes, 4) historical fraction and 5) the model-by-model ensemble spread.



Results

Relative Changes in the Land Surface Hydrological Budget

☐ General features of regional responses

- Significantly **increasing WUE** across regions because of higher carbon fixation efficiency
- Domination of canopy partitioning among all terms (fractions)
- Significantly **inverse relationship** between $\Delta C/P$ and $\Delta Q/P$, $\Delta C/P$ and $\Delta S/P$, with weaker relationship between $\Delta Q/P$ and $\Delta S/P$, highlighting that C/P exerts a control on both the other two

☐ Partitioning analysis of regional BWT

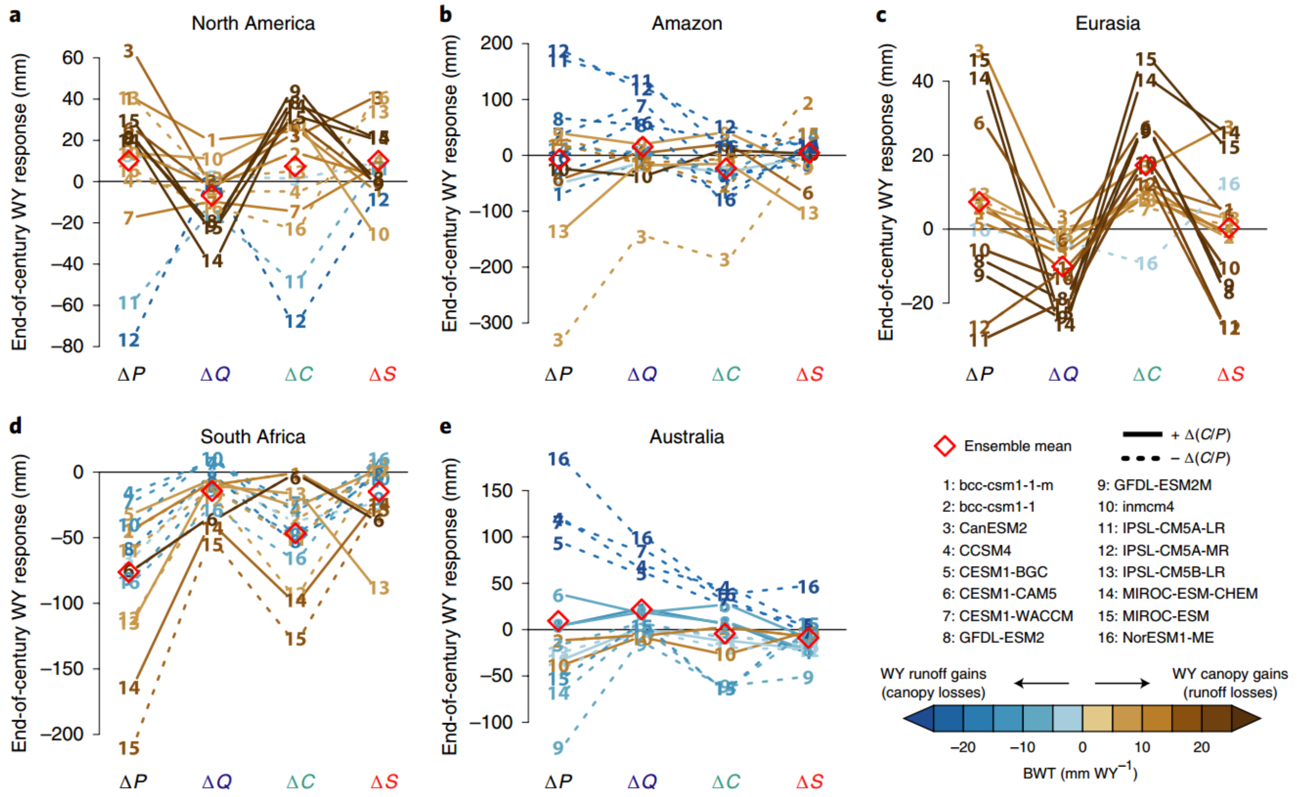
- North America: Q/P declines as a consequence of modest increase in C/P and S/P
- Eurasia: both Q/P and S/P decrease; significant rise in C/P comes with most significant increased ΔLAI
- South Africa: precipitation declines, leading to increased dryland partitioning to S
- Amazon and Australia: both Q/Ps increase; increases in R_s may outpace or be compensated by additional canopy water demands from modest increase in LAI

Results

Absolute Changes in the Land Surface Hydrological Budget

☐ Significance of absolute changes

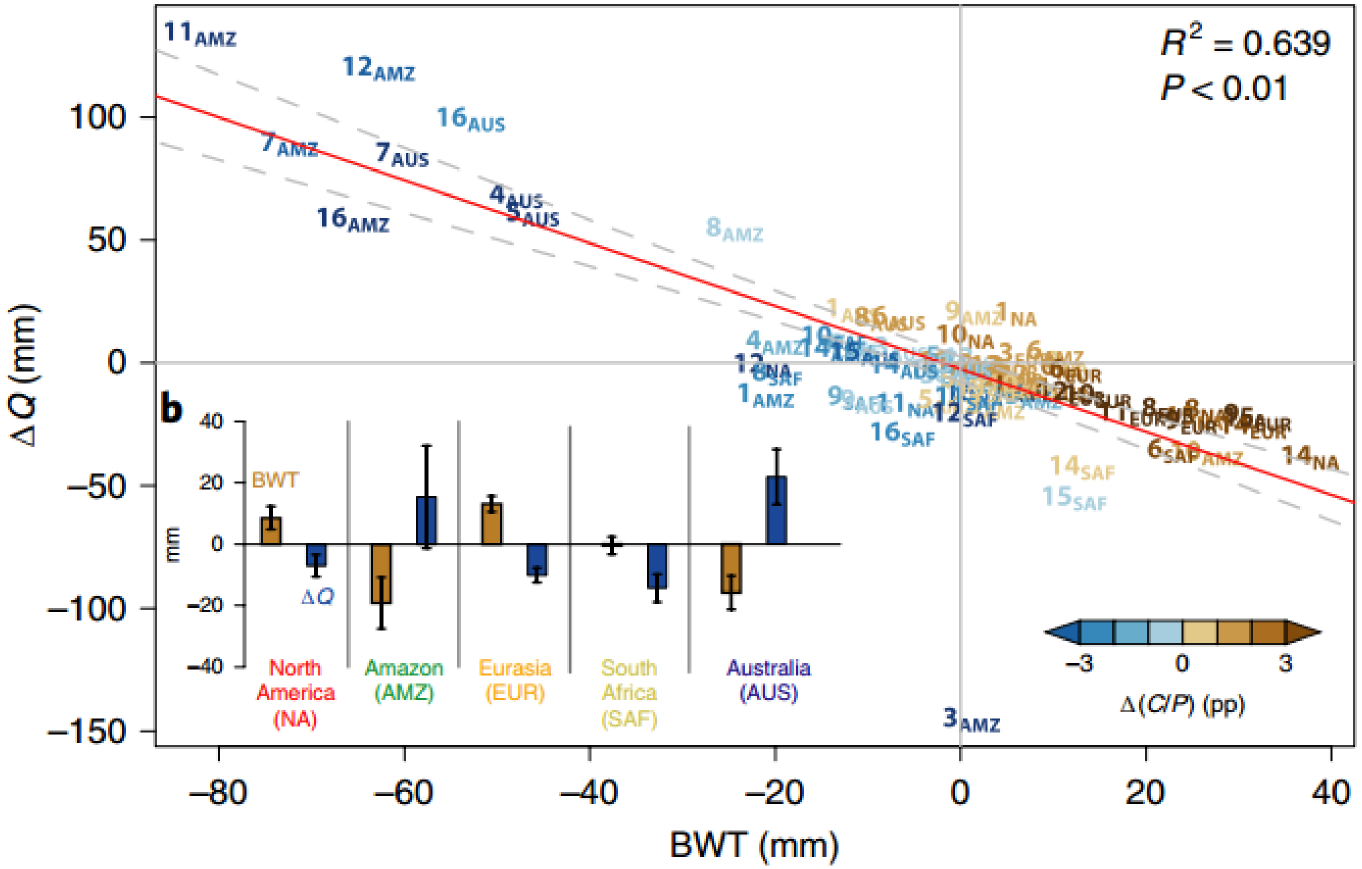
- ➢ Since **precipitation is also changing**, it's worth discussing that whether above relative changes in precipitation partitioning matter for absolute changes in water availability.



- ➢ Close association between relative (BWT, $\Delta C/P$) and absolute changes
- ➢ A 'down, up, down' pattern in regions and models with positive BWT
- ➢ Model uncertainty across all regions

Linkage between Relative and Absolute Hydrological Changes

➢ Increased BWT is associated with WY runoff declines, explaining **~64%** (adjusted R^2) of the inter-model and regional variance in all runoff changes.



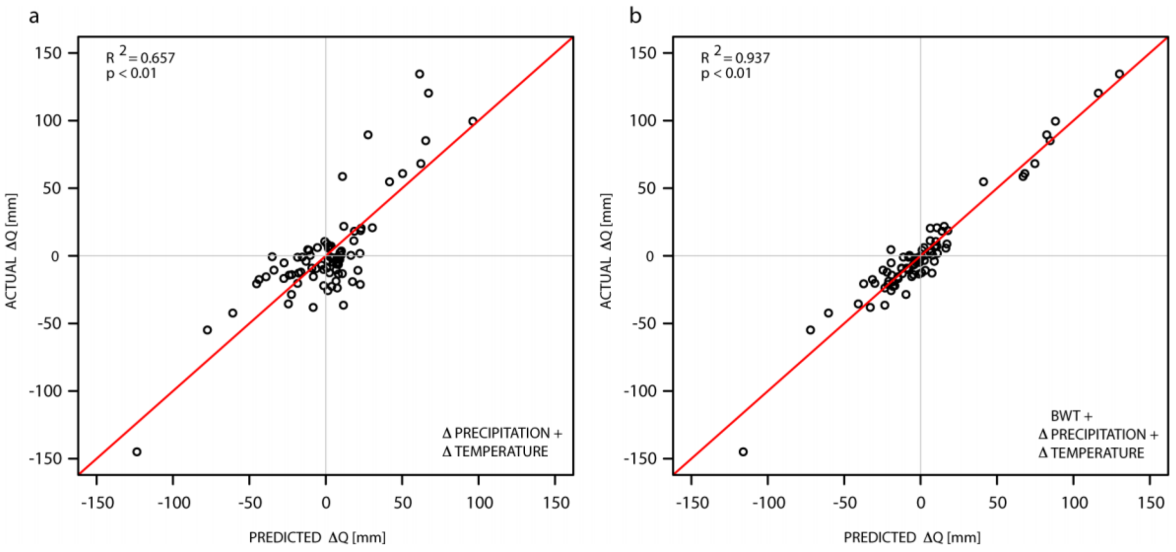
Results

BWT Accounting for Runoff Changes

- Linear models for ΔQ

a): $\widehat{\Delta Q_{rm}} = \beta_0 + \beta_1 \Delta P + \beta_2 \Delta T + \beta_3 (\Delta P * \Delta T)$

b): $\widehat{\Delta Q_{rm}} = \beta_0 + \beta_1 \Delta P + \beta_2 \Delta T + \beta_3 (\Delta P * \Delta T) + \beta_4 \mathrm{BWT}$



- Statistical model without BWT (a) shows **~66%** connection between precipitation (or temperature) and ΔQ, which is similar to that between BWT and ΔQ, implying the same importance of BWT and *P* or *T* in accounting for centennial-scale runoff changes.
- When adding BWT (b), **~94%** of the variance in each model and region's runoff changes can be collectively explained, emphasizing that the combined biogeophysical effects of high [CO_2] on plants can result in an overall drier land surface for vast regions already plagued with water stress.

Results

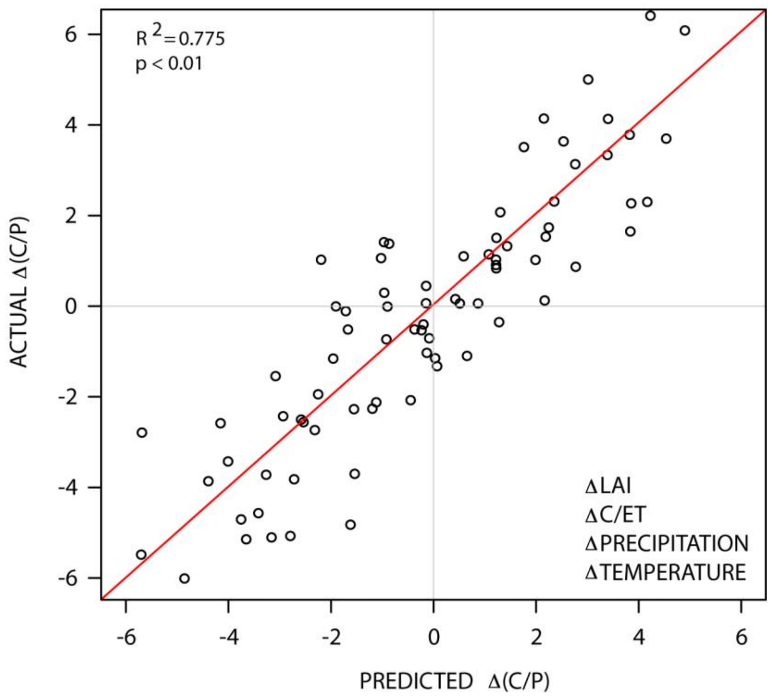
Observational Constraints on Vegetation–Runoff Tradeoffs

◻ Need for observational constraints

- ➢ Model uncertainty in precipitation partitioning raises questions about the trustworthiness of projection results.
- ➢ Model biases in the canopy fraction of ET (*C*/ET) would affect ensemble estimates of BWT and consequent ΔQ.

◻ Linear models for $\Delta C/P$

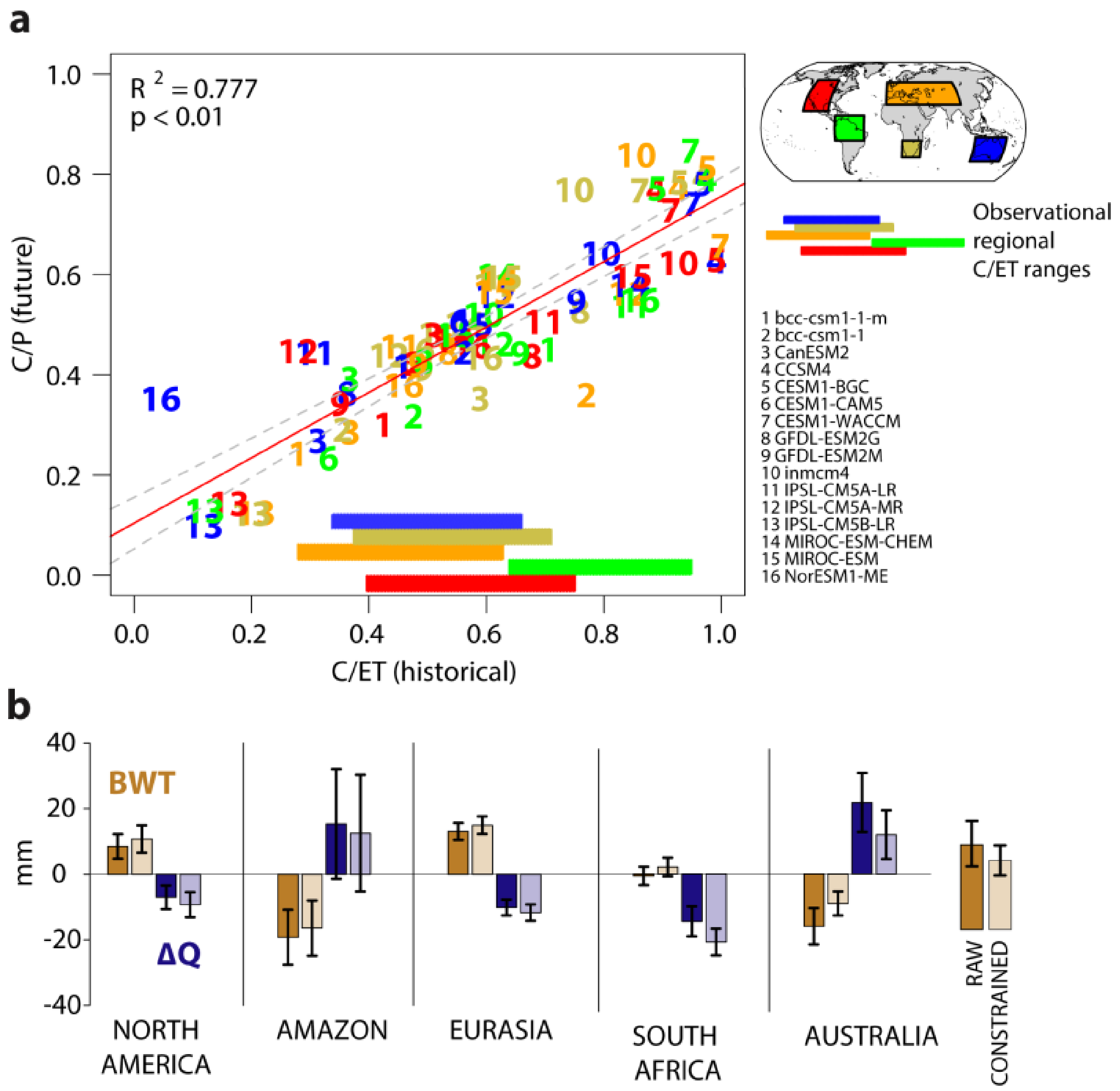
$$\Delta(\widehat{C/P})_{rm} = \beta_0 + \beta_1 \Delta \mathrm{LAI} + \beta_2 \Delta(C/\mathrm{ET}) + \beta_3 \Delta P + \beta_4 \Delta T + \beta_5 (\Delta P * \Delta T)$$



- ➢ Approximately 78% variance of $\Delta C/P$ can be accounted for by this model- and region-based liner model.
- ➢ Future changes of canopy partitioning is dominated by ΔC/ET, for whose **coefficient is the largest** among all terms.

Results

Observational Constraints Strengthening Preceding Results



- Recent (1982-2014) observations of *C*/ET (estimated as (*T*+*I*)/ET) from a dataset containing 108 observational sources (Wei et al., 2017) were used, as a constraint on the ensemble range in both BWT and runoff changes.

- Projection results after constraining show a modest reduction in +Δ*Q* in the Amazon and Australia and a deepening of –Δ*Q* in North America, Eurasia and South Africa, **all consistent with the BWT responses.**

Conclusions

- Increase in the global mean runoff due to aggregate plant responses to climate change is driven primarily by **the already wet tropics and low-water-demand high latitudes**, obfuscating the vast continental regions where plant responses reduce water availability at the land surface, even in the face of increasing precipitation.

- Terrestrial vegetation plays a **significant but unresolved** role in shaping future regional freshwater availability, one that will not ubiquitously ameliorate future warming-driven surface drying.

Thank you for your time!