BioEarth: Envisioning and Developing a New Regional Earth System Model to Inform Natural and Agricultural Resource Management

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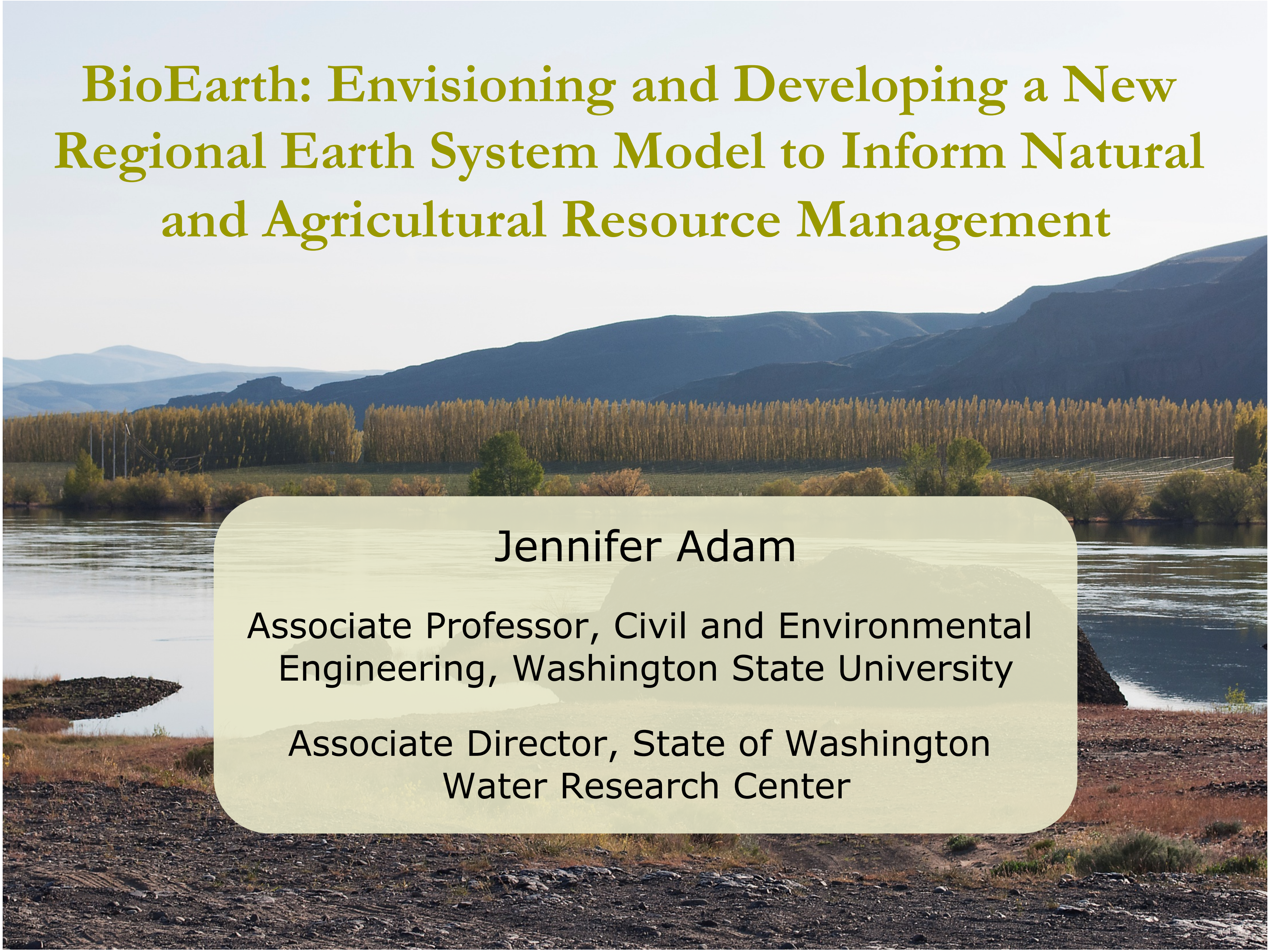

“BioEarth” Team of Collaborators

Washington State University:

Bio. Sciences: Dave Evans, Sarah Anderson, Justin Poinsatte

Bio. Systems Eng.: Claudio Stöckle, Roger Nelson, Keyvan Malek

Center for Sustaining Agriculture and Natural Resources: Chad Kruger, Elizabeth Allen, Georgine Yorgey

Civil and Env. Eng.: Jennifer Adam, Mike Barber, Kirti Rajagopalan, Kiran Chinnayakanahalli, Mingliang Liu, Julian Reyes, Shifa Dinesh

Computer Sciences: Ananth Kalyanaraman, Tristan Mullis

Economics: Michael Brady, Jonathan Yoder, Bhagyam Chandrasekharan

Extension: Andy Perleberg

Lab for Atmospheric Research: Brian Lamb, Serena Chung, Joseph Vaughan, Fok-Yan Leung, Tsengel Nergui

School of the Environment: John Harrison, Cody Miller

Clark University: Jennie Stephens

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Oregon State University: Yong Chen

Pacific Northwest National Lab: Alex Guenther, Ruby Leung, Jin-ho Yoon

University of California, Santa Barbara: Christina Tague, Elizabeth Garcia, Jun Zhu, Janet Choate

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- Christl. Tague[2], M.L. Liu[1], E. Garcia[2], K. Rajagopalan[1], S. H. Chung[1]

Motivation

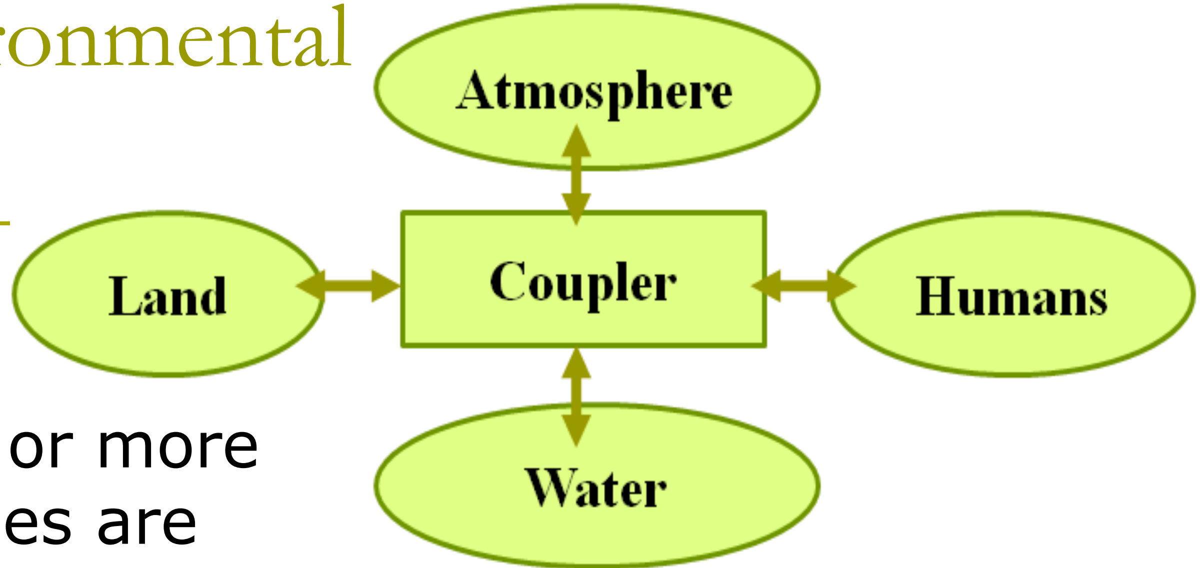
- Societal actors needing to make resource management decisions in the face of global change are confronted with uncertainties in very complex systems, *many of which are scale related.*
- Climate science information is under-utilized for decision making (Weaver et al. 2013).
- There is a need to close the gap between science information deemed usable by scientists vs non-academic societal actors (Lemos et al. 2012).

Objectives of this Talk

- To discuss factors that will enable movement of integrated modeling projects along the continuum from generating primarily scientific knowledge to *also* producing actionable information that can inform resource management decisions.

- Use “BioEarth” as an example.

Integrated Environmental Modeling



Definition:
"Models from two or more academic disciplines are integrated such that they behave like a unit to external stimuli." – Andy Soos, ENN

Advantages over Stand-Alone Models:

- Can explores 2-way effects & feedbacks
- Can reveal unintended consequences of proposed changes in policy or management practices by considering the Earth "*as a system*"

Biosphere-relevant Earth System Model ("BioEarth") Goals

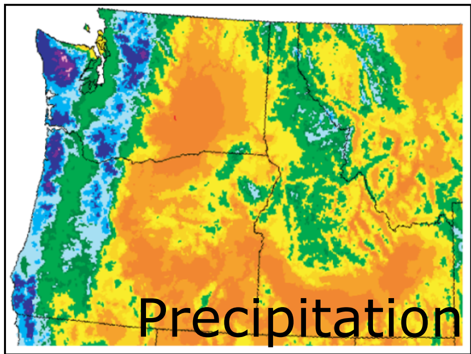
- To improve understanding of the interactions between coupled $C:N:H_20$ dynamics and human actions at regional and decadal scales under global change to
  - better understand the role that resource management activities have in impacting earth systems dynamics, and
  - inform sustainable resource management decisions.

What is the BROADER CONTEXT (e.g., UNINTENDED consequences) of a particular management practice or policy that aims to provide for human needs while sustaining our natural resources?

Adam et al. (2014) "BioEarth" Envisioning and developing a new regional earth system model to inform natural and agricultural resource management", Climatic Change

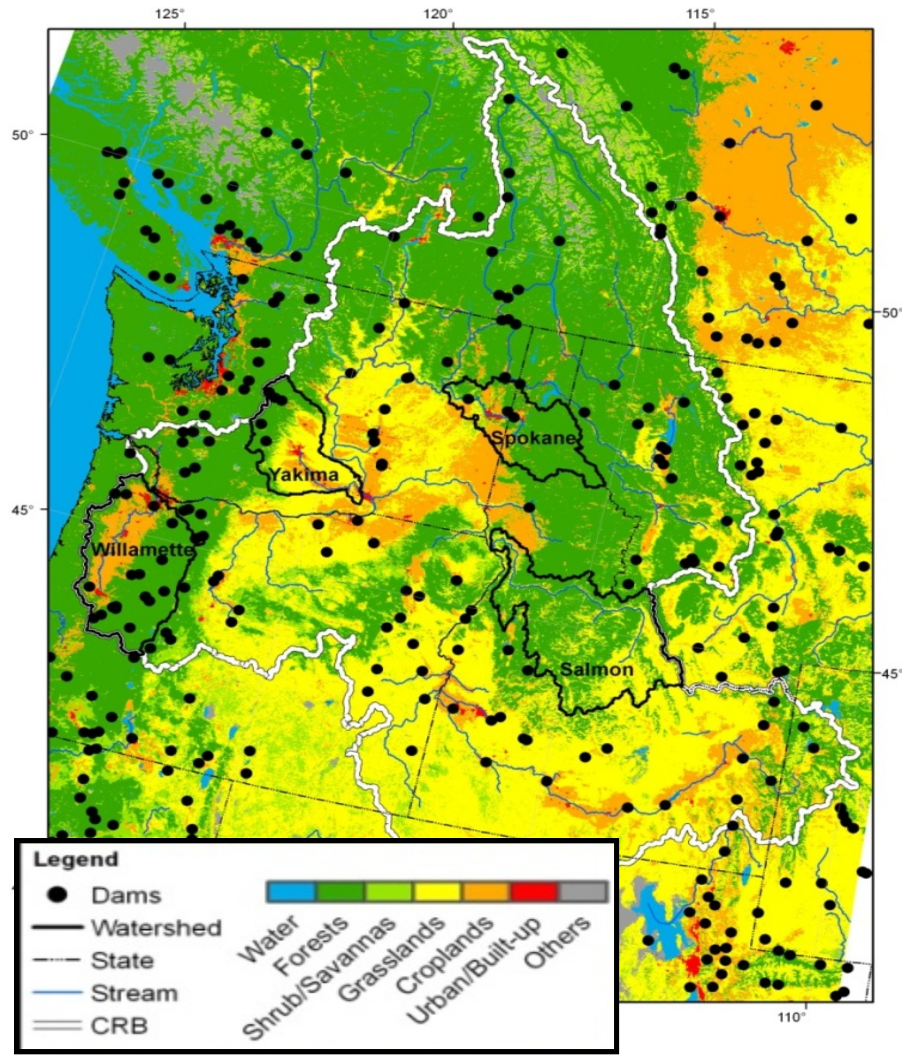
Some Key Needs for Earth System Models to Provide Usable Information

- Regionally specific (Giorgi 1995; Hibbard and Janetos 2013)
- Capturing of decision-making processes under investigation (Hibbard and Janetos 2013; Kraucunas et al. 2014)
- Spatio-temporal resolutions that capture relevant processes and interactions (Diffenbaugh et al. 2005; Liu et al. 2007; Smith et al. 2011; Wood et al. 2011)
- Stakeholder engagement (Callon 1999; Cash et al. 2003; Philippson et al. 2012)



Regional Context: The Columbia River Basin (CRB) as a Natural and Agricultural Resource

- Projected temperature and precipitation changes anticipated to exacerbate water quantity and quality problems
- Multiple competing in- and out-of-stream water uses
- U.S.-Canadian water management; the 1961 Columbia River Treaty is currently under review
- Intensifying issues: fish and habitat, tribal considerations, increased need for renewable energy, etc.
- Need to incorporate regionally-specific processes/information



Incorporating Resource Management into BioEarth's Modular Framework

Example Management Scenarios

Cropland: crop selection/ rotations, irrigation, fertilization, tillage

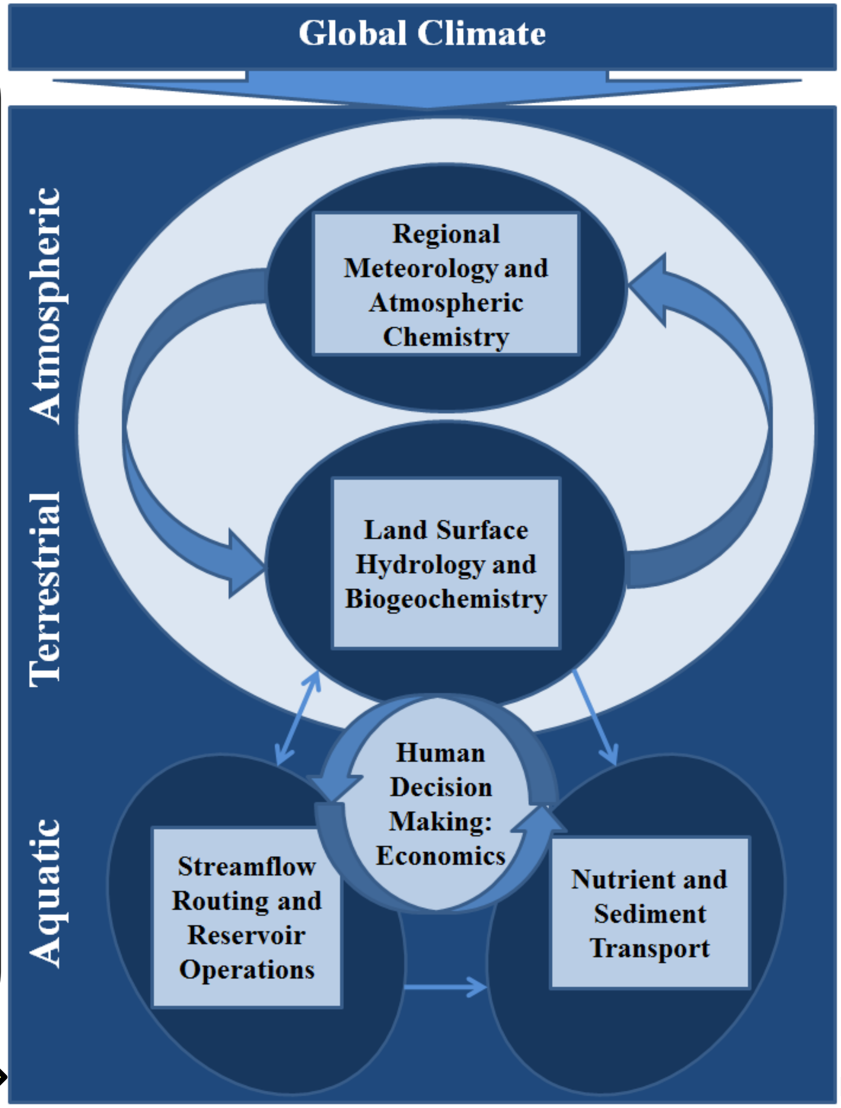
Rangeland: grazing, restoration

Forests: fuel and carbon management, restoration

Water supply: reservoirs, water rights curtailment, water transfers

Air quality: regulations for emission of pollutants

Exogenous agents: policy, international trade, domestic demand



Example Model Outputs

Air quality: GHG emissions and other pollutants

Water quantity and deficit: soil moisture, rivers, reservoirs, unmet demand

Water quality: dissolved inorganic/organic nitrogen and carbon

Terrestrial ecosystem health: species composition, net primary productivity, water stress, nutrient limitations

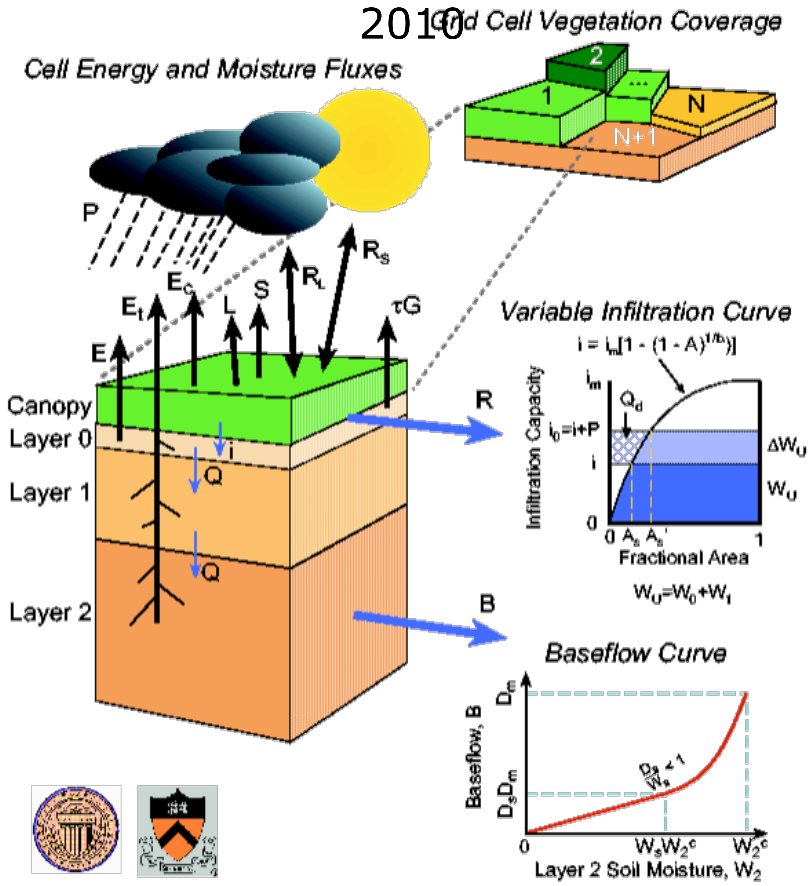
Economic: crop yield, forest/range productivity, hydropower generation, carbon mitigation

Incorporation of Cropping System Management

VIC

Hydrology

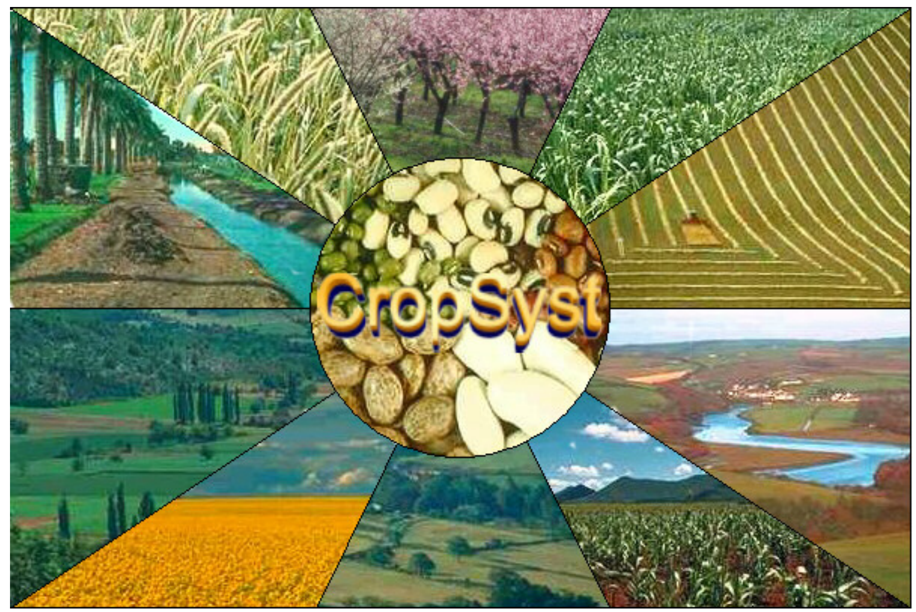
Liang et al, 1994 and Elsner et al, 2010



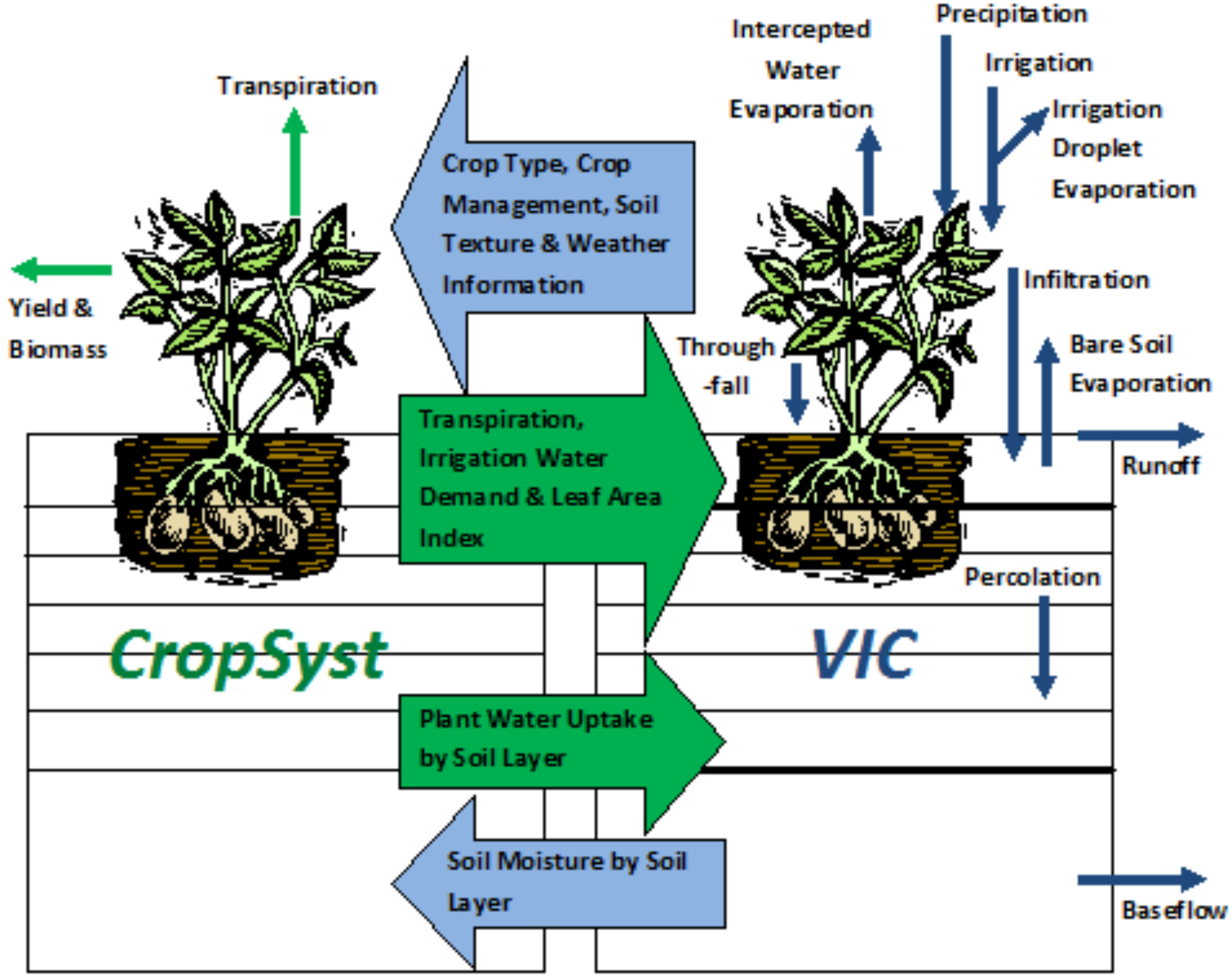
CropSyst

Cropping Systems

Stockle and Nelson 1994

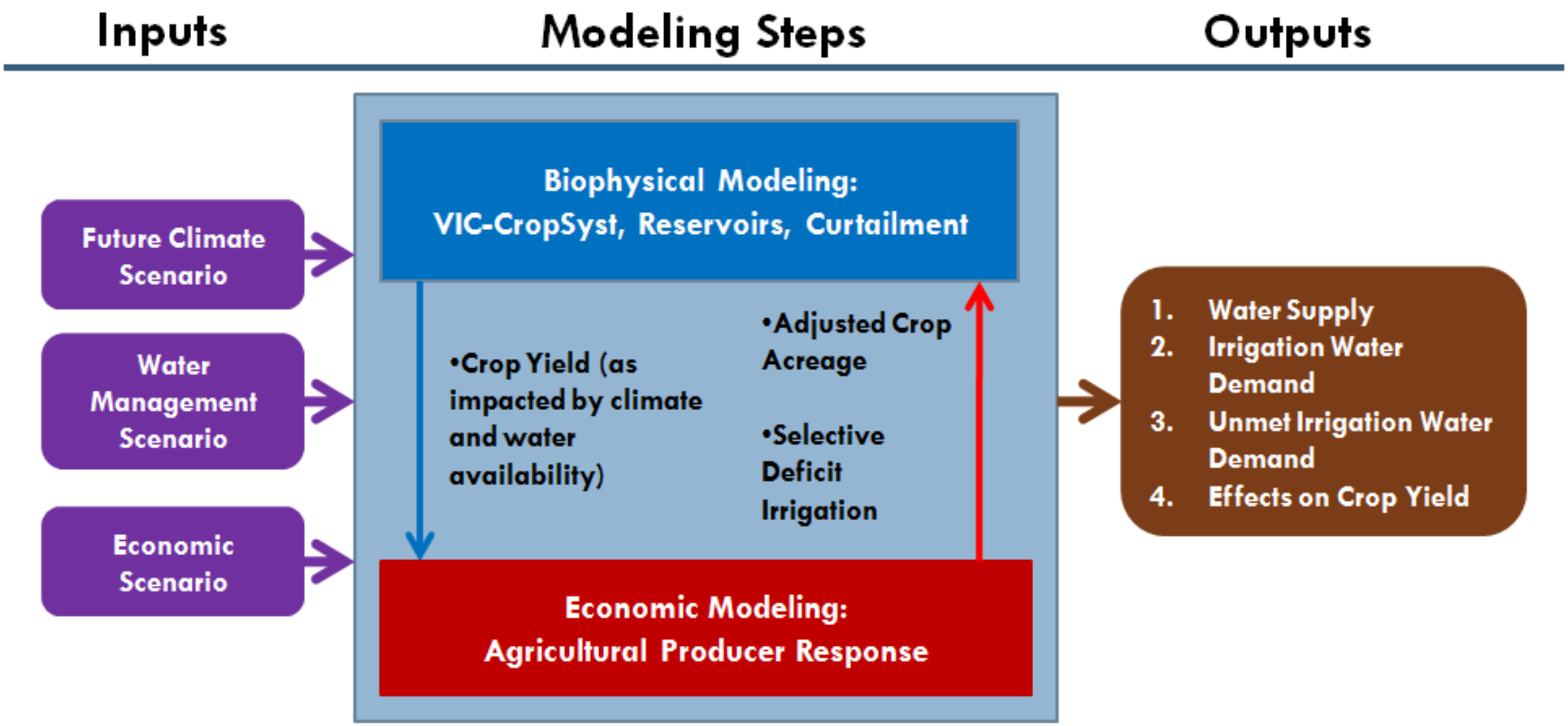


VIC-CropSyst Integration



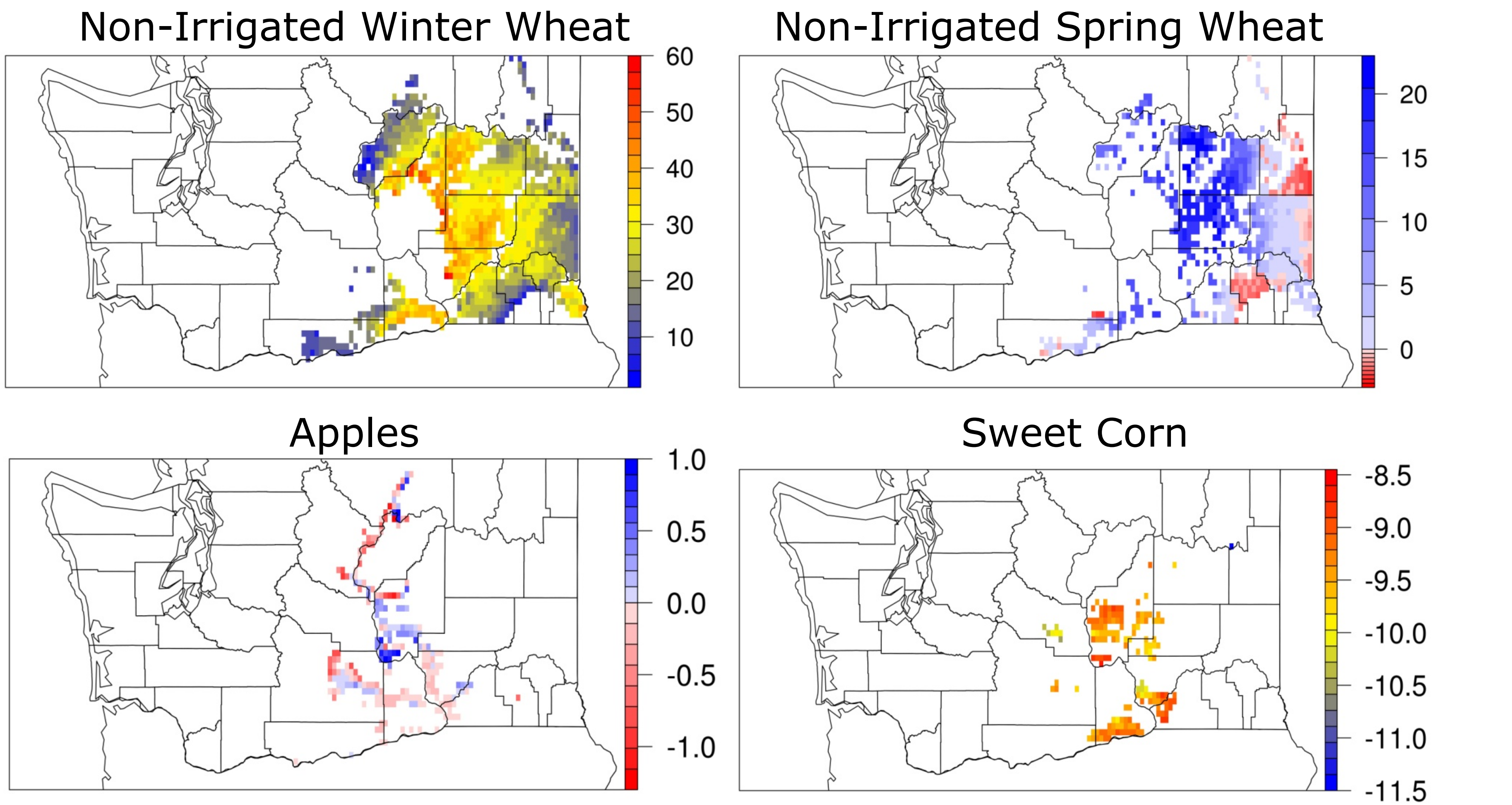
Malek et al. (in prep)

Interactions with Economic Modeling



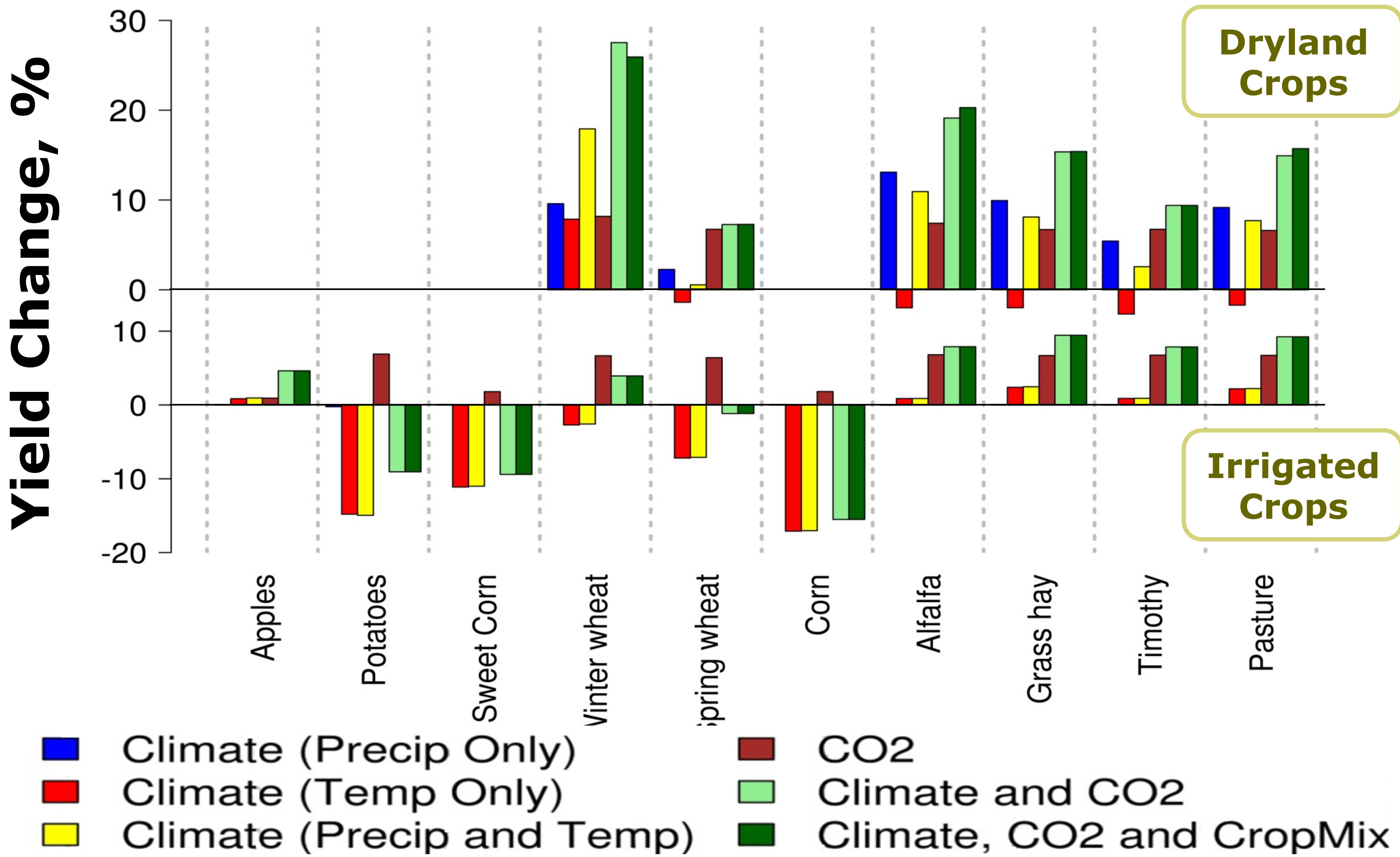
Washington State Water Supply and Demand Projection Project
Yorgey et al. (2011); Rajagopalan et al. (in prep)

Example Results: Projected Climate Change and CO_2 Impacts on Crop Yield (% Change for 2030s)



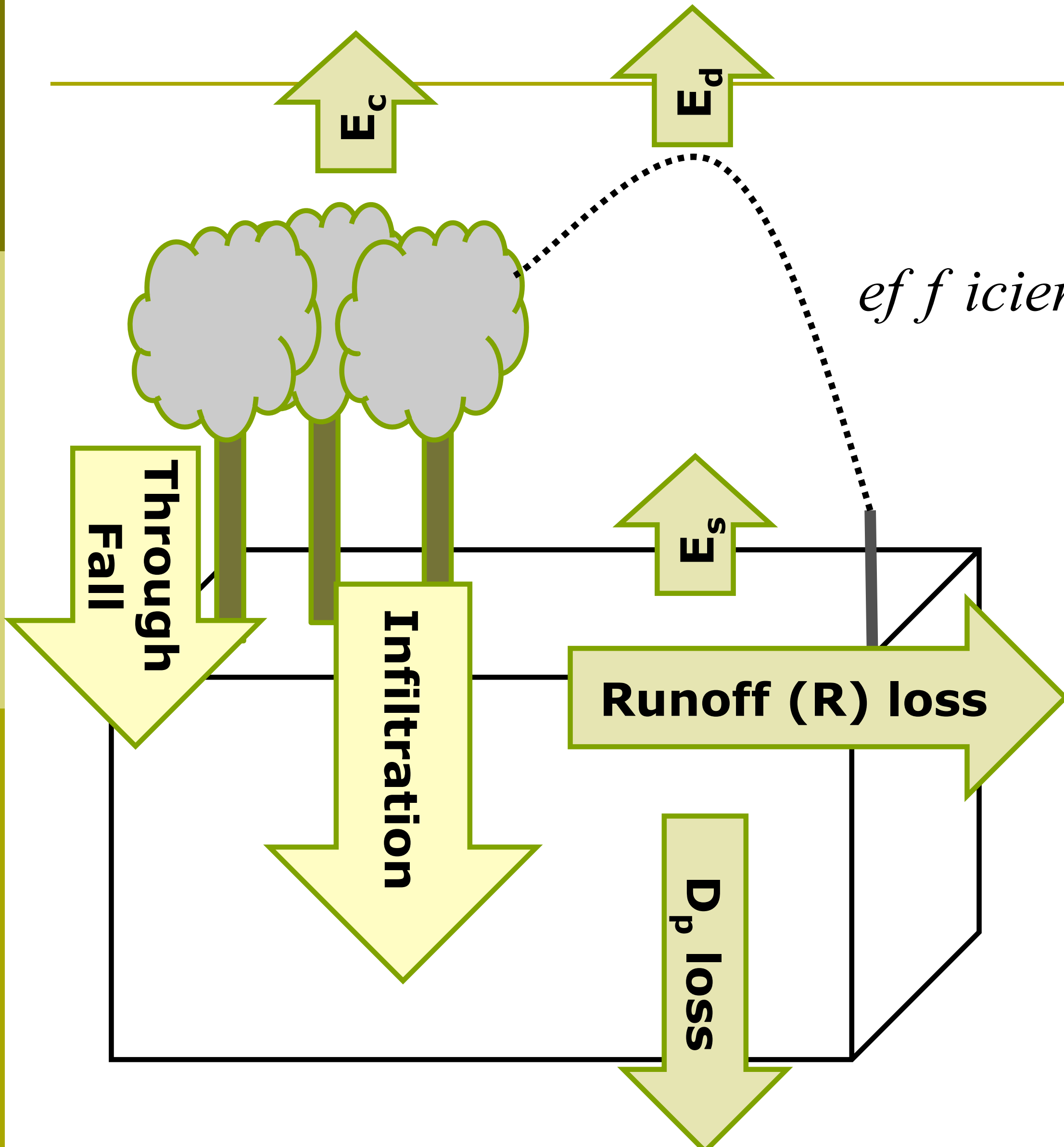
Rajagopalan et al. (in prep)

Year 2030 Projected Impacts on WA Crop Yield: Climate, CO_2, Crop Patterns



Rajagopalan et al. (in prep)

Irrigation Management

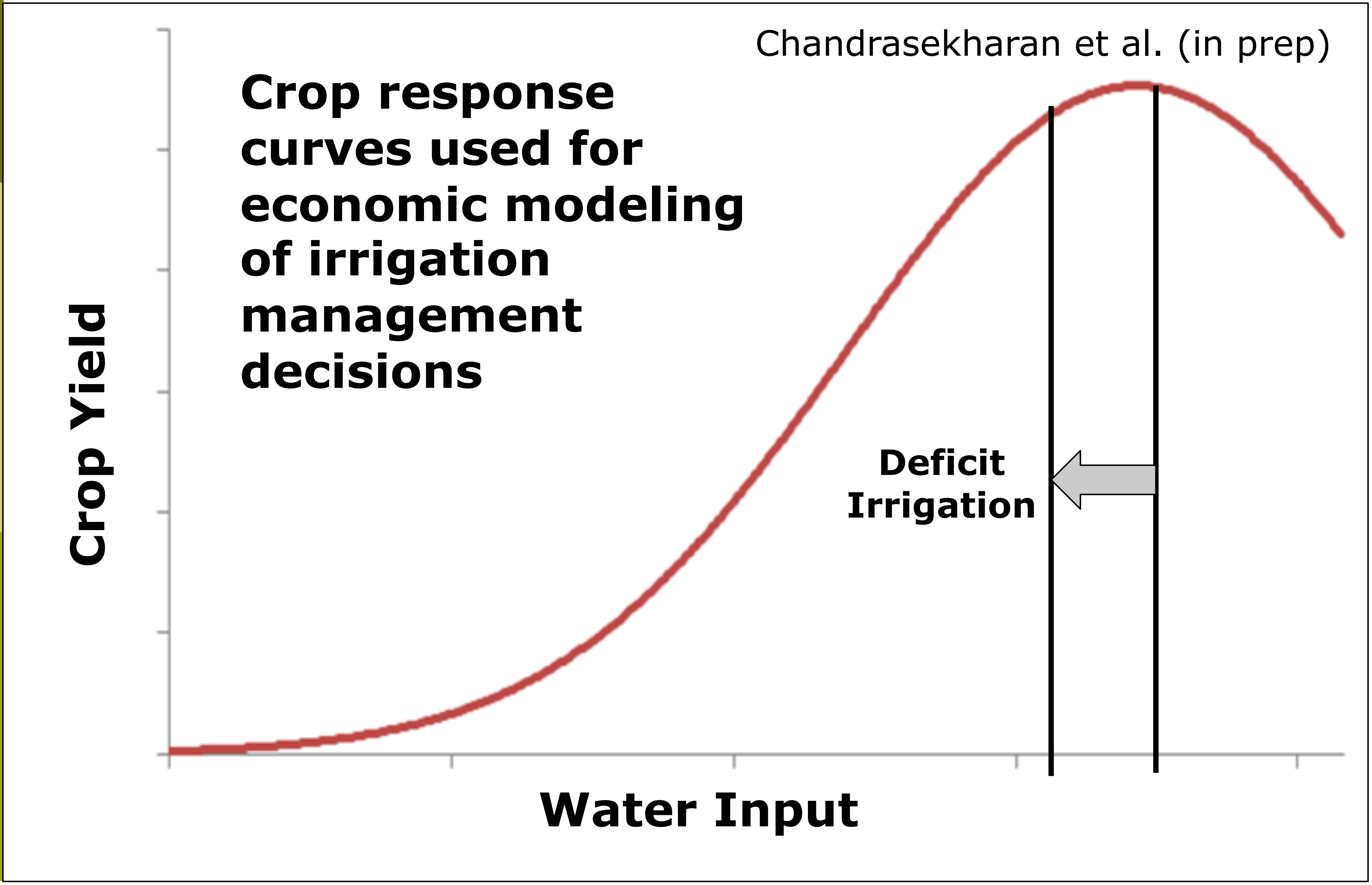


$$efficiency = 1 - \frac{E_d + E_s + E_c + R + D_p}{total\ applied\ water}$$

Ec: evaporation from canopy intercepted water
Es: evaporation from soil
Ed: evaporation from irrigation droplet
Dp: deep percolation loss
R: Runoff loss

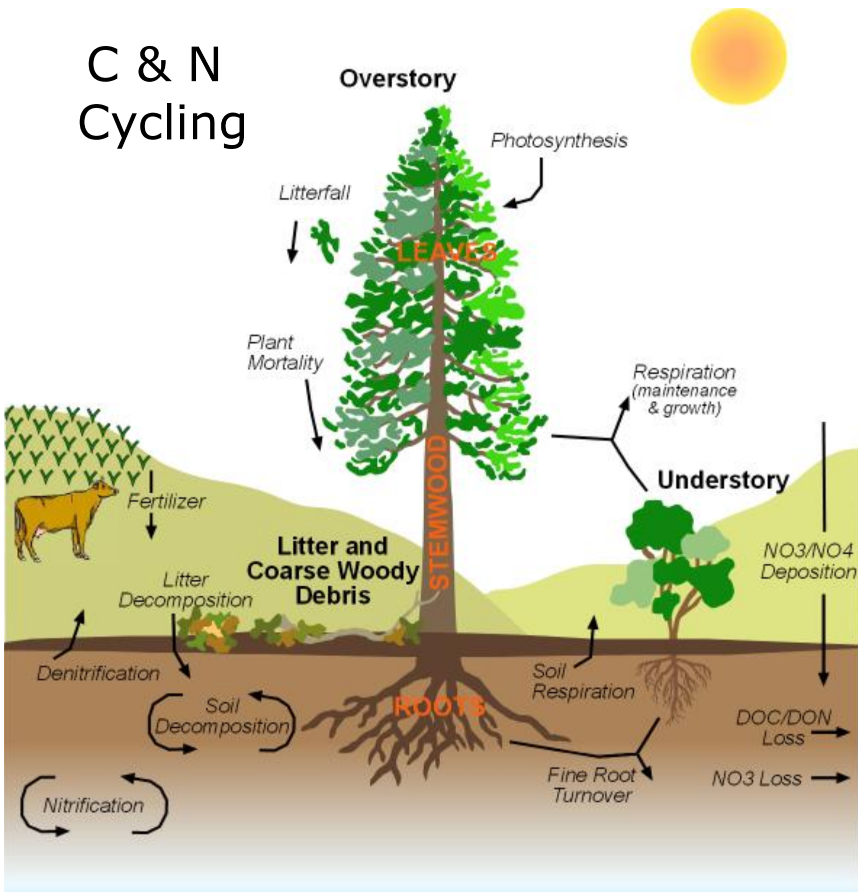
Malek et al. (in prep)

Irrigation Management

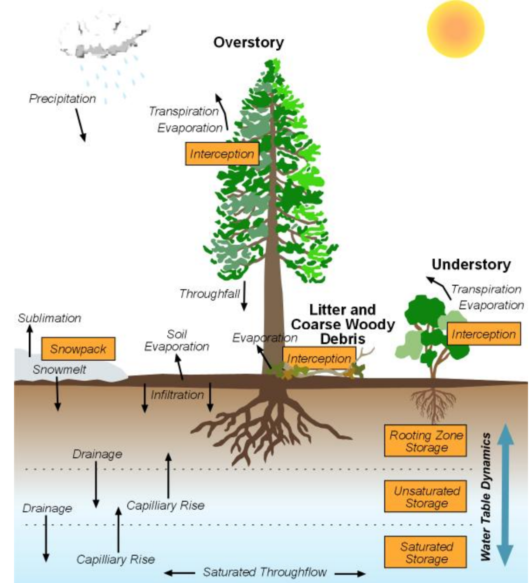


Forest and Rangeland Management: Regional Hydro-Ecologic Simulation System (RHESSys)

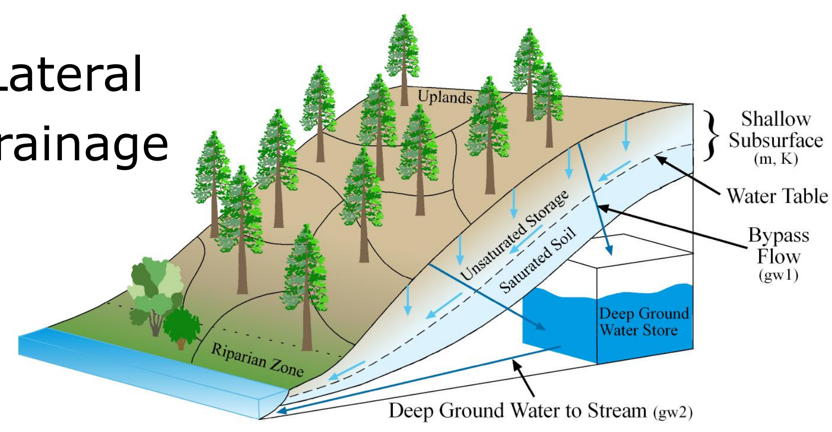
C & N Cycling



Vertical Drainage



Lateral Drainage



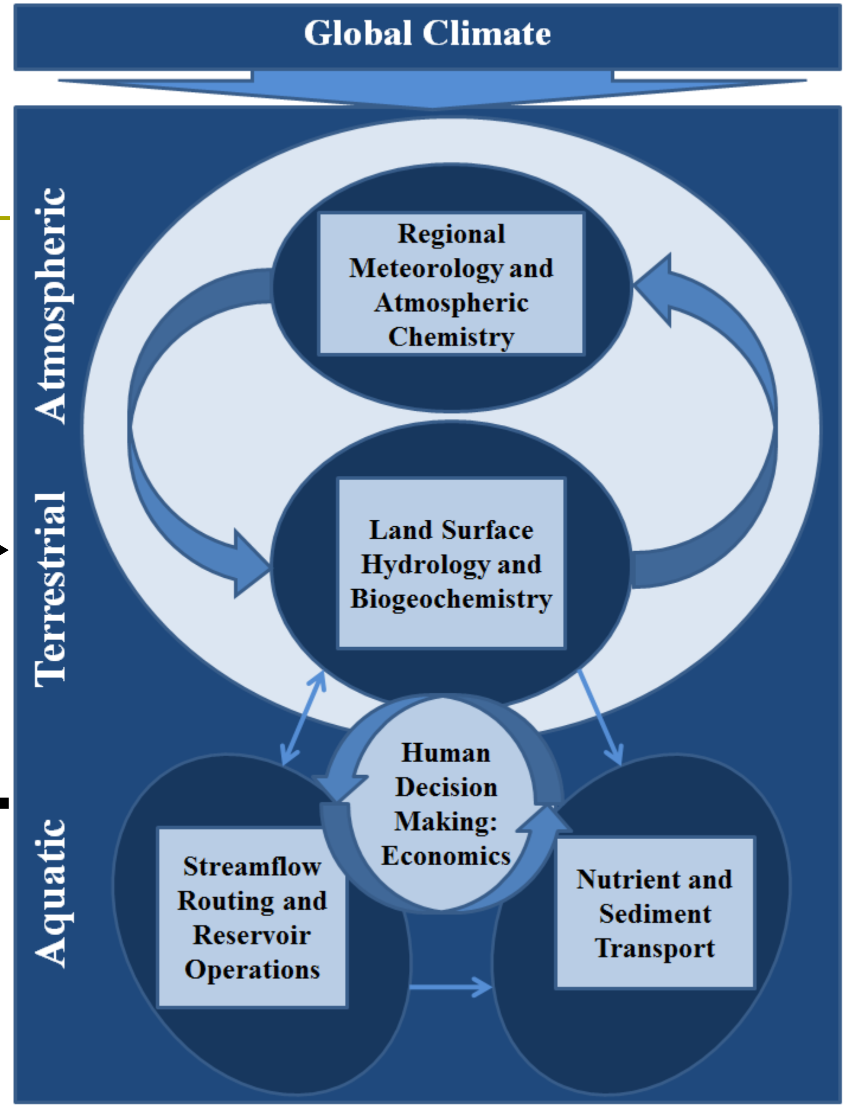
Tague and Band, *Earth Interactions,* 2004
http://fiesta.bren.ucsb.edu/~rhessys

Field Experiments
CZO, LTER, NEON Sites
Experimentalists

Flexible-Open Source Watershed Scale Ecohydrologic Modeling

Relevant model improvements

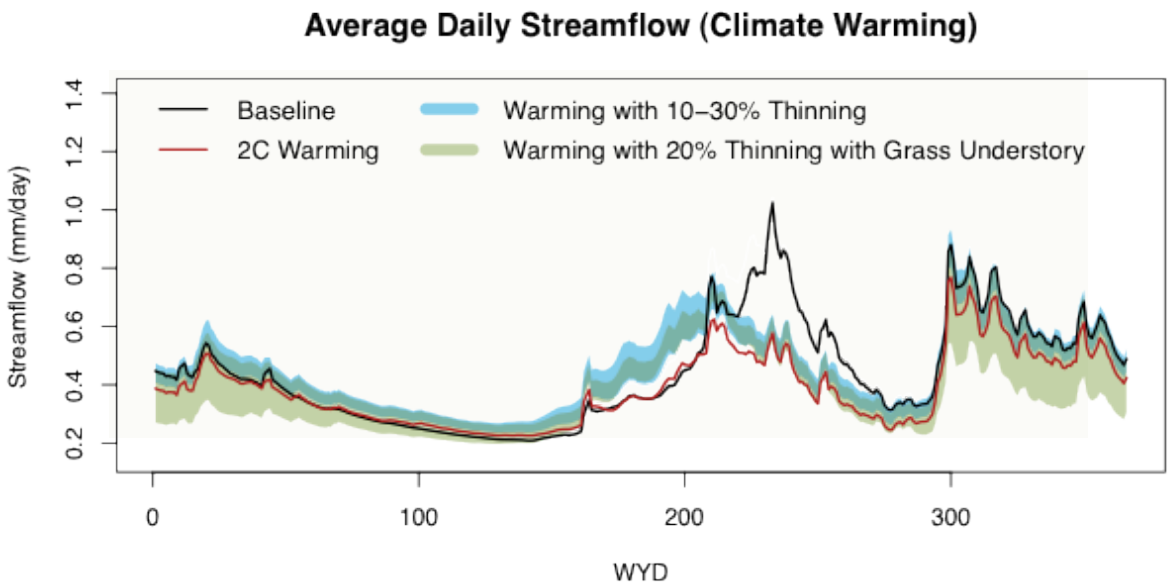
Climate & Ndep scenarios



Implication of CC & land management practices for local watershed H_2O, C & N Flux

Slide courtesy C. Tague, UCSB

Effects of Forest Thinning in Santa Fe Municipal Watershed



* Thinning has the potential to offset reductions in annual streamflow due to warming, however the timing of streamflow shifts to earlier in the year.

Climate	Change in center of mass timing				Percent change in water yield			
	Base	Thin 20%	Thin 30%	Thin 20% + Grass (LAI 0.5)	Base	Thin 20%	Thin 30%	Thin 20% + Grass (LAI 0.5)
Historical	-	- 4 days	- 6 days	- 5 days	-	+ 16%	+ 27%	- 4%
+2° C	- 13 days	- 16 days	- 17 days	- 16 days	- 13%	+ 1%	+ 10%	- 17%
+4° C	- 25 days	- 26 days	- 27 days	- 27 days	- 23%	- 11%	- 3%	- 27%

Dugger 2014 (in prep)

C & N Cycle in Rangeland Systems

Human N cycle

Management
- Grazing intensity
- Grazing methods
  - Temporal
  - Spatial

Agro-ecosystem impact
- Forage quality & quantity

Changes in climate
- Increased CO_2
- Precipitation and temperature shifts

Environmental impact
- N emission
- Methane emission

Grassland N

Soil organic matter (SOM)

C storage

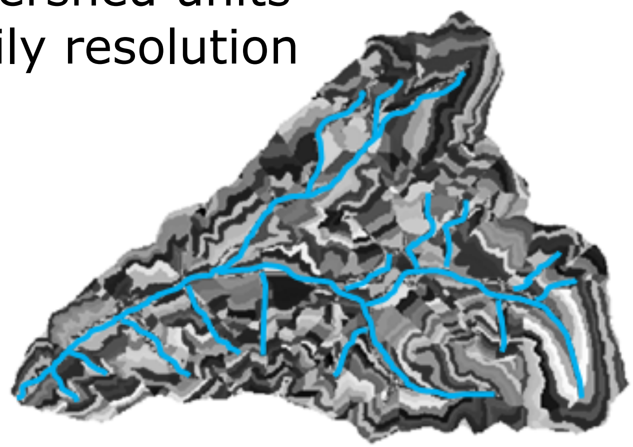
Soil structure

Slide courtesy Julian Reyes

Model Differences Related to Scale and Lateral Connectivity

RHESSys Approach

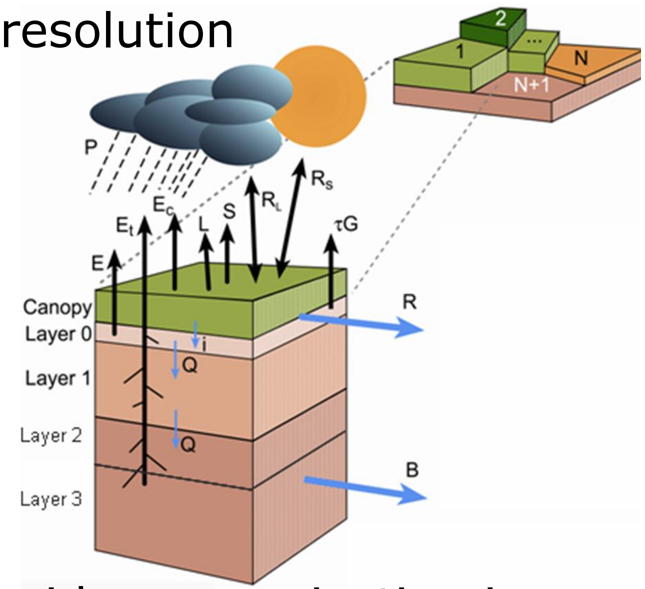
•Spatially-explicit, fine-resolution patchs within watershed units
•Daily resolution



•Dynamic patch-to-patch interaction
•Surface flow routing

VIC Approach

•Statistical sub-grid heterogeneity
•Sub-daily resolution

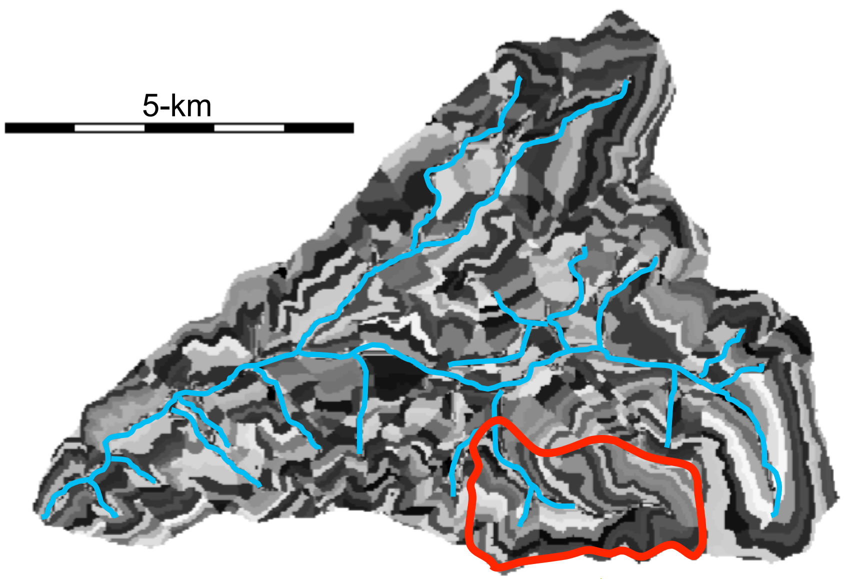


•Grid-to-grid communication is offline and for surface flow routing only

Kepler workflows are in development for implementation of RHESSys over larger scales (Mullis et al. 2014)

Upscaled-RHESSys for Regional Implementation

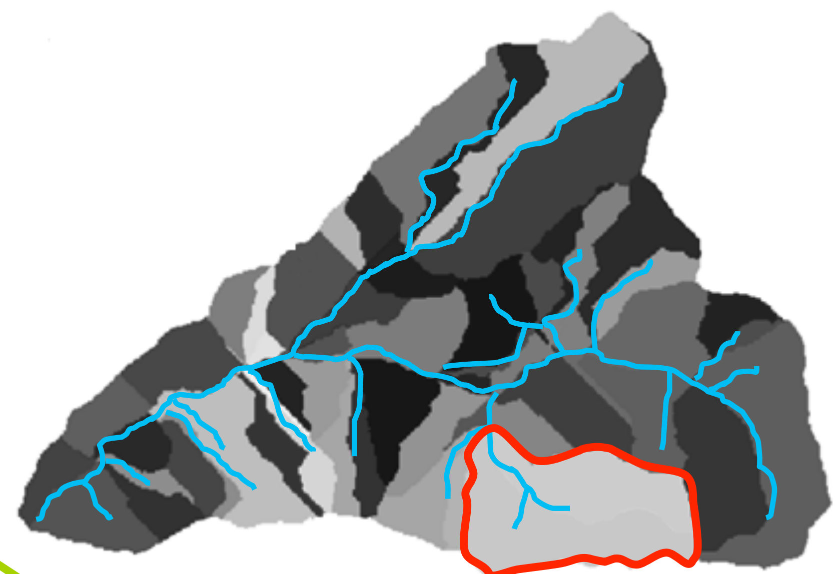
- Spatial patches with explicit spatial information

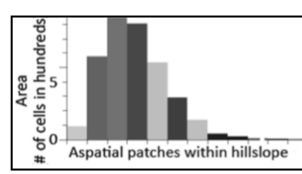


Strategy	# patches	NSE	log NSE	% error
Spatially Explicit	4313	0.73-0.78	0.74-0.92	3.2-4.8
Aspatial Embedded	633	0.70-0.72	0.75-0.86	1.8-8.9

- Upscaled Spatial Patches:

  Larger patches with embedded statistical distribution of land cover type

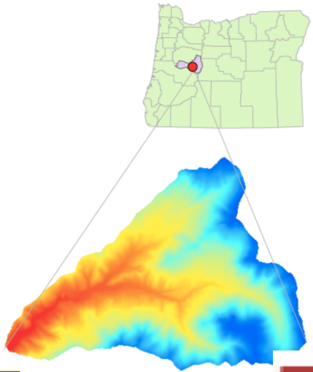


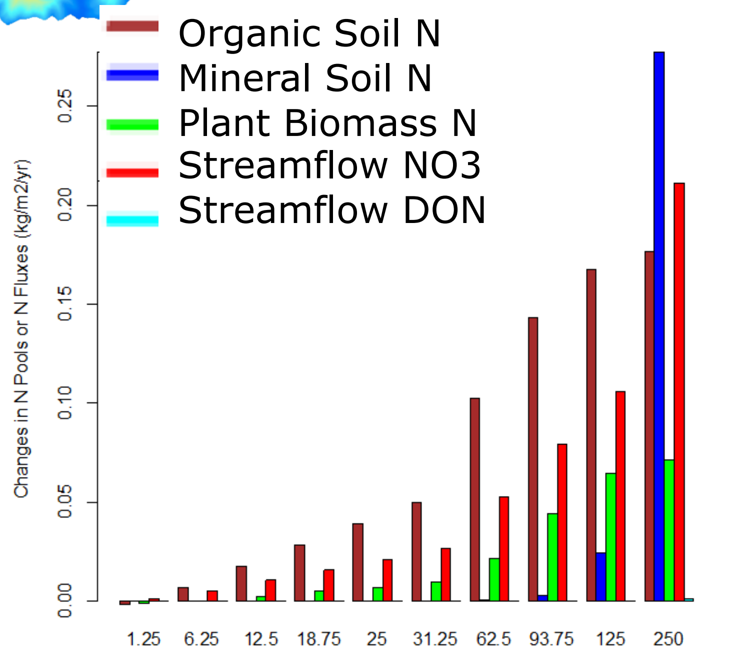


Exploring the Importance of Fine-Scale Land Surface Heterogeneity for Large-Scale Studies

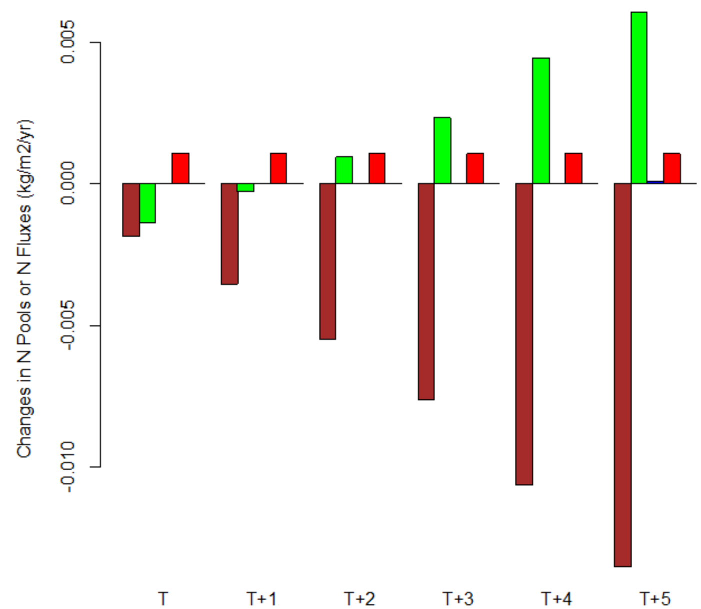
- What types of heterogeneities (at what scales) must be represented to adequately capture large-scale aggregate land surface response to an invoked change?
  - Does fine-scale parameter heterogeneity matter? For which biomes and metrics of interest is fine-scale land surface response to an invoked change nonlinear?
  - Why does it matter? What type of heterogeneity is driving this response (parameter heterogeneity or lateral connectivity)?
  - How can this information inform upscaling of RHESSys to the regional scale?

Sensitivity of N-Retention and Export to Temperature and Nitrogen Deposition at the HJ Andrews Experimental Site (Coniferous Forest)





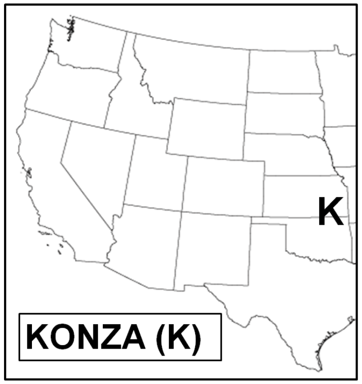
Changes in N stores and fluxes with increasing N deposition



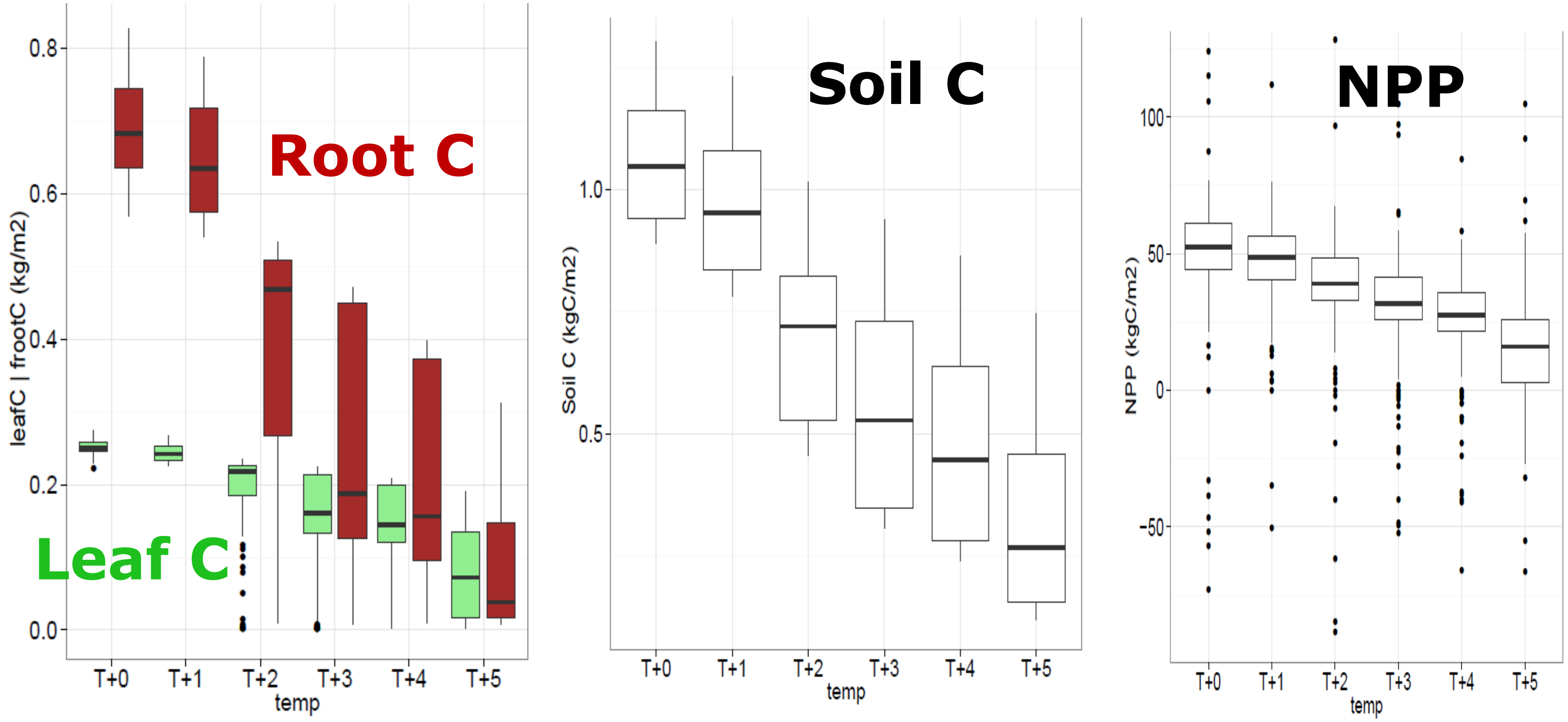
Changes in N stores and fluxes with increasing temperature

For both temperature and N-deposition increase scenarios, responses are relatively linear and the thresholds, where ecosystem behavior shows dramatic changes in the pattern of response, are not likely to be reached within the next decades.

Zhu et al. (in prep)



Sensitivity of C Stores and Fluxes to Temperature in Tallgrass Prairie



Changes in C stores and fluxes with increasing temperature

Reyes et al. (in prep)

Stakeholder Engagement Process

Will improve our understanding of:

1. The factors driving resource management decisions and information needs of decision makers.

2. How stakeholders prioritize their various environmental and economic concerns.

3. What decision makers want to know about future change (for example, possible climate scenarios or effects of alternative regulatory mechanisms).

Informing:

- Model development (processes, priorities)
- Model scenarios (e.g., changes in practices, policies; scales of interest)
- Communicating and vetting results

2013

Nitrogen

Water Supply

2014

Air Quality

Forests

Rangeland

2015+

Water Quality

Continuing communication of model outputs, model refinement based on stakeholder input

Allen et al. 2013

Overall Summary and Conclusions

- Integrated modeling frameworks can and should be used for *informing* policy and management decisions; e.g., highlighting trade-offs, feedbacks, and thresholds; and uncovering unintended consequences.
- There are numerous opportunities to increase the usability of these frameworks
  - Regional specificity: e.g., the regulatory and legal environment that governs competing water uses
  - Explicit inclusion of decision processes
  - Representation of spatial heterogeneity; e.g., as governed by the sources of heterogeneity that control the response of a system to changes in climate or management activities
  - Stakeholders as team members


Thank you!
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DEPARTMENT OF
ECOLOGY
State of Washington
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State of Washington Water Research Center
WASHINGTON STATE
UNIVERSITY

Overall Summary and Conclusions

- Need for flexible and modular integrated modeling frameworks:
  - Flexibility: e.g., representing types of land surface heterogeneity at different scales
  - Modularity: e.g., uncoupled, loosely-coupled, and tightly-coupled options; options for different models; options to include bias correction
  - Implementation specific to the research question, taking into account the scales that drive system response, the scales and interconnectivity of the decision process under investigation, and the information needs of the end user

Scenario Construction

Paradigm 1:

Predict, Then Act

A best-guess is made about the future, then management plans, investments or policies are designed accordingly.

Guiding Question: What is most likely to happen?

Places unrealistic demands on modeling and climate science.

Paradigm 2:

Seek Robust Solutions

Vulnerabilities for a range of possible futures identified, then decisions that perform well across that range.

Guiding Question: How does the system work? What are possible unintended consequences of decisions?

Accounts for complexity and uncertainty in earth systems & human decision-making

Slide courtesy Liz Allen

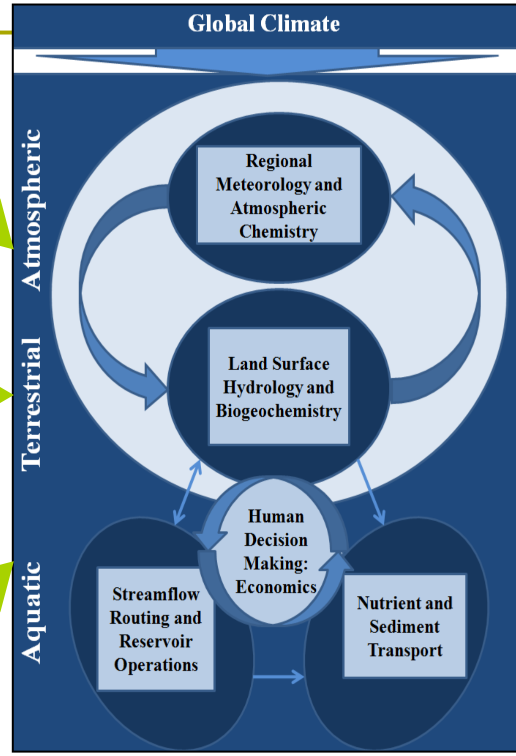
Weaver et al., 2013

"Not predicting, but projecting"

Resource Managers (Industry, Landowners, Government)

Policy Makers (Federal, State Local and Tribal Government)

Other Stakeholders (Advocacy groups, Researchers)



Future Scenario A

Future Scenario B

Future Scenario C

Future Scenario D

How could insight into possible (uncertain) futures influence the decisions we make about management, investments and policy?

Slide courtesy Liz Allen

Exploring the Importance of Fine-Scale Land Surface Heterogeneity for Large-Scale Studies

- Types of Spatial Heterogeneity
  - Parameter Heterogeneity
    - Parameters (land cover, soil, topography, etc.) that control land surface processes
    - Spatial organization of heterogeneity may not matter
  - Lateral Connectivity
    - Moisture and nutrient redistribution: non-local sources that are often neglected in large-scale studies
    - Spatial organization matters!

Regional Simulations: Consideration for Computational Efficiency

RHESSys "Embedded Aspatial Patches"

when the aggregate effect of spatial heterogeneity matters but not its spatial pattern

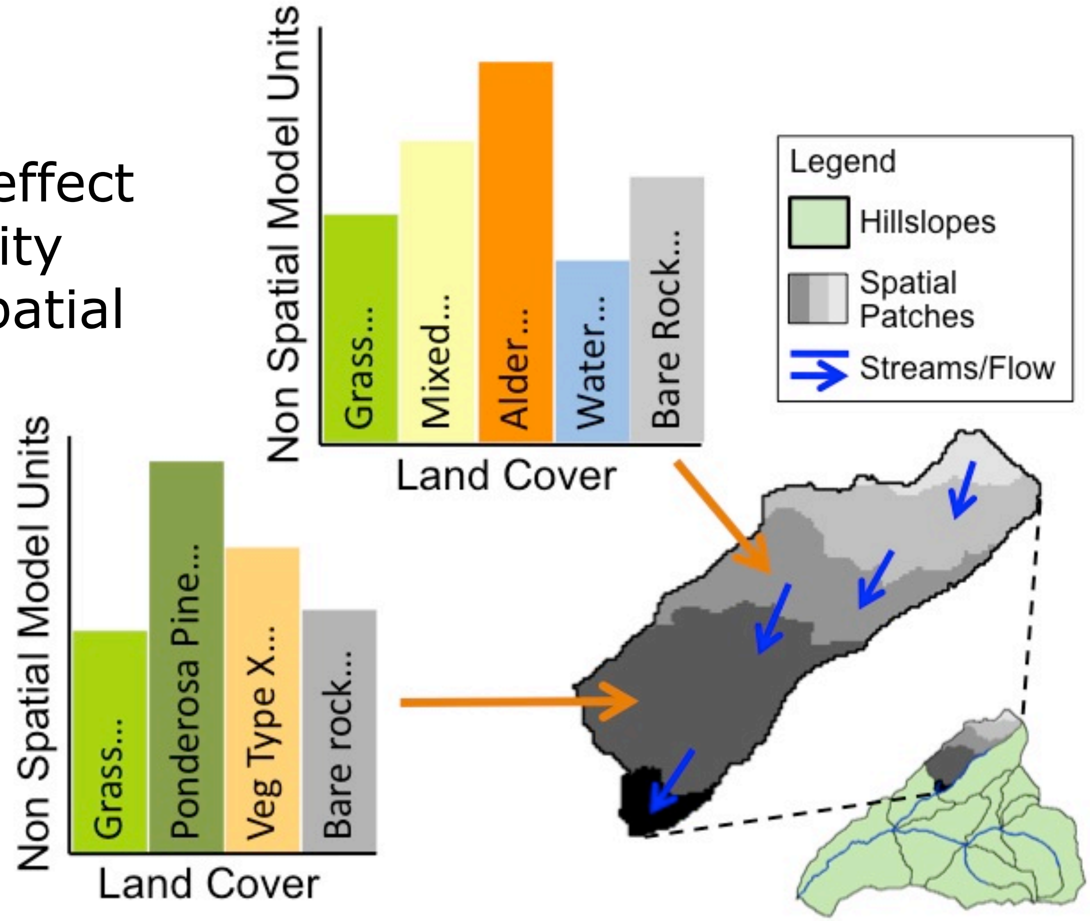
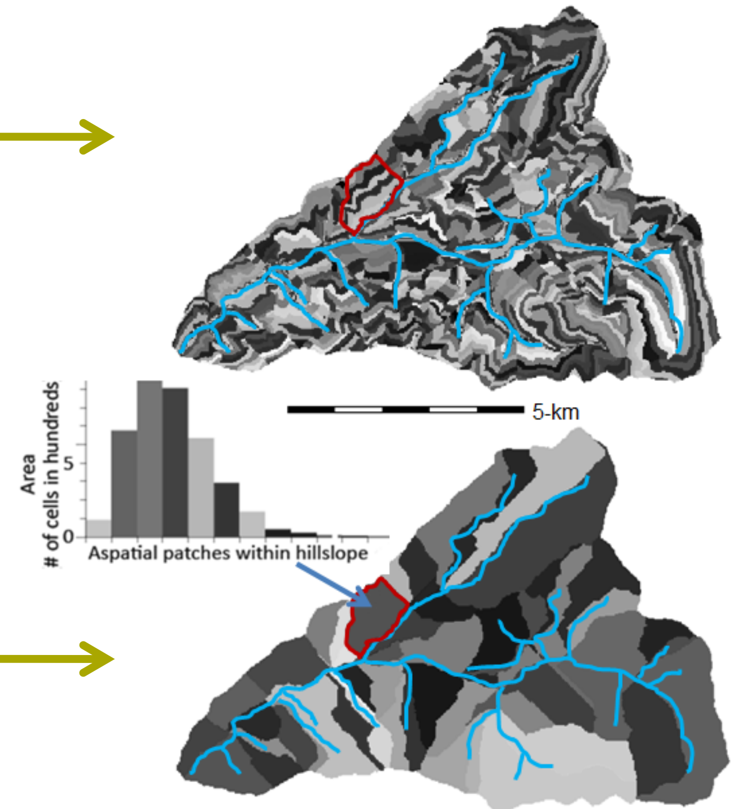


Diagram courtesy J. Choate, UCSB

Representing Land Surface Heterogeneity in RHESSys

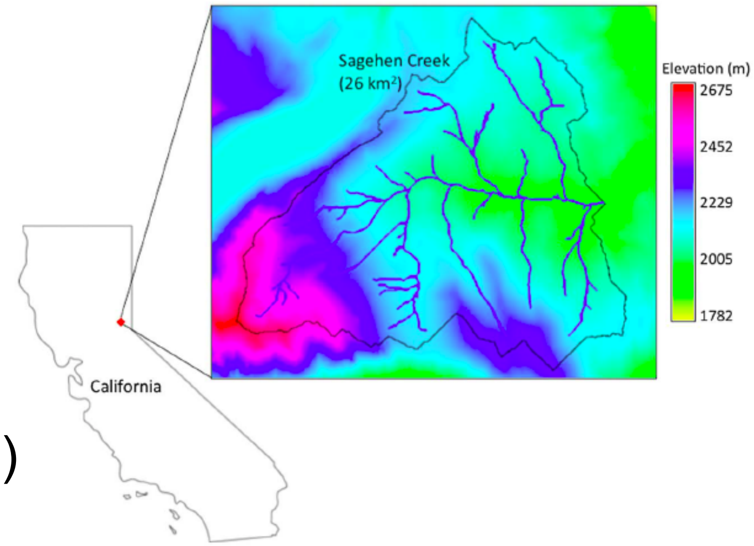
Diagram courtesy J. Choate, UCSB

- *Explicit patch representation:* captures both parameter heterogeneity and lateral connectivity at fine scales
- *Embedded aspatial patch representation:* captures parameter heterogeneity at fine scales and lateral connectivity at moderate scales



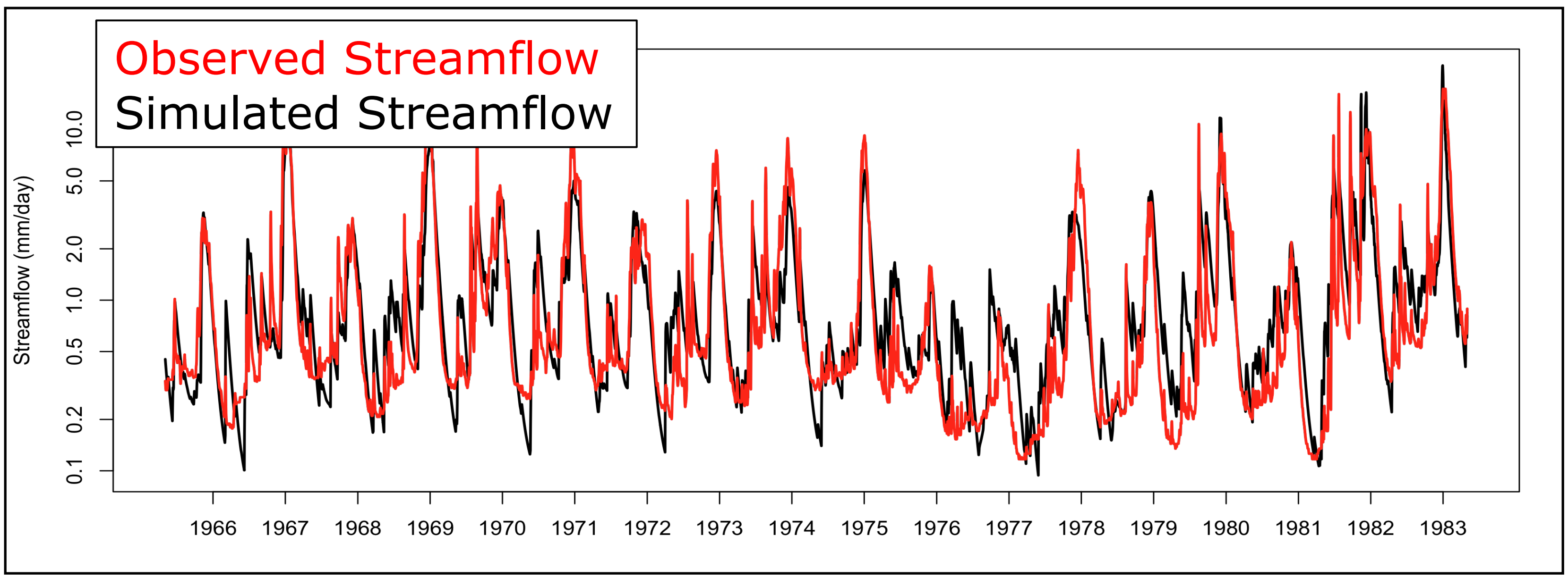
RHESSys' "aspatial patches" allows users the flexibility to choose the scales representing each type of heterogeneity while considering computational efficiency for large-scale studies.

Lateral Redistribution Experiment



Sagehen Experimental Watershed
(UC Berkley Field Station)

Sierra Nevada Mountain watershed (183ha)
Elevation range *1800-2700m*
Vegetation: conifer (Jeffrey and Lodgepole pine and fir with substantial meadows)



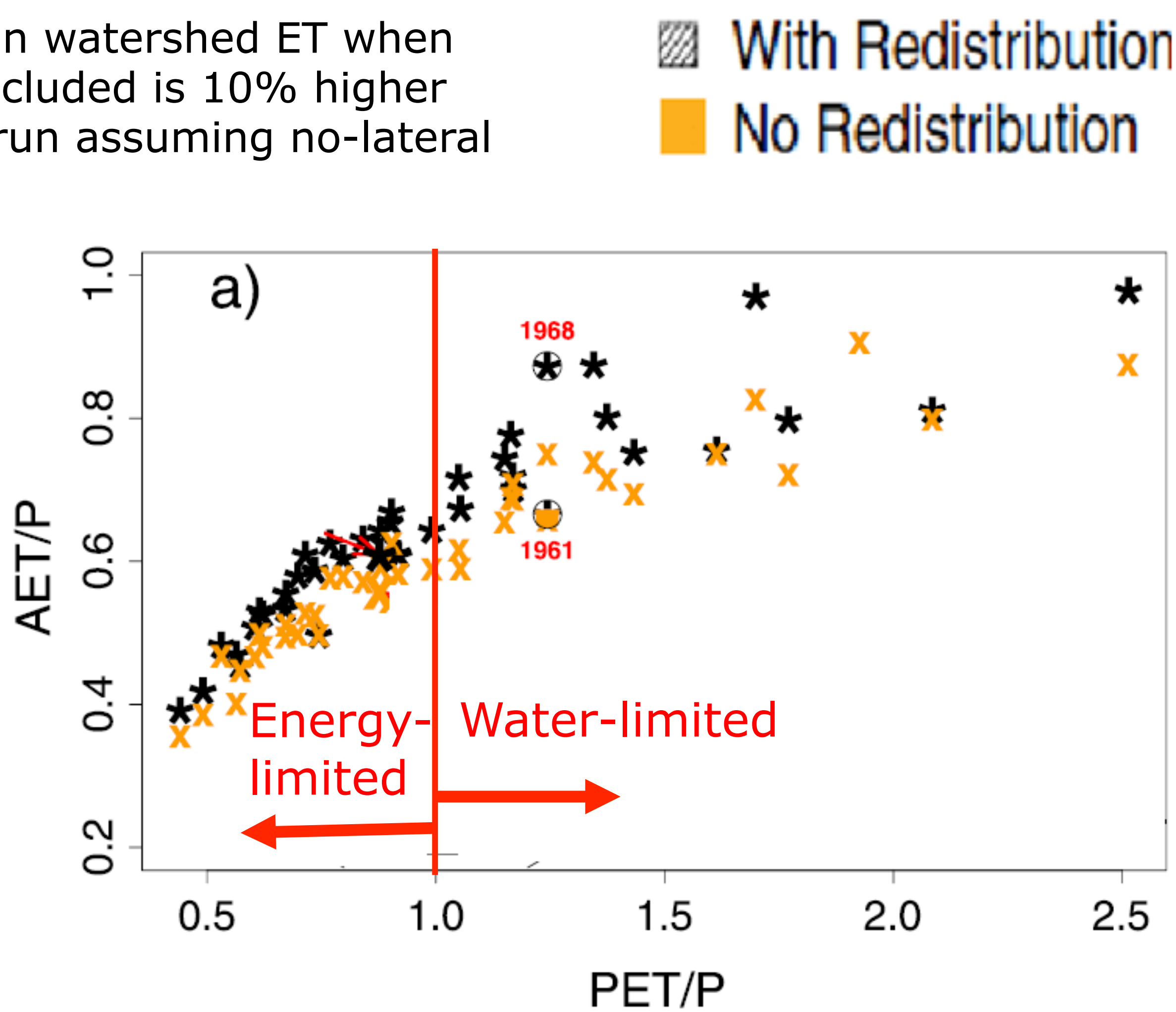
Tague and Peng 2013

Contribution of Lateral Redistribution of Water

All else being equal, mean watershed ET when lateral redistribution is included is 10% higher then when watershed is run assuming no-lateral redistribution.

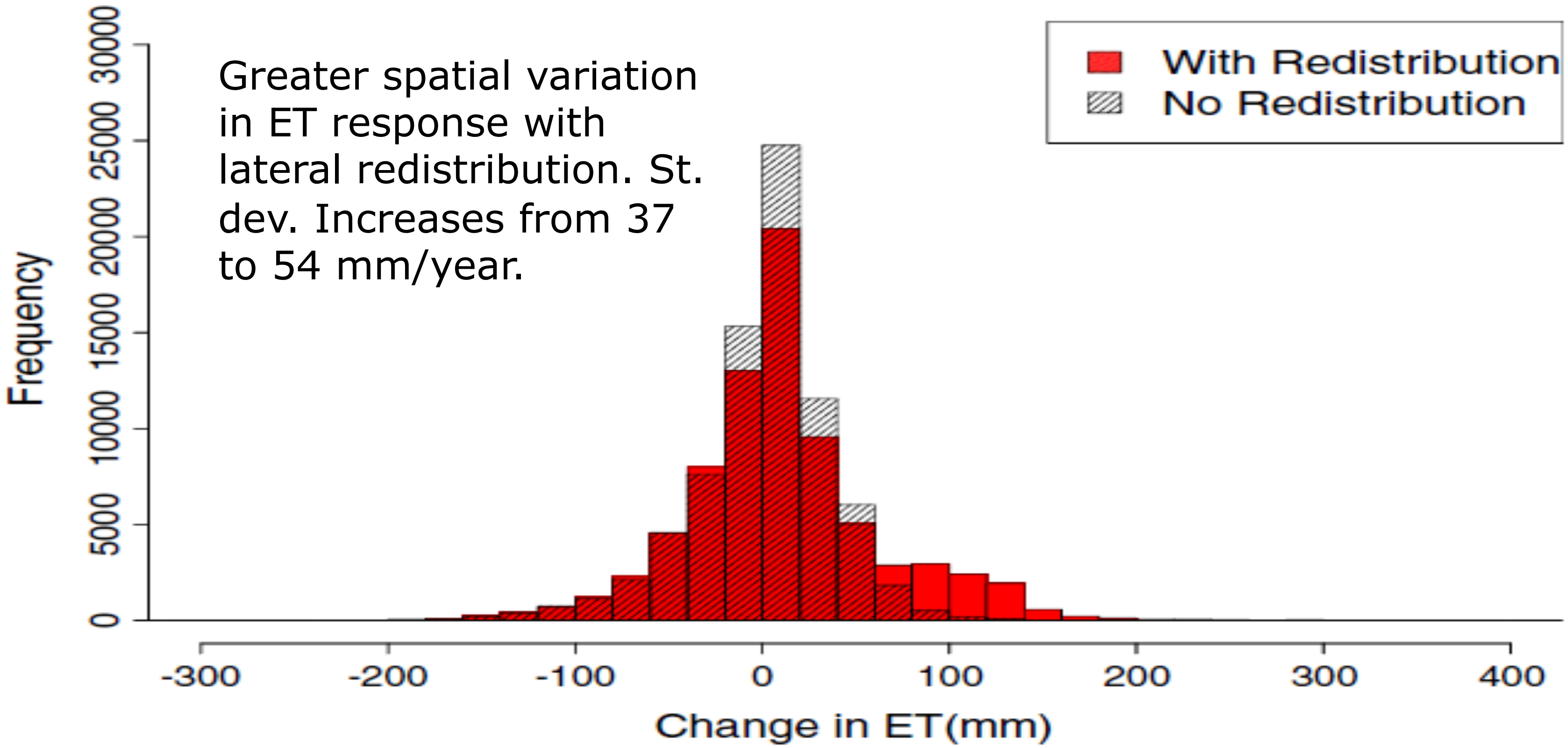
ET increases at all elevations, but disproportionately more so at lower elevations.

Accounting for redistribution moves actual ET towards its theoretical upper limits.



Tague and Peng 2013

Patch ET Distribution Effects of 3˚C Warming With and Without Lateral Redistribution



Some implications include modeling of fluxes back to the atmosphere and water stress in forests.

Tague and Peng 2013

Determining What Types of Spatial Heterogeneity are Important

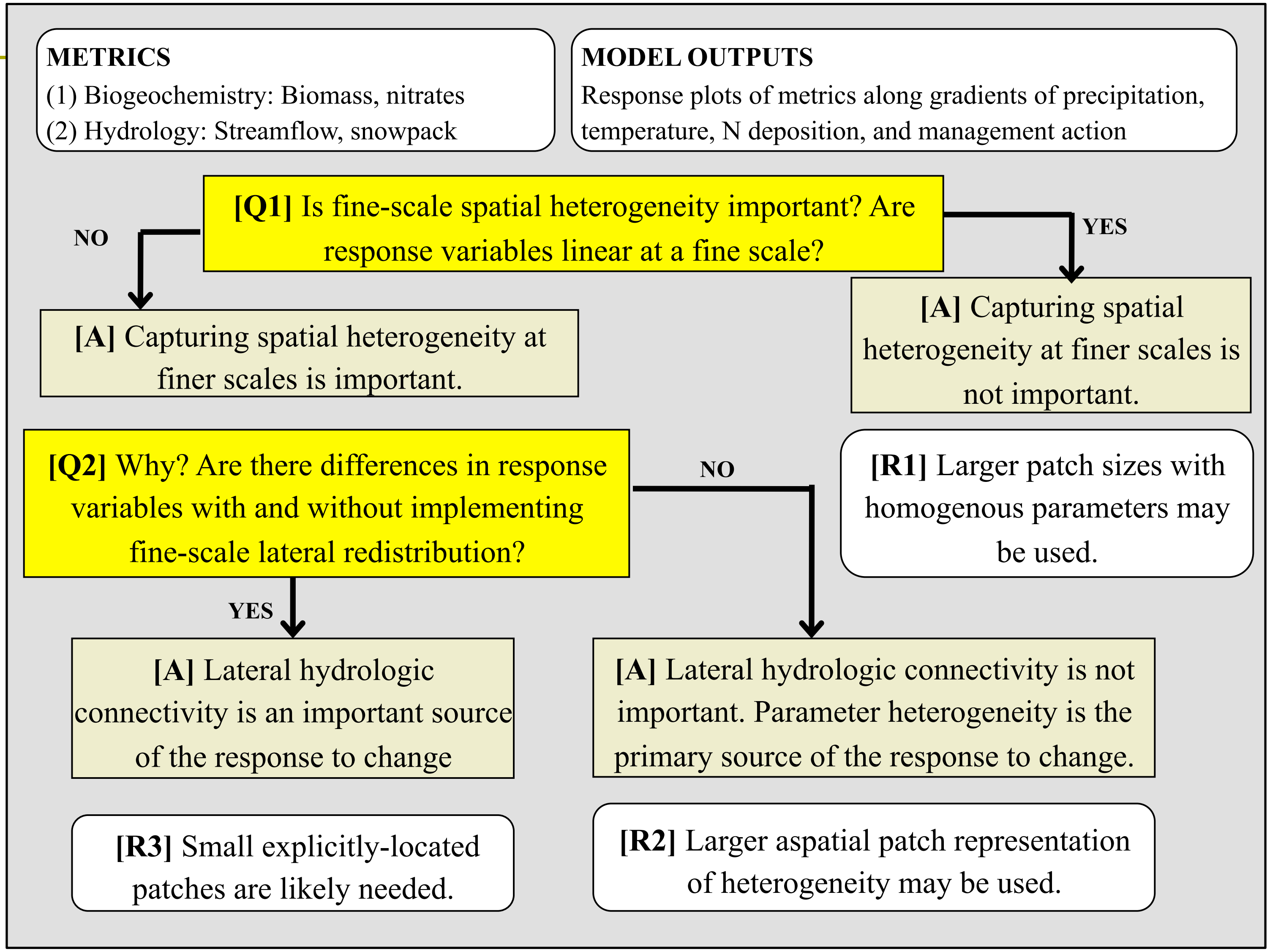


Diagram courtesy J. Reyes

What is the Importance of Climate Model Bias to Land Surface Response?

- Motivation:
  - Land surface simulations driven with biased meteorological data can result in less useful information for decision-making (Muerth et al. 2013).
  - In fully coupled (land-atmosphere) studies, bias correction of modeled meteorology destroys dynamical consistency in simulated variables.
  - However, for climate change impact studies, often only the *response* of the variable to a change in climate is of interest.

Liu et al. (2014) What is the importance of climate model bias when projecting the impacts of climate change on land surface processes? Biogeosciences

What is the Importance of Climate Model Bias to Land Surface Response?

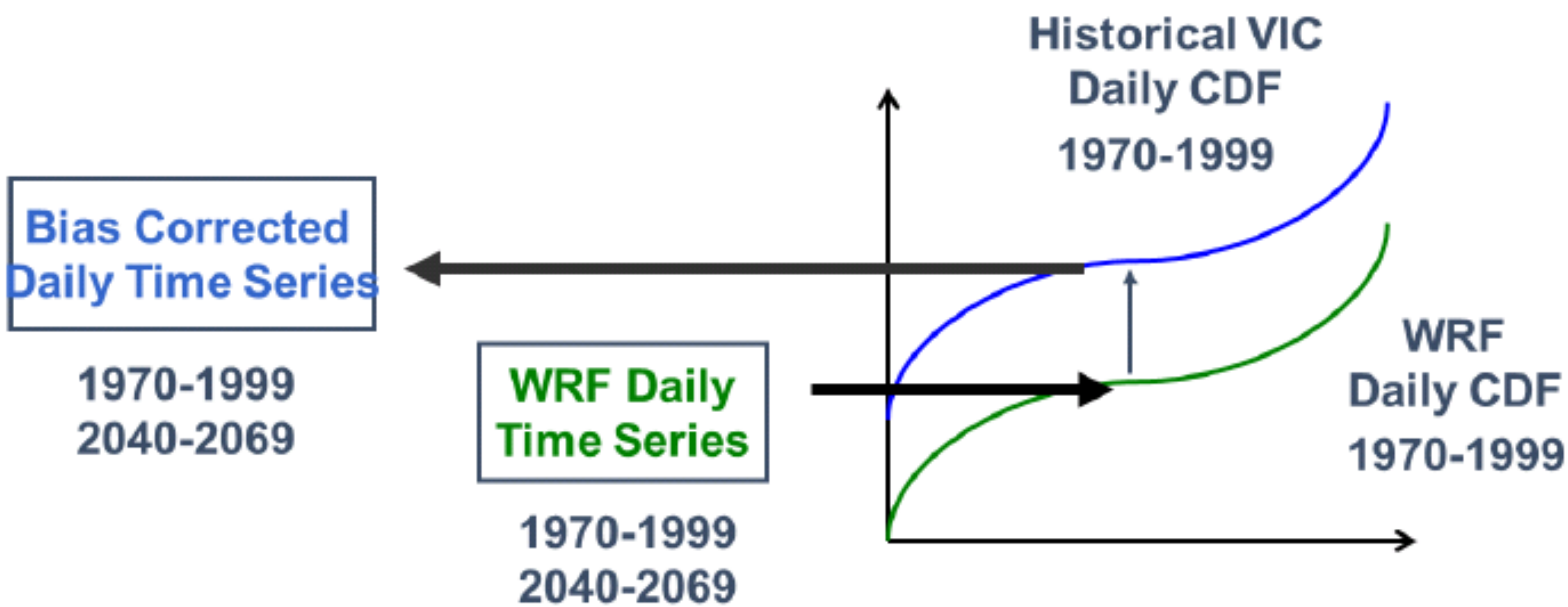
- Research Questions
  - How does performing bias correction affect the response of the land surface, specifically with respect to
    - Hydrology: Runoff, ET, Snow Water Equivalent (SWE)
    - Agriculture: Crop Yield (irrigated and dryland), Irrigation Water Demand
    - Forest Ecosystems: Net Primary Productivity (NPP)
    - Air/Water Quality: Biogenic Emissions, Nutrient Export
  - How can we use these results to inform BioEarth development and application for specific studies?

Liu et al. (2014) What is the importance of climate model bias when projecting the impacts of climate change on land surface processes? Biogeosciences

Statistical Downscaling and Bias Correction (BCSD) Procedure

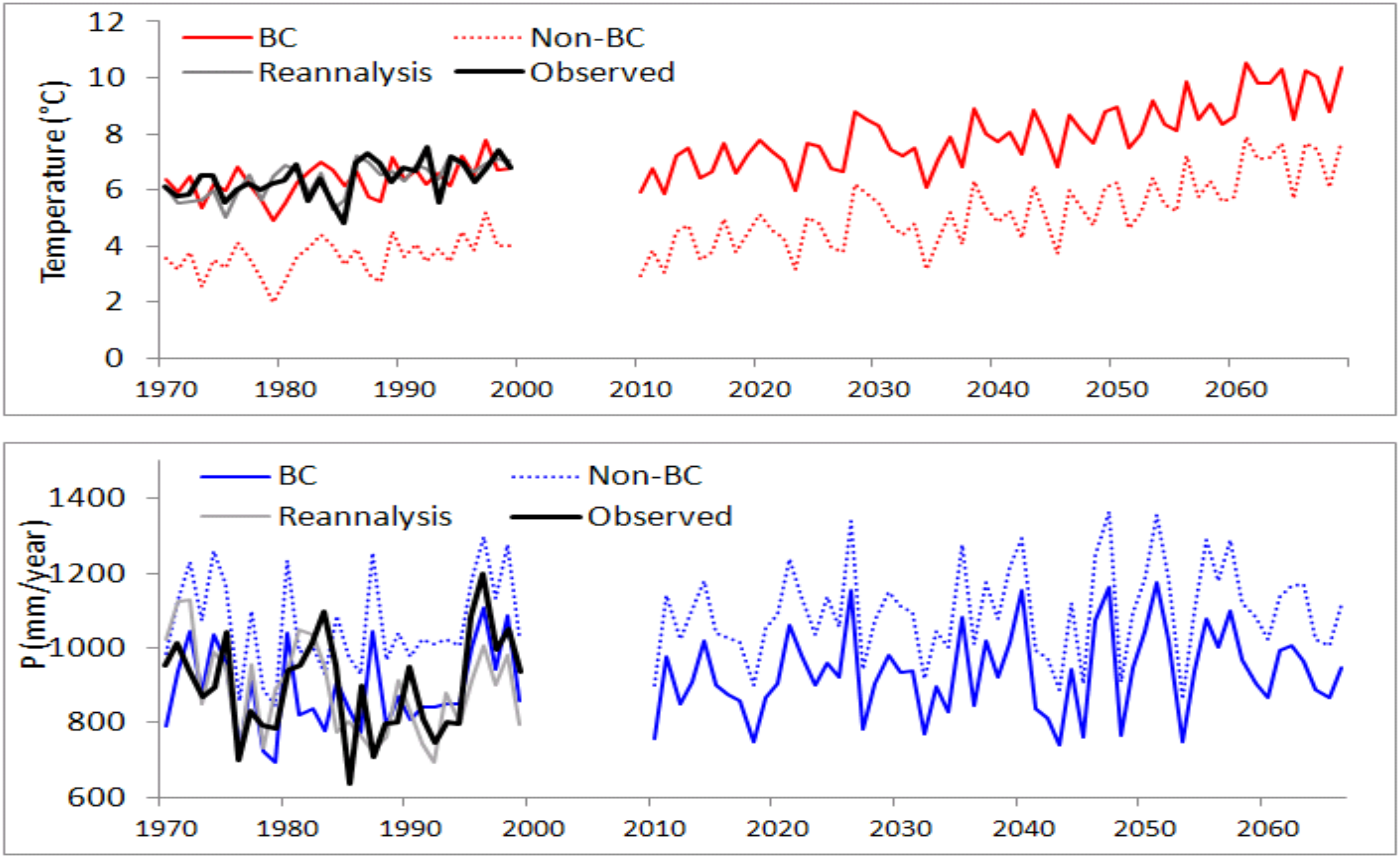
BCSD strengths:

- Bias corrects the entire distribution
- Intended to preserve the GCM climate change signal



Salathé, E.P., A.F. Hamlet, M. Stumbaugh, S. Lee, R. Steed (2012) Estimates of 21st Century Flood Risk in the Pacific Northwest Based on Regional Scale Climate Model Simulations.

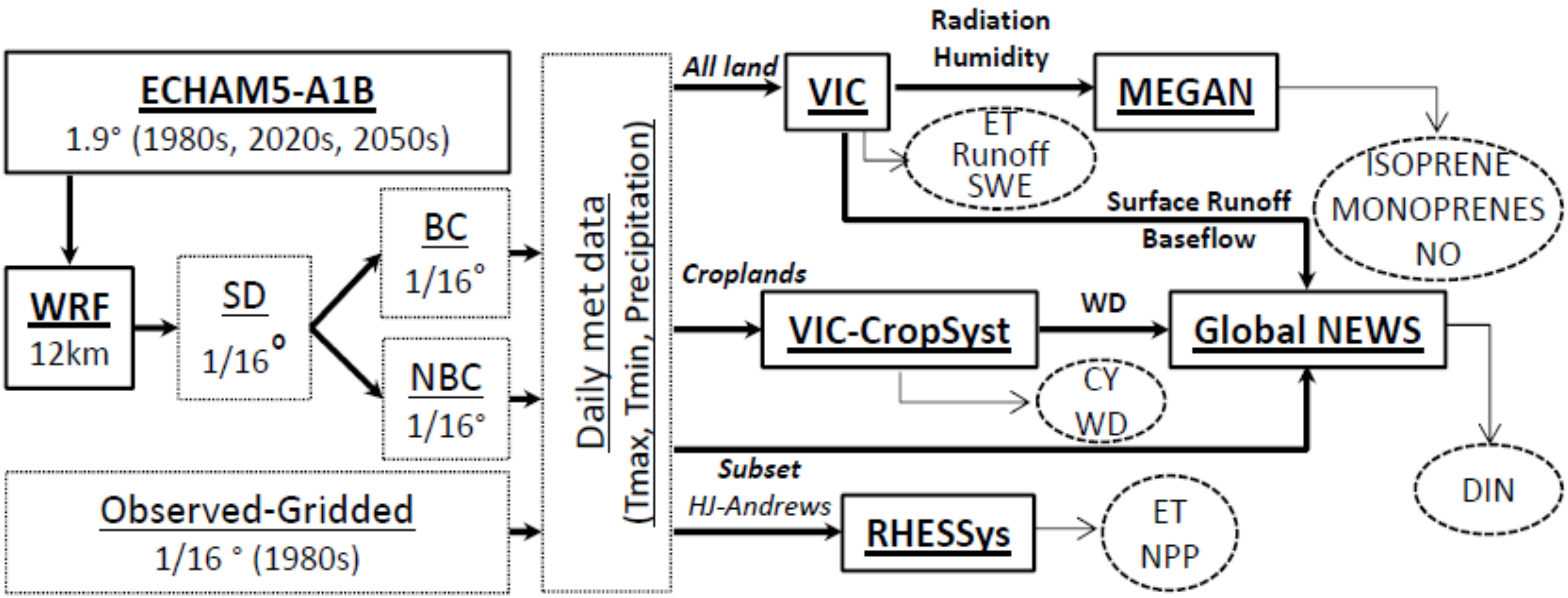
Comparing BC & Non-BC for Precipitation and Temperature



Therefore…

- Bias correction resulted (on average over space and annually) in a drier and warmer climate over the region.
- Is the land surface response to climate change different in this drier, warmer climate?
- Nonlinearities, critical thresholds, competing effects, and spatio-temporal scales matter.

Model and Data Flowchart



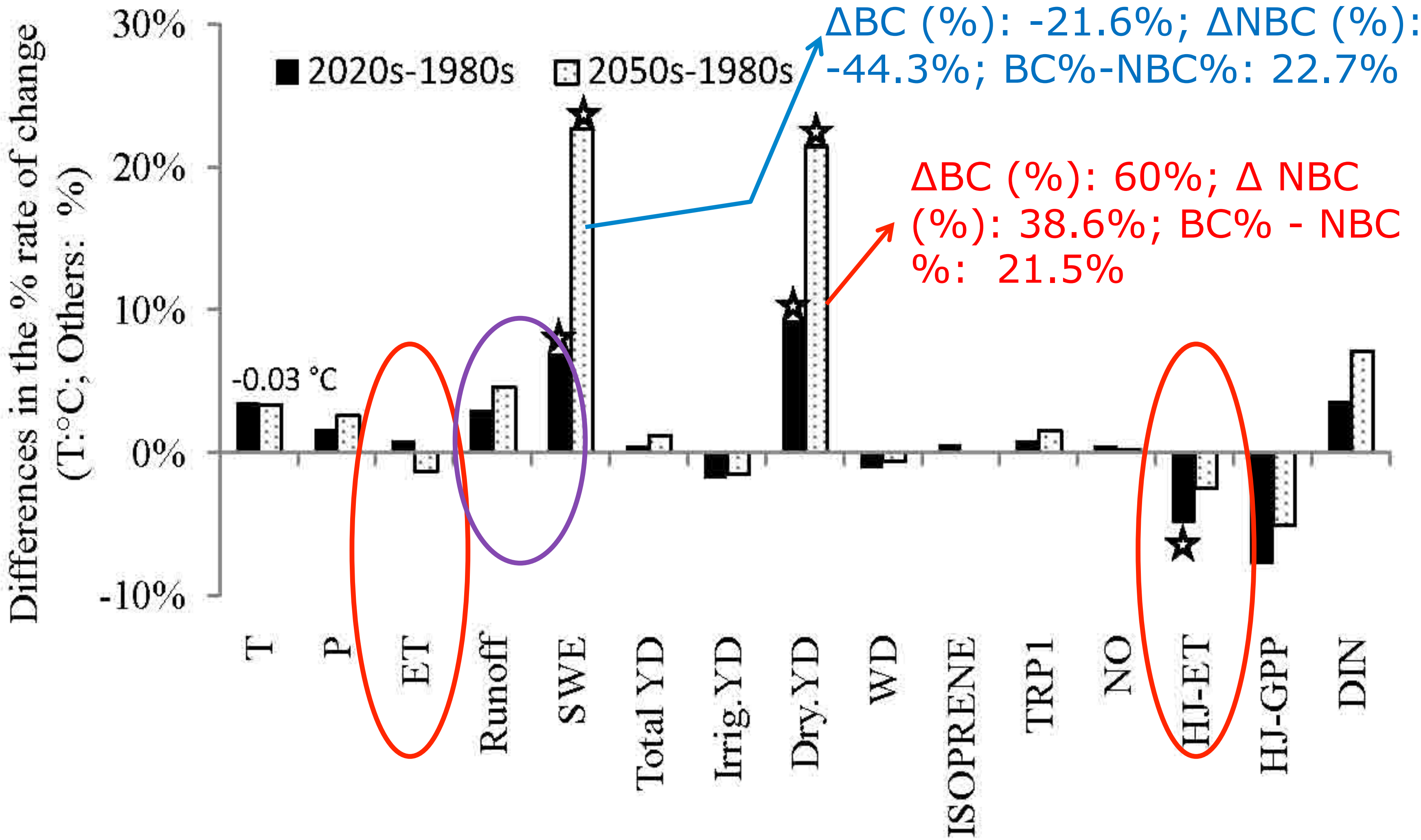
Abbreviations & Legend:

SD: Statistical Downscaling; **BC**: Bias Correction; **NBC**: No Bias Correction; **CY**: Crop Yield; **WD**: Water Demand; **DIN**: Dissolved Inorganic Nitrogen ; **ET**: Evapotranspiration; **NPP**: Net Primary Productivity; **SWE**: Snowpack Water Equivalent; **NO**: Nitrogen Monoxide

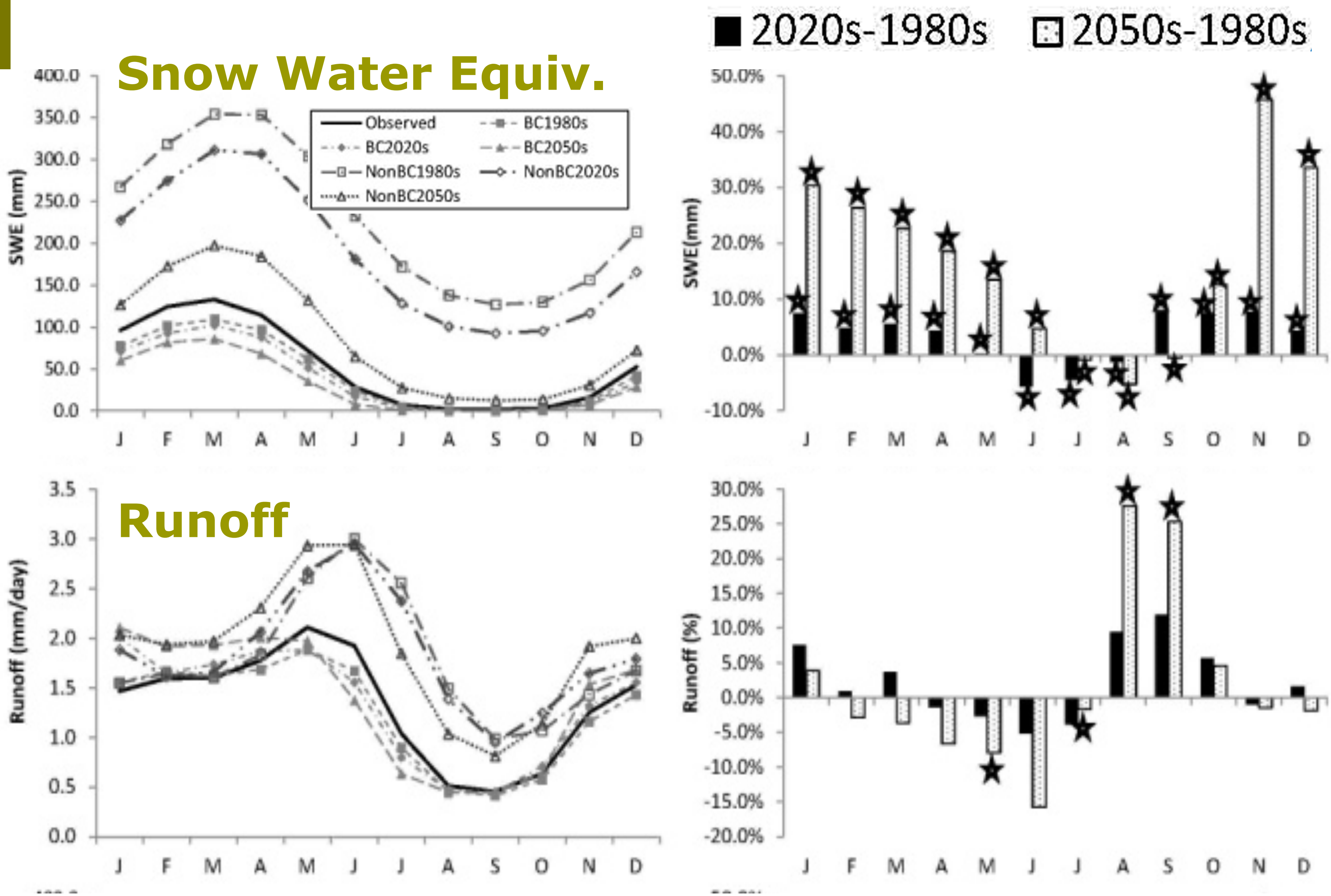
Output variables from models — Model

Data flow — Data

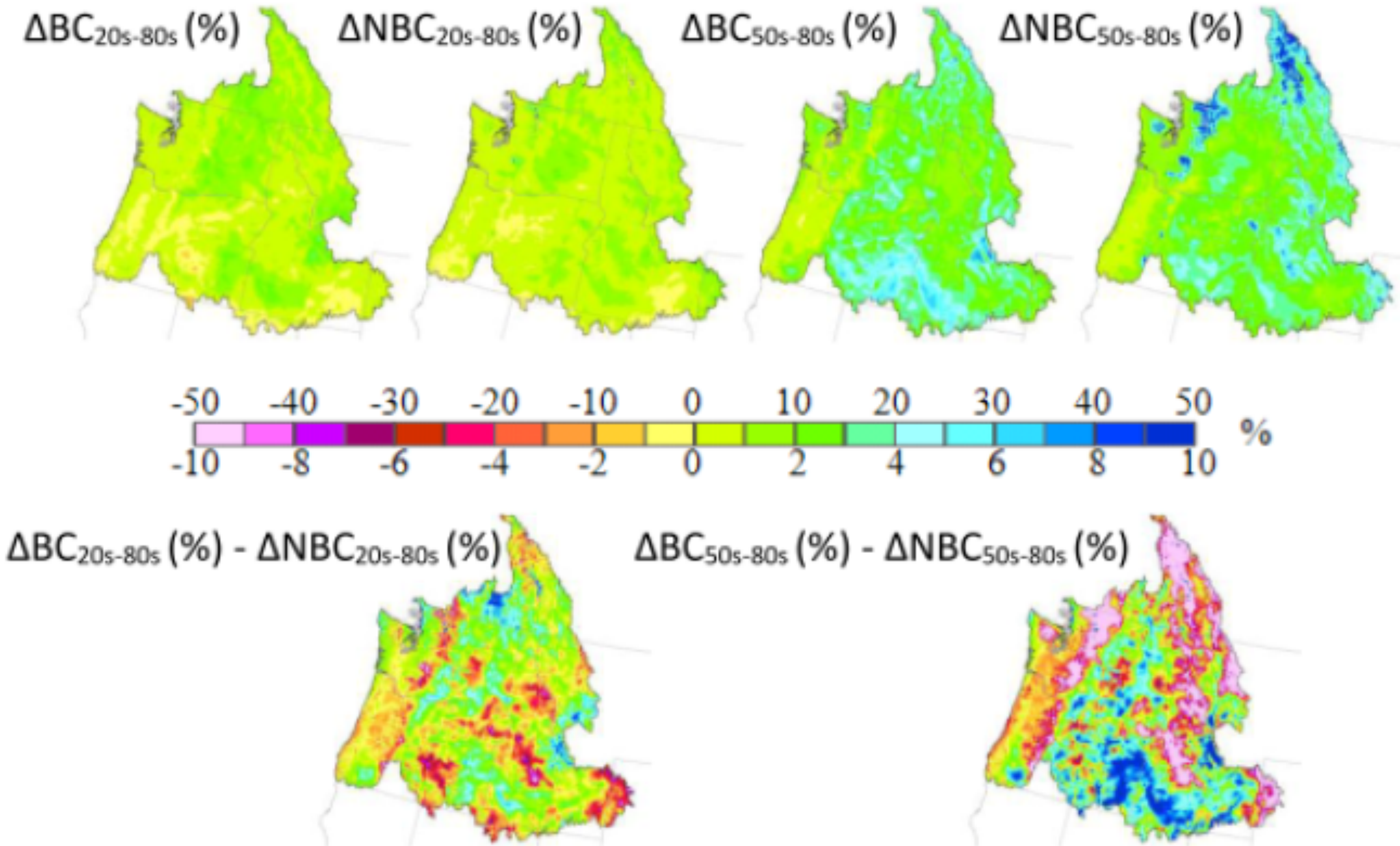
Annual Differences in Response to Climate Change due to BC (BC% - NBC %)



Seasonal Differences (BC% - NBC %)



Evapotranspiration



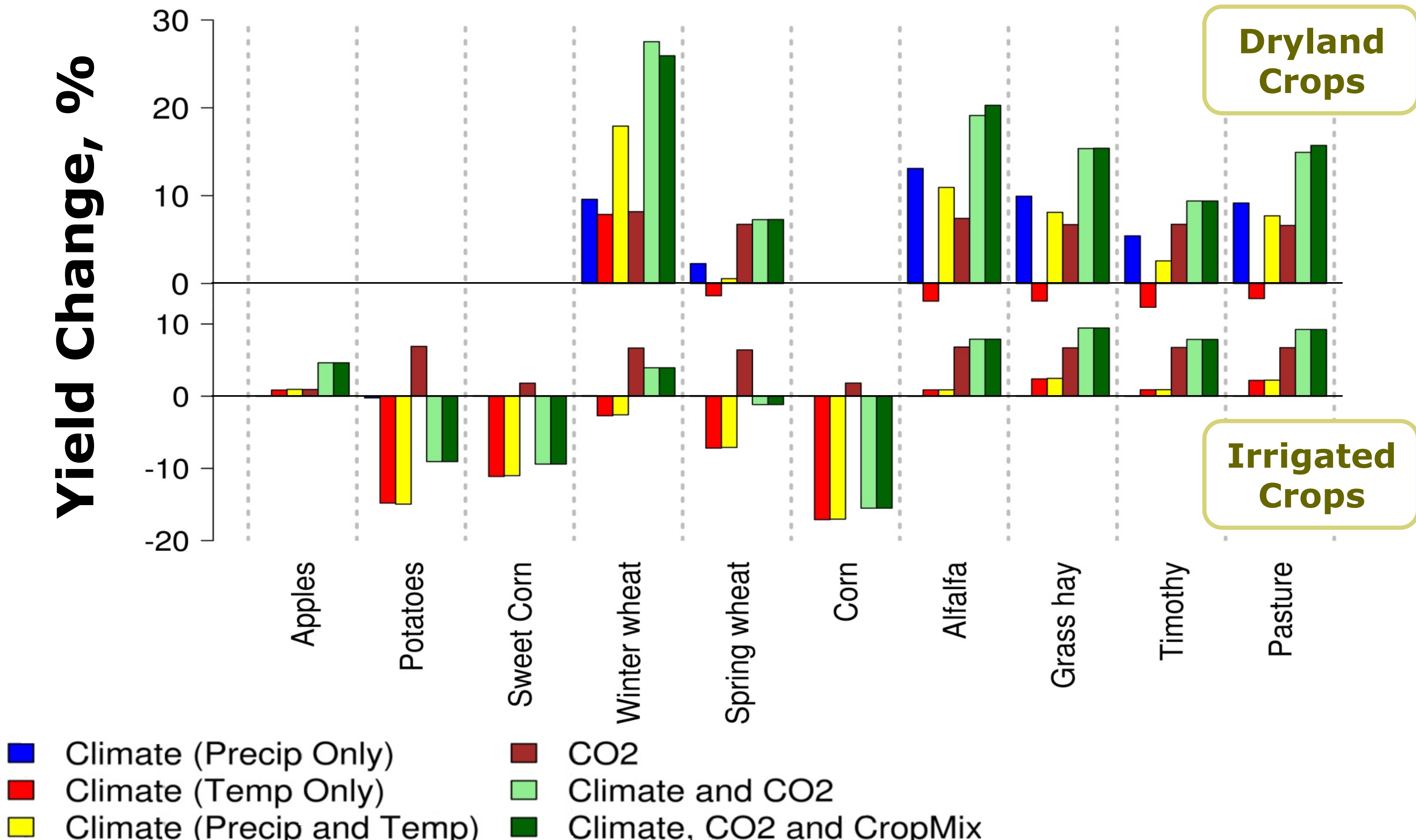
Conclusions to Bias Correction (BC) Study

- Nonlinearities, critical thresholds, and competing effects may necessitate BC of climate model outputs.
- However, whether or not BC has a significant effect on land surface response also depends on spatial and temporal scales of interest.
- Even for tightly-coupled land-atmosphere interaction studies, lack of BC can have significant effects on feedbacks to the atmosphere (snow albedo, ET fluxes, biogenic emissions, etc.).
- As trade-offs exist, the pros and cons of BC should be explored and (when possible) effects quantified for each specific study under investigation. This may partially guide the degree of model coupling.

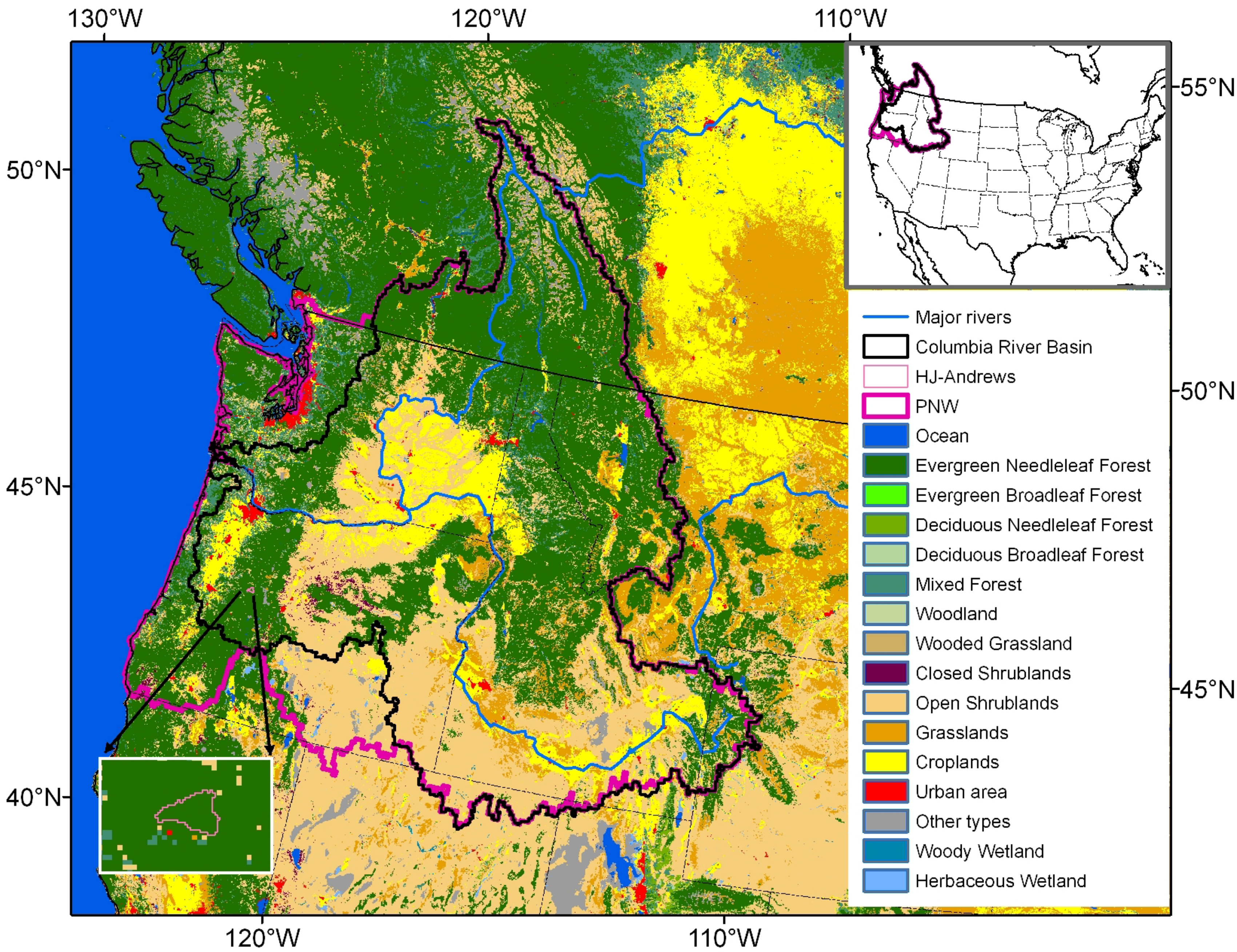
Example Research Questions: Sustainable Adaptation to Drought

Cropping Systems	Rangelands	Forests
Q1. How can agriculture in the western U.S. adapt to increasing frequency and severity of droughts, while minimizing environmental impacts?	**Q2.** How can rangelands be managed to reduce competition by invasive species and sensitivity to drought in the context of climate change?	**Q3.** How can forests be managed to adapt to increasing frequency and severity of extreme events, drought mortality and wildfire?
Atmospheric Interactions: Q4. How do proposed changes in resource management practices affect atmospheric dynamics/ chemistry? How do these feed back to the land surface?		
Water Resource Interactions: Q5. What are the consequences of changes in land management practices and climate on water quality; instream flows for habitat and hydropower; and flood risk?		

Year 2030 Projected Impacts on WA Crop Yield: Climate, CO_2, Economics



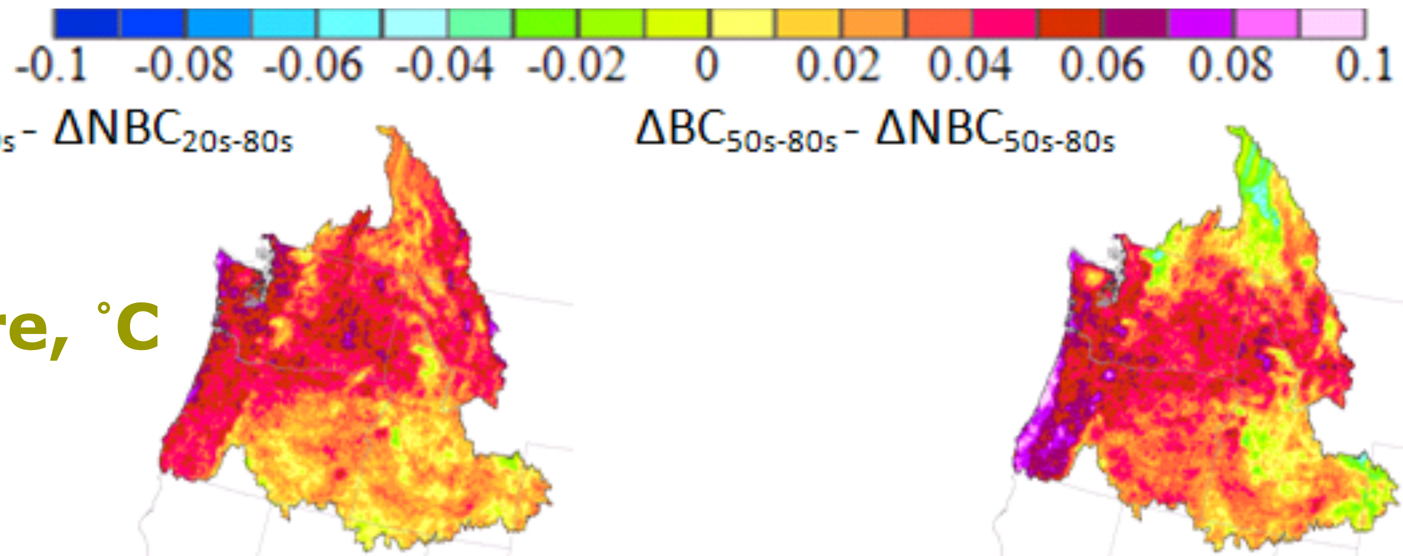
Rajagopalan et al. (in prep)



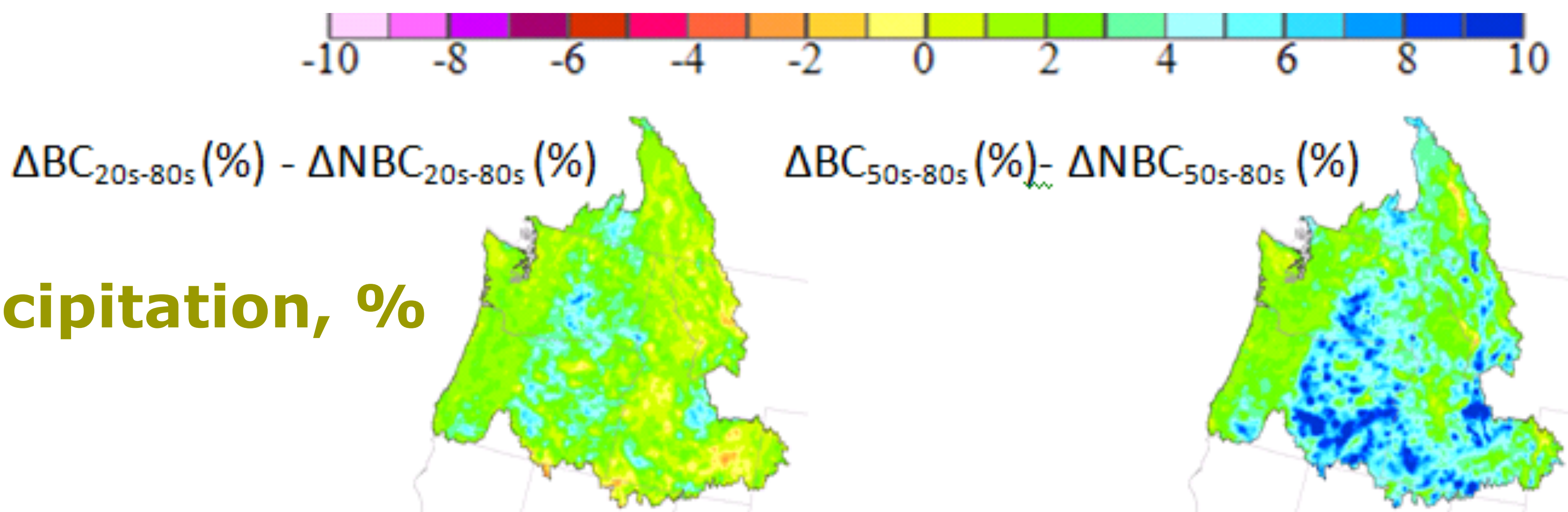
130°W
120°W
110°W
55°N
50°N
45°N
40°N
50°N
45°N
120°W
110°W
Major rivers
Columbia River Basin
HJ-Andrews
PNW
Ocean
Evergreen Needleleaf Forest
Evergreen Broadleaf Forest
Deciduous Needleleaf Forest
Deciduous Broadleaf Forest
Mixed Forest
Woodland
Wooded Grassland
Closed Shrublands
Open Shrublands
Grasslands
Croplands
Urban area
Other types
Woody Wetland
Herbaceous Wetland

Differences in Climate Signal due to Bias Correction (ΔBC - ΔNBC)

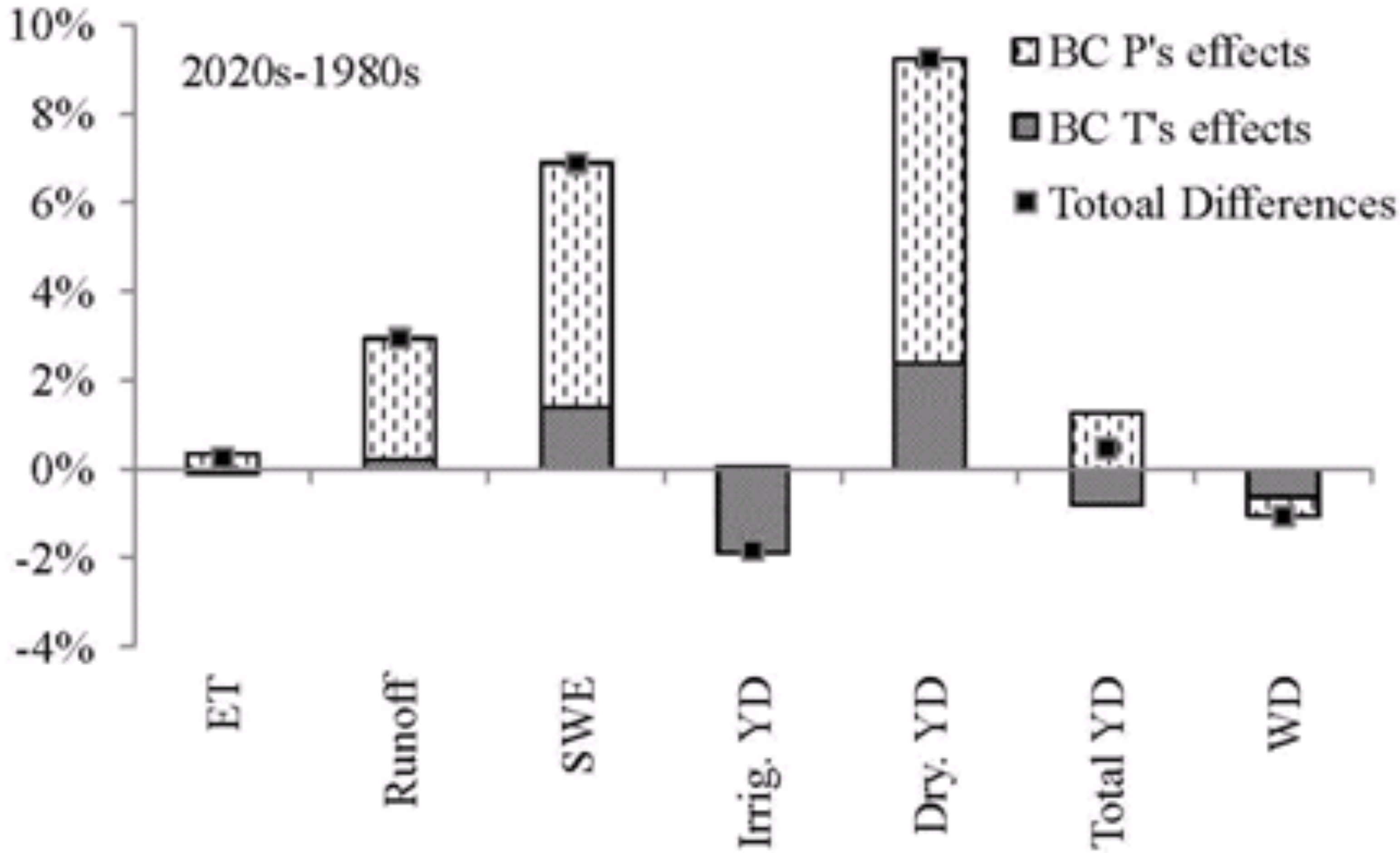
Temperature, ˚C



Precipitation, %



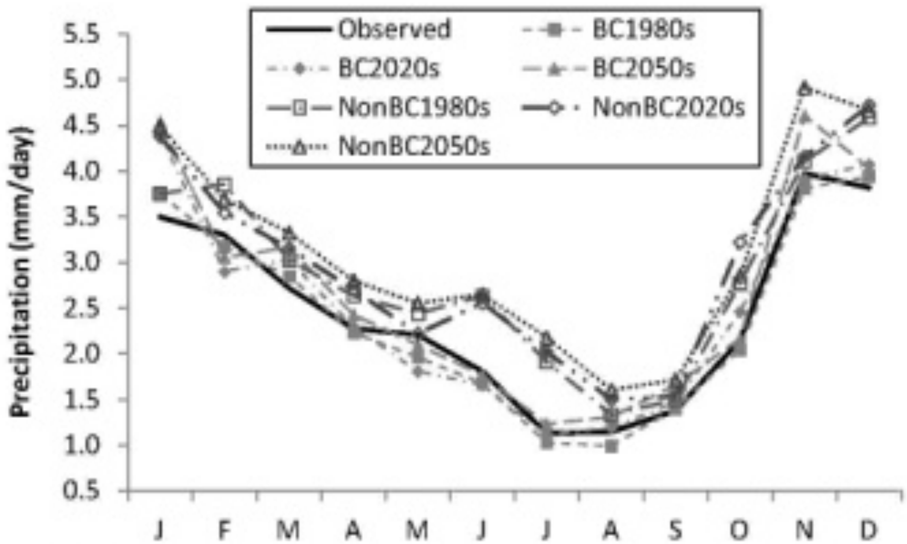
Attribution of Effects: BC of Temperature vs BC of Precipitation

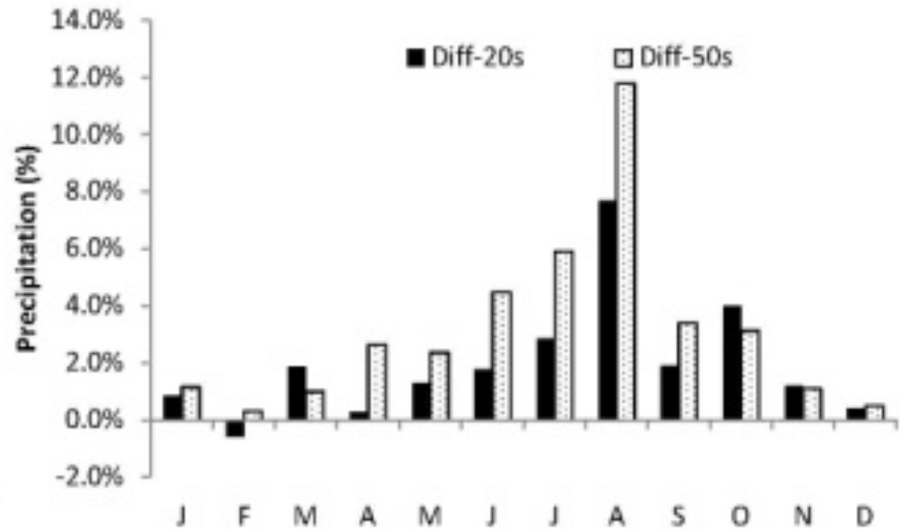


Seasonal Differences (BC% - NBC %)

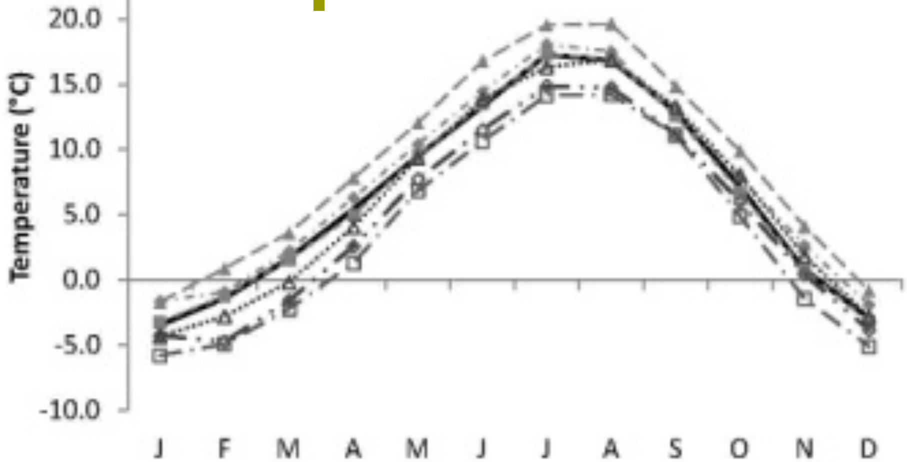
■ 2020s-1980s ☐ 2050s-1980s

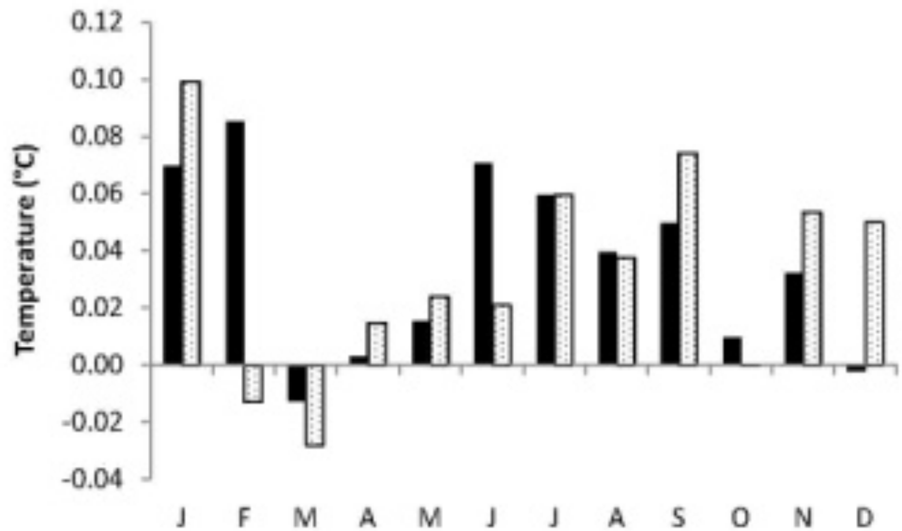
Precipitation



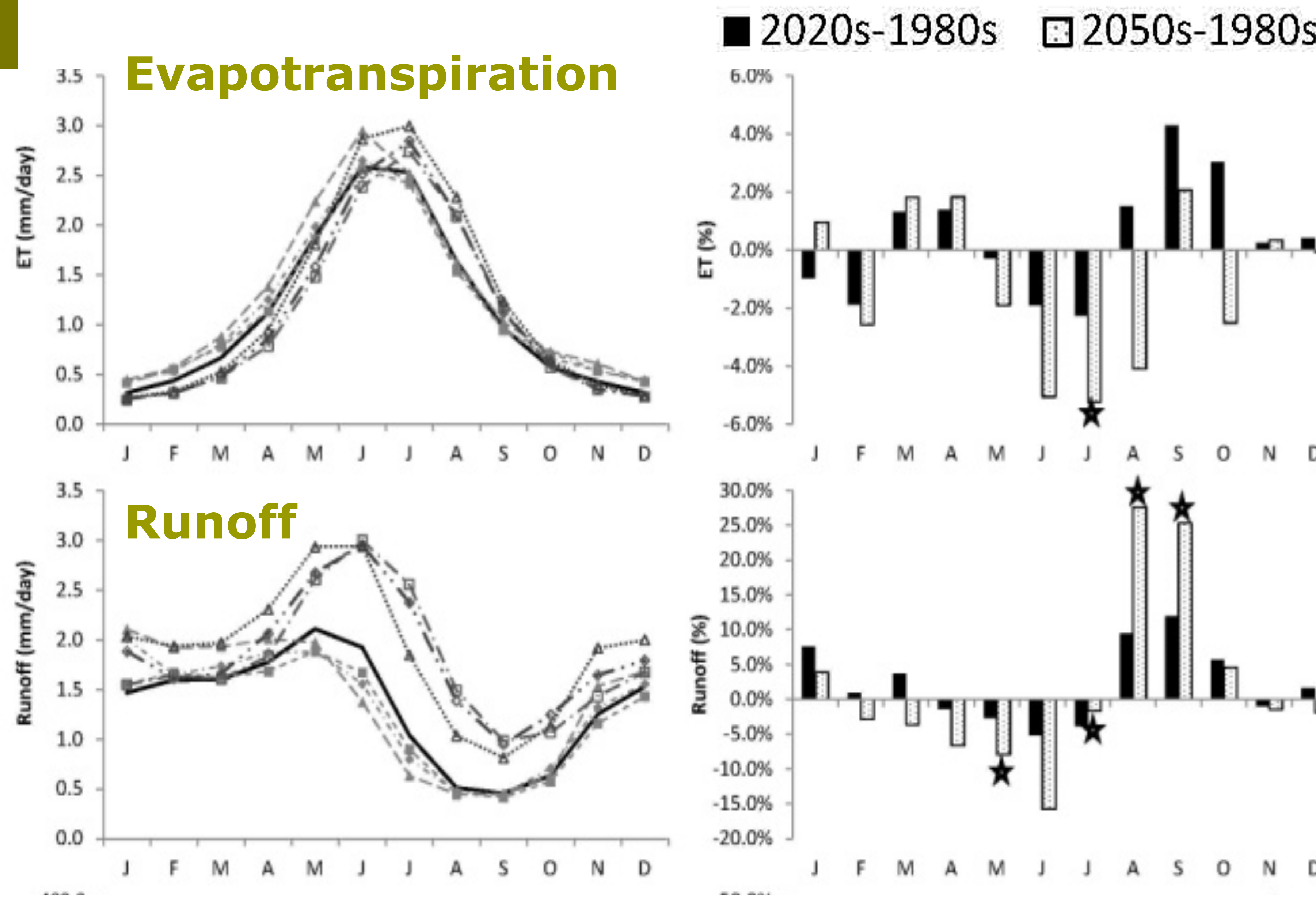


Temperature

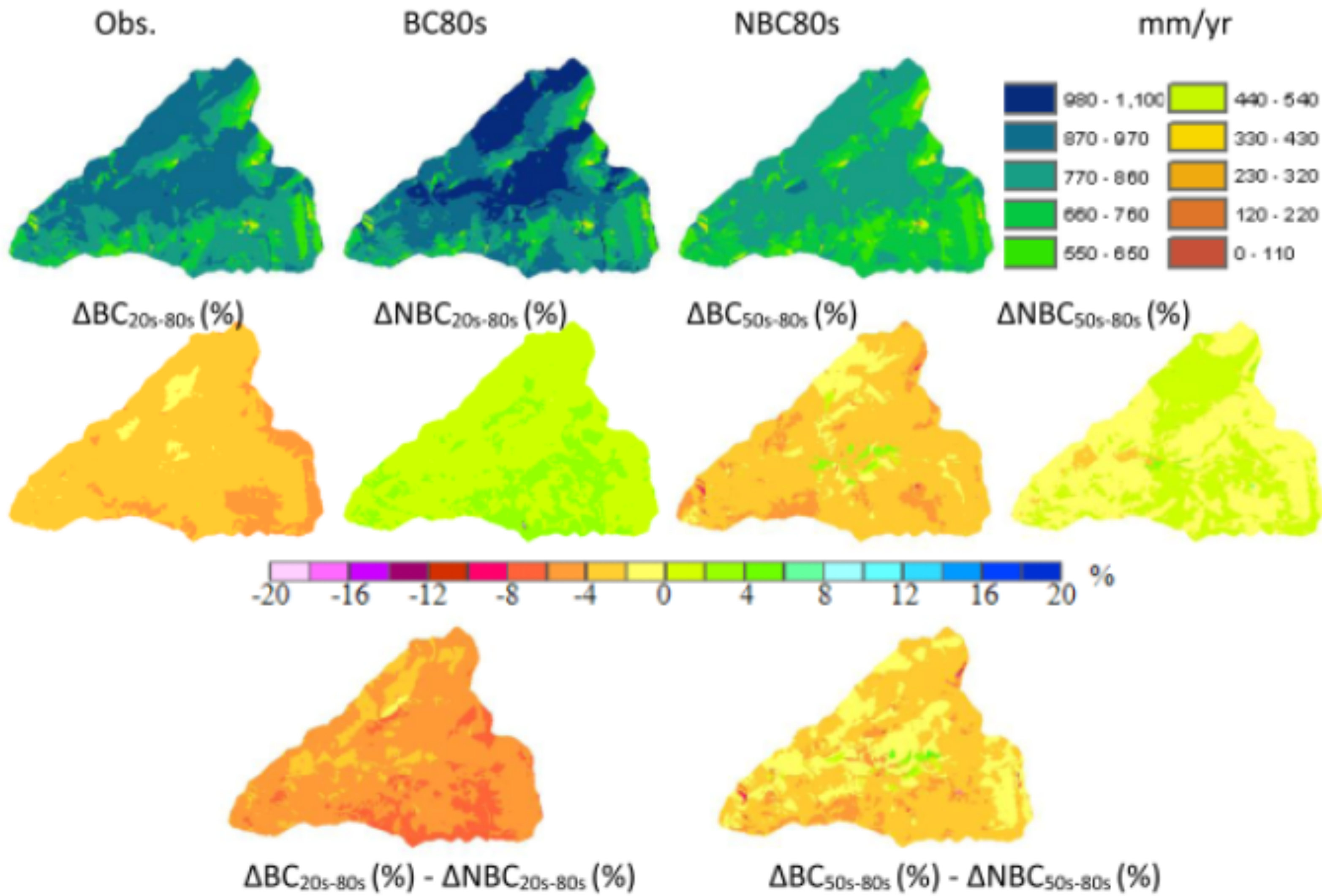




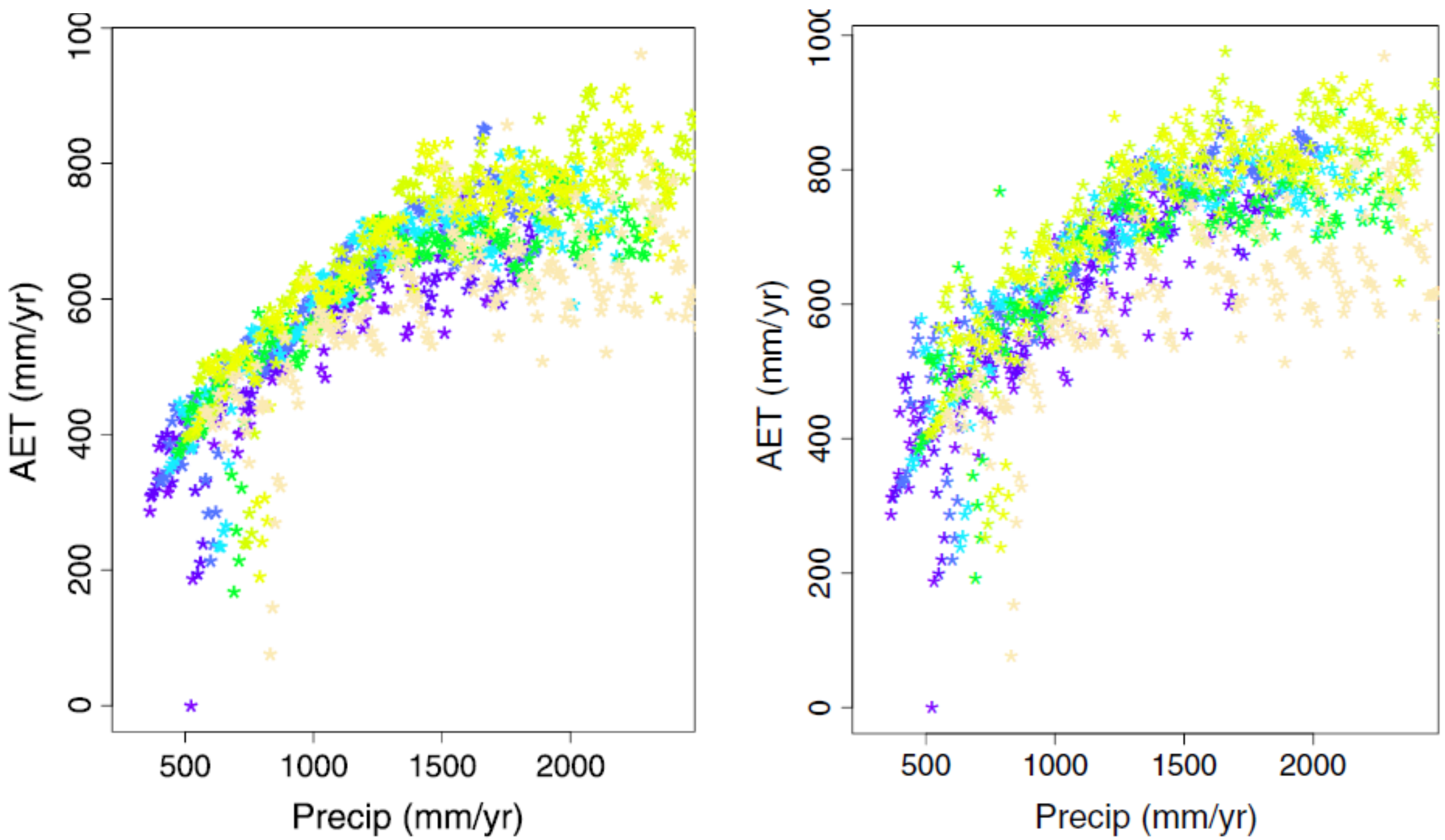
Seasonal Differences (BC% - NBC %)



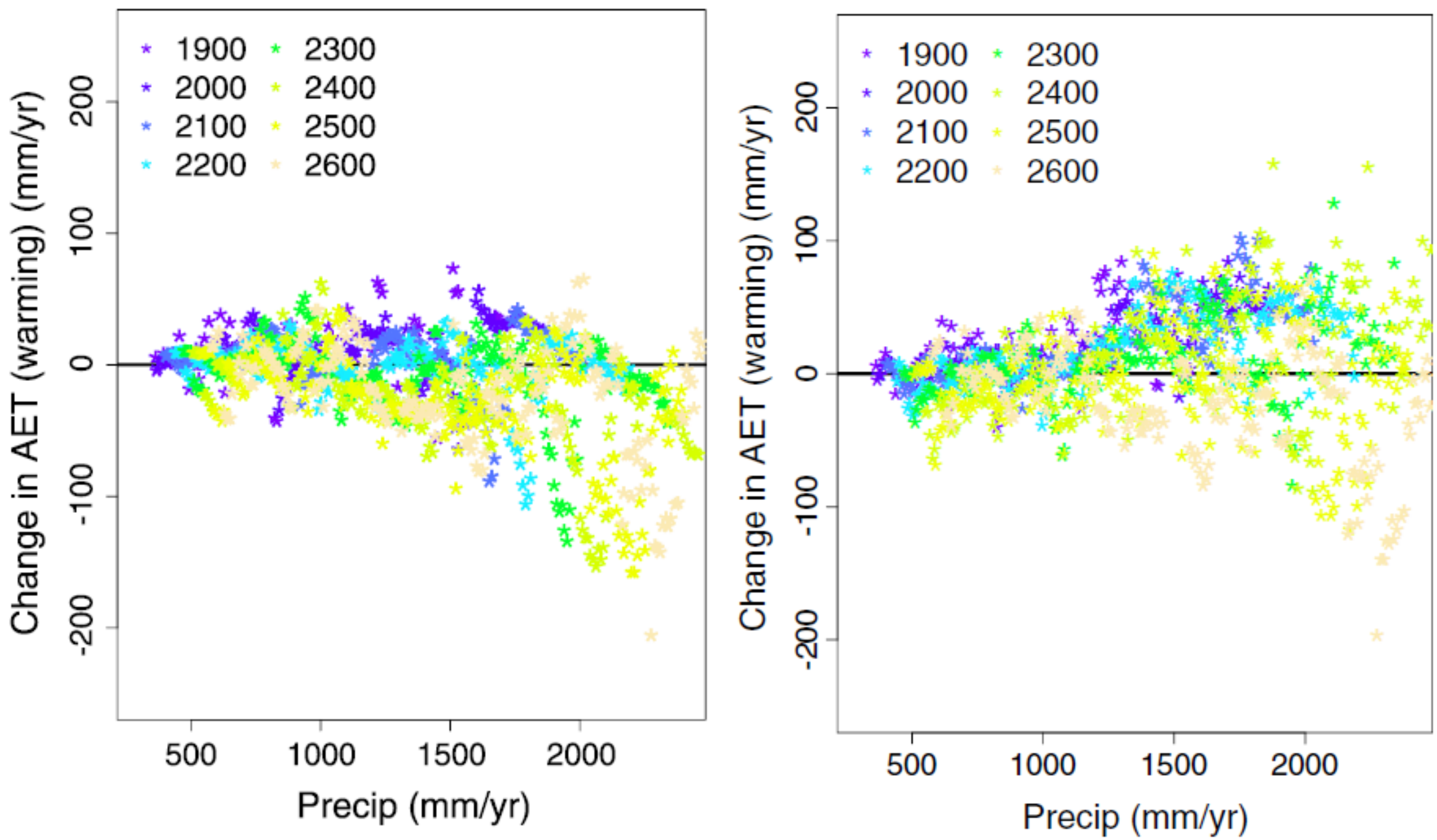
HJ Andrews Evapotranspiration (mm/year)



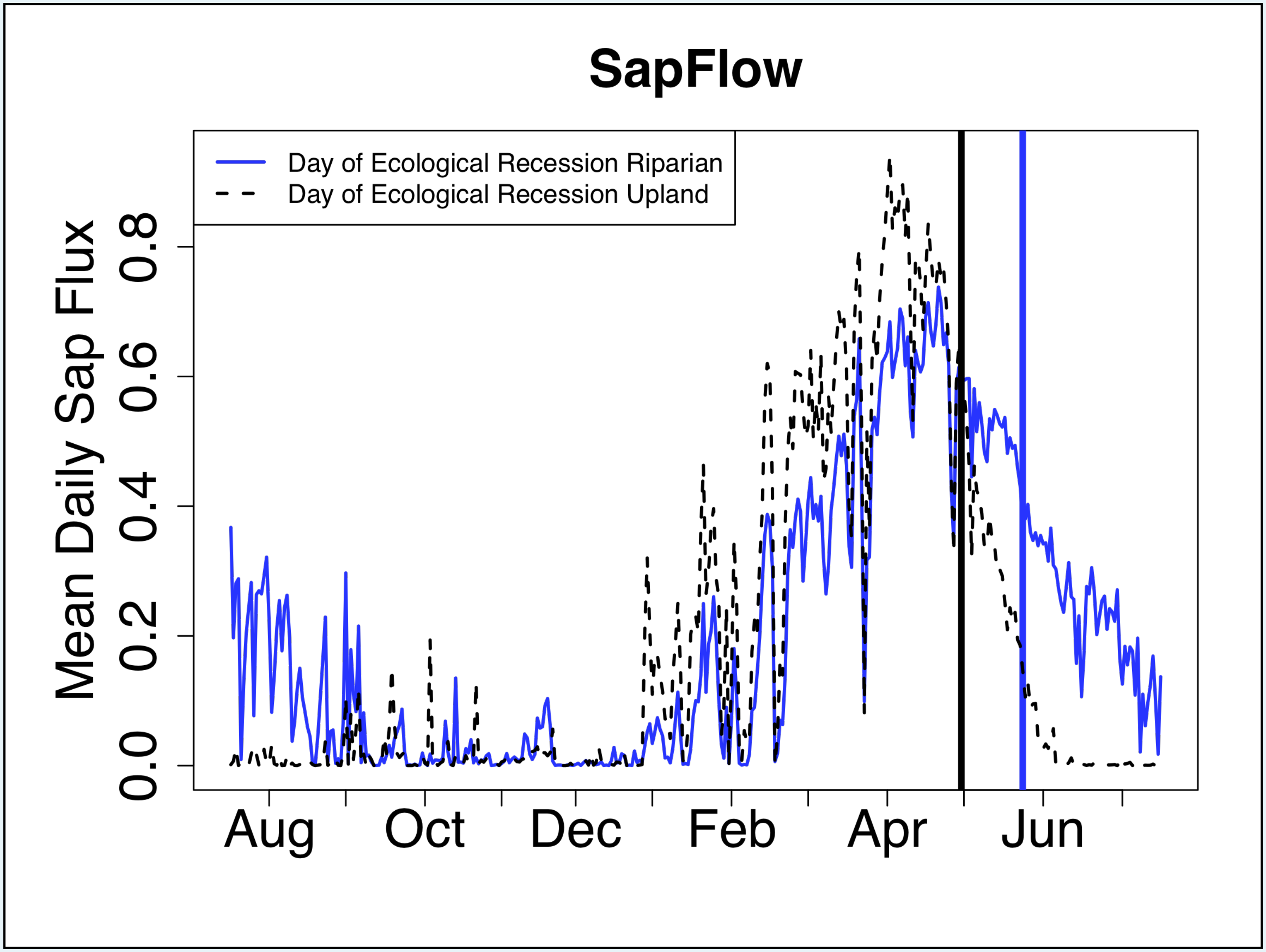
Redistribution Affects the Relationship between ET and P

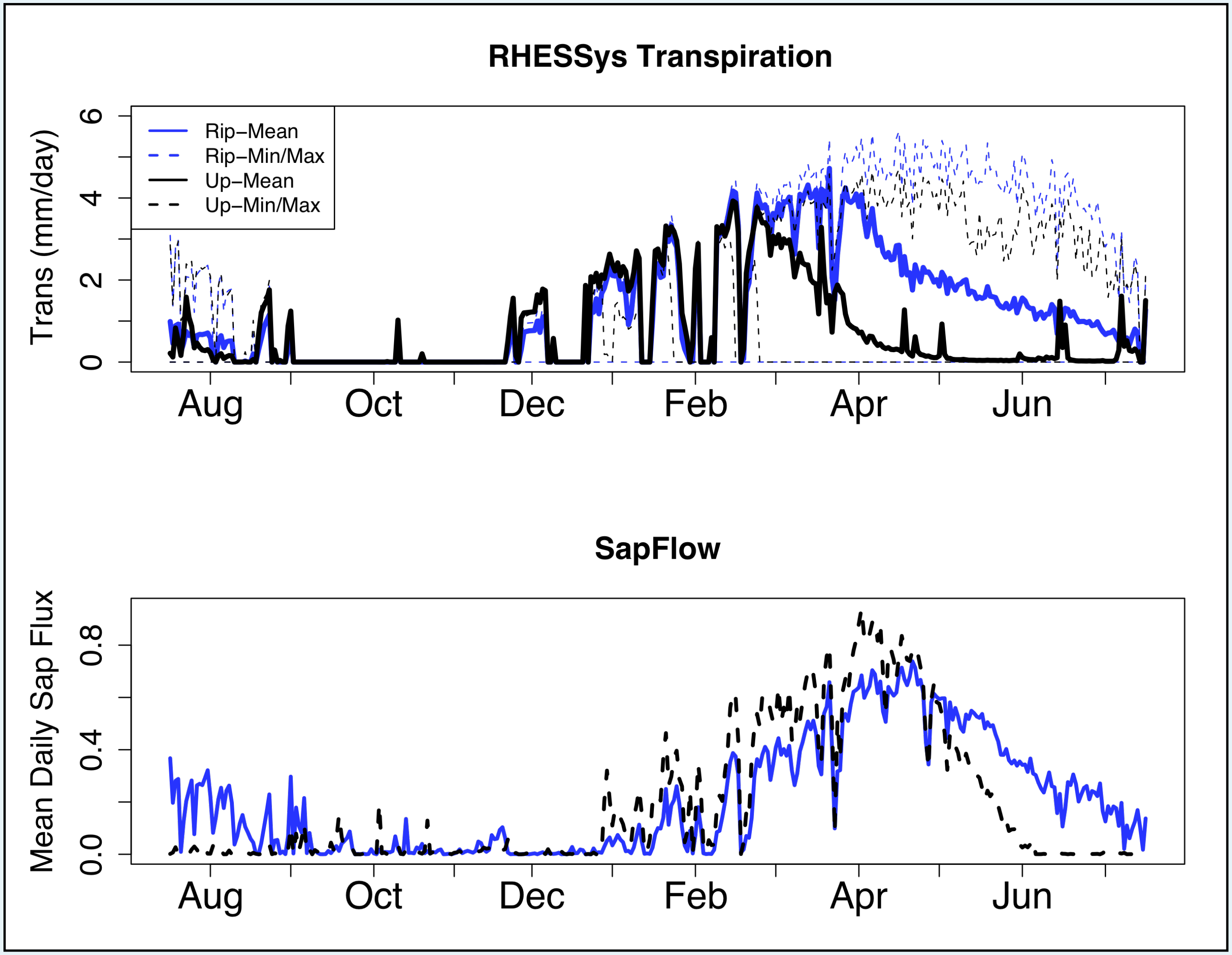


Redistribution Affects Change in ET with Temperature



Sap flow measurement consistent with later ecological recession in riparian areas (sap flow from locations at similar elevations)

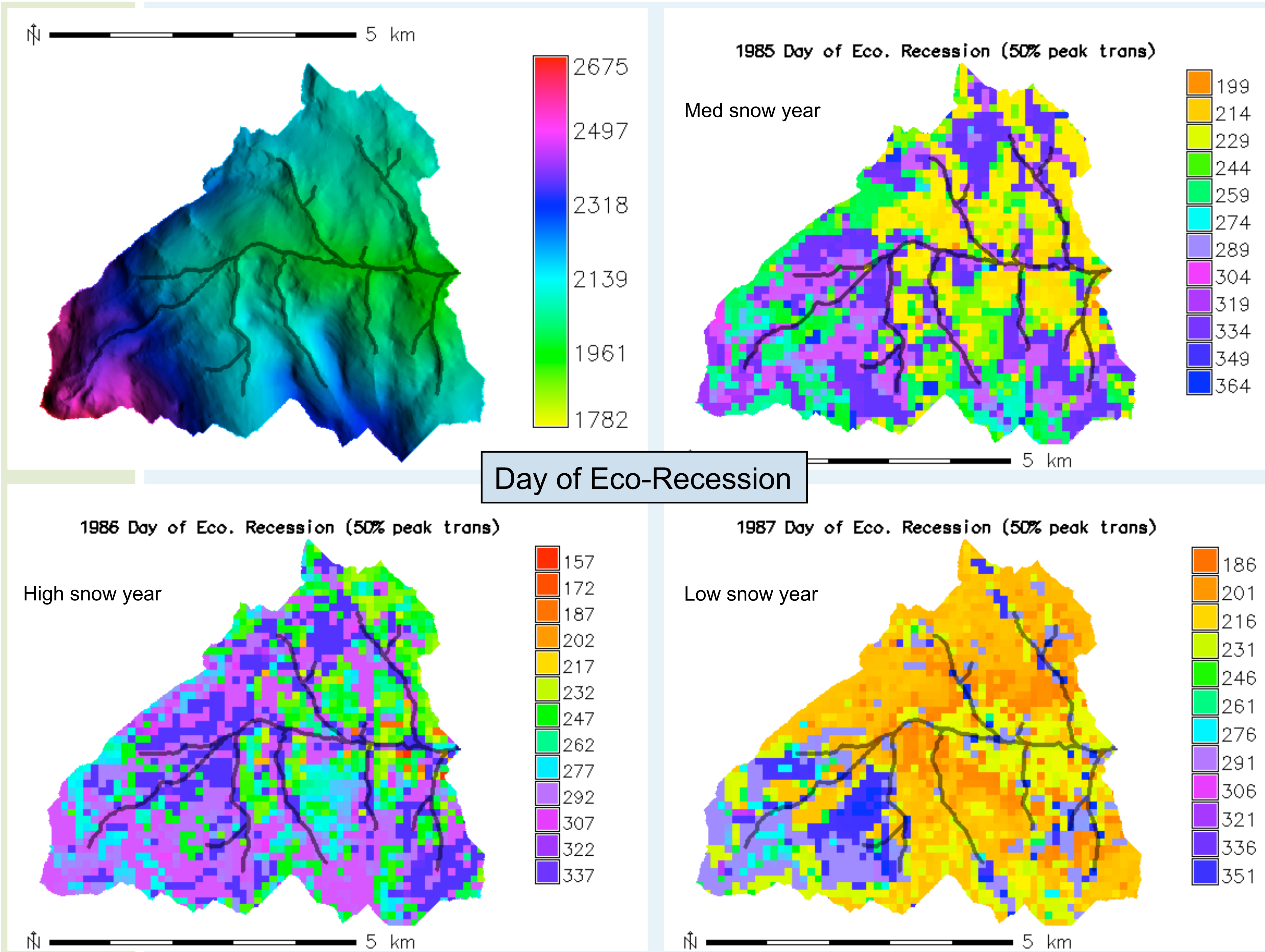




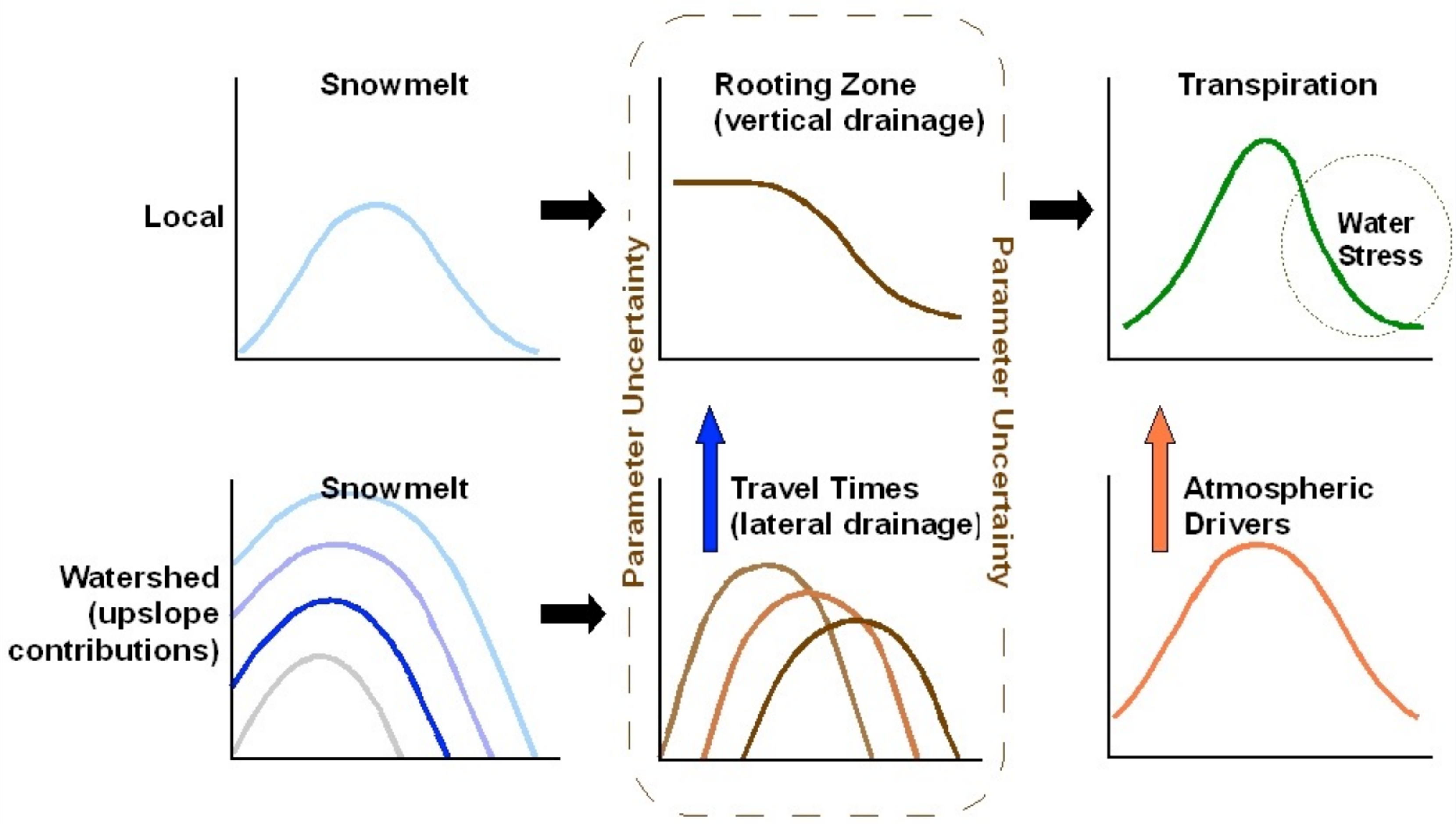
Compare model timing of forest stomatal closure late in the summer with sap flow data …

can we capture the difference between upslope and riparian areas?

➢YES, but highly sensitive to soil parameters – additional calibration required


Day of Eco-Recession
5 km
2675
2497
2318
2139
1961
1782
1985 Day of Eco. Recession (50% peak trans)
Med snow year
199
214
229
244
259
274
289
304
319
334
349
364
5 km
1986 Day of Eco. Recession (50% peak trans)
High snow year
157
172
187
202
217
232
247
262
277
292
307
322
337
5 km
1987 Day of Eco. Recession (50% peak trans)
Low snow year
186
201
216
231
246
261
276
291
306
321
336
351
5 km

Spatial pattern of responses across elevation range in the watershed



Spatial patterns of snow – changes in % basin cover and depletion trajectories

0.4℃/decade since the 1970's but no change in annual precipitation