Increasing Resilience Across the Food, Energy, and Water Sectors in the Columbia River Basin

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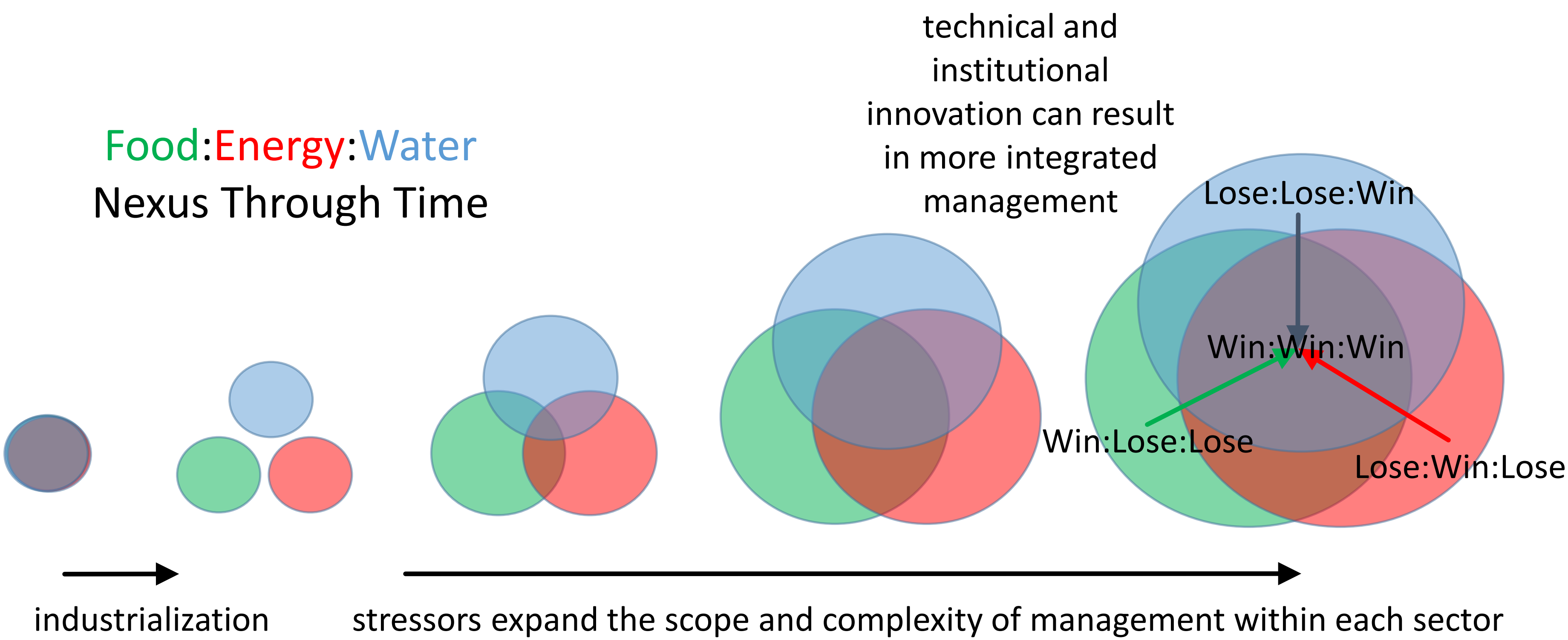
University of Utah: Mike Barber

***Pacific Northwest National Lab*:** Maoyi Huang, Ian Kraucunas, Hongyi Li, Nathalie Voisin

Evolution of FEW Nexus



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

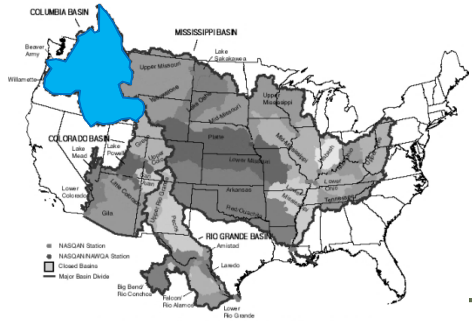
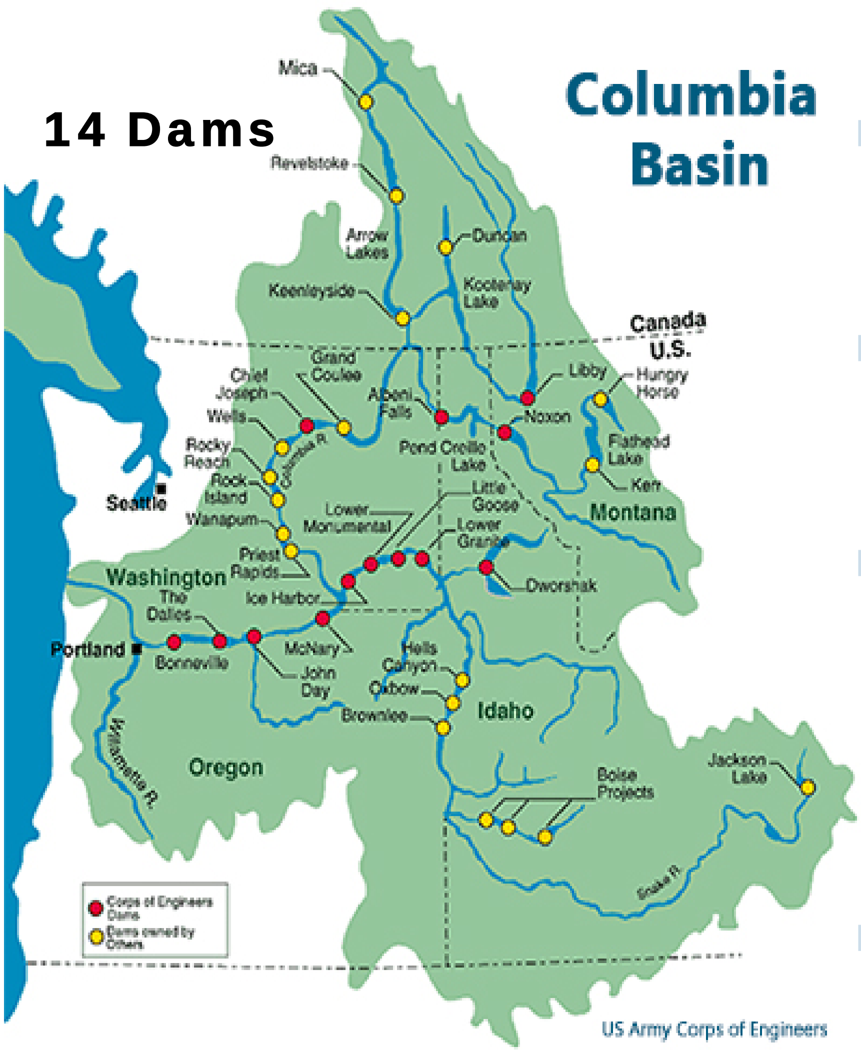
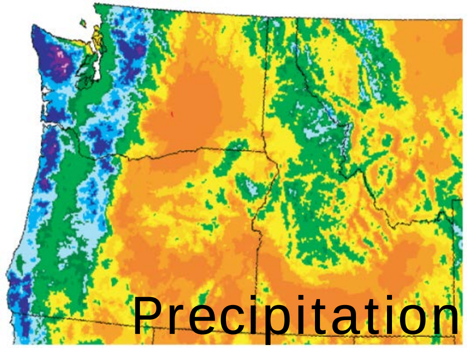


Figure 2. Subbasins defined by stations operated by NASQAN during FY1997.



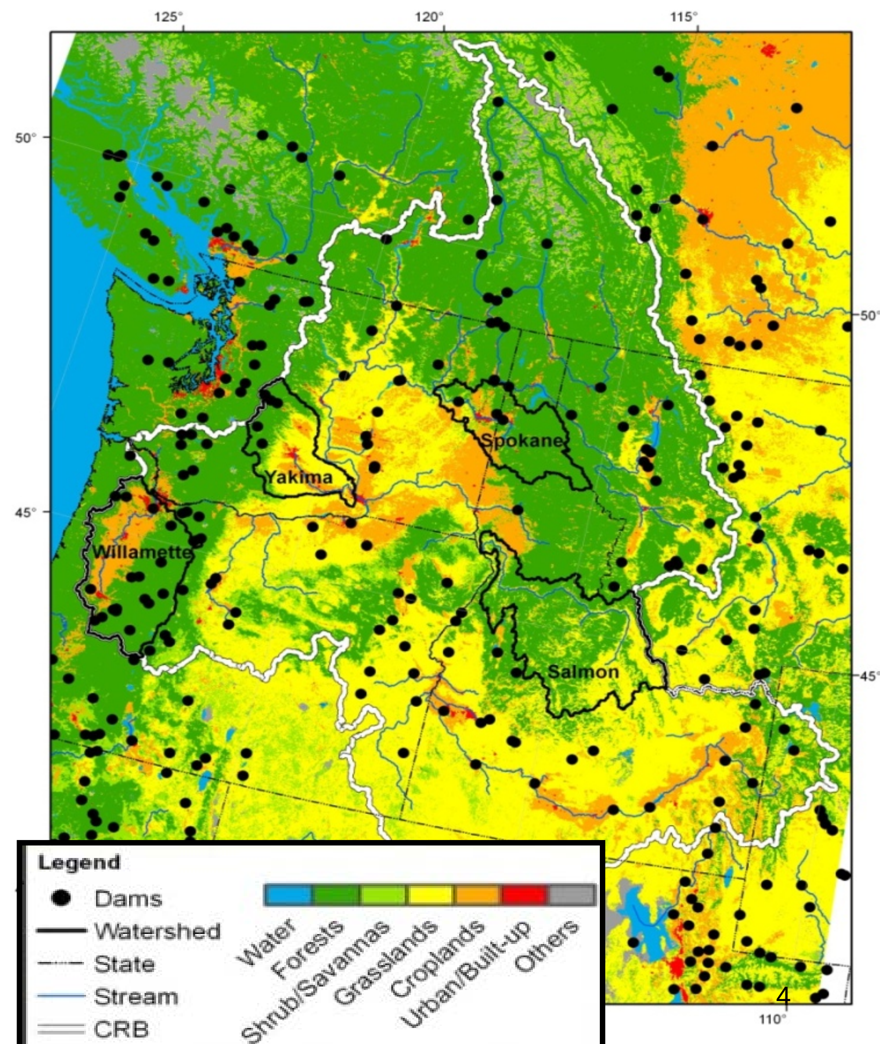
- Spans 7 states, 13 Native American Reservations and 2 countries (668,000 km^2)
- Total CRB storage is <50% of mean annual discharge, snowpack dominated
- Supports withdrawals for:
  - Agricultural irrigation (5.8 km^3/yr, $2B),
  - Hydropower (~12k MW/yr, $950M)
    - 70% of regional power (40% of US power)
  - Offers substantial flood control and recreation
- Home to four species of endangered fish (salmon & trout)



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

Emerging and existing stressors:

- Climate change to exacerbate water quantity & quality problems
- US-Canada water management; 1961 Columbia River Treaty is currently under review
- Inc. number of multiple competing in- and out-of-stream water uses
  - fish habitat (ESA-listed species), tribal needs, increased need for renewable energy, etc.

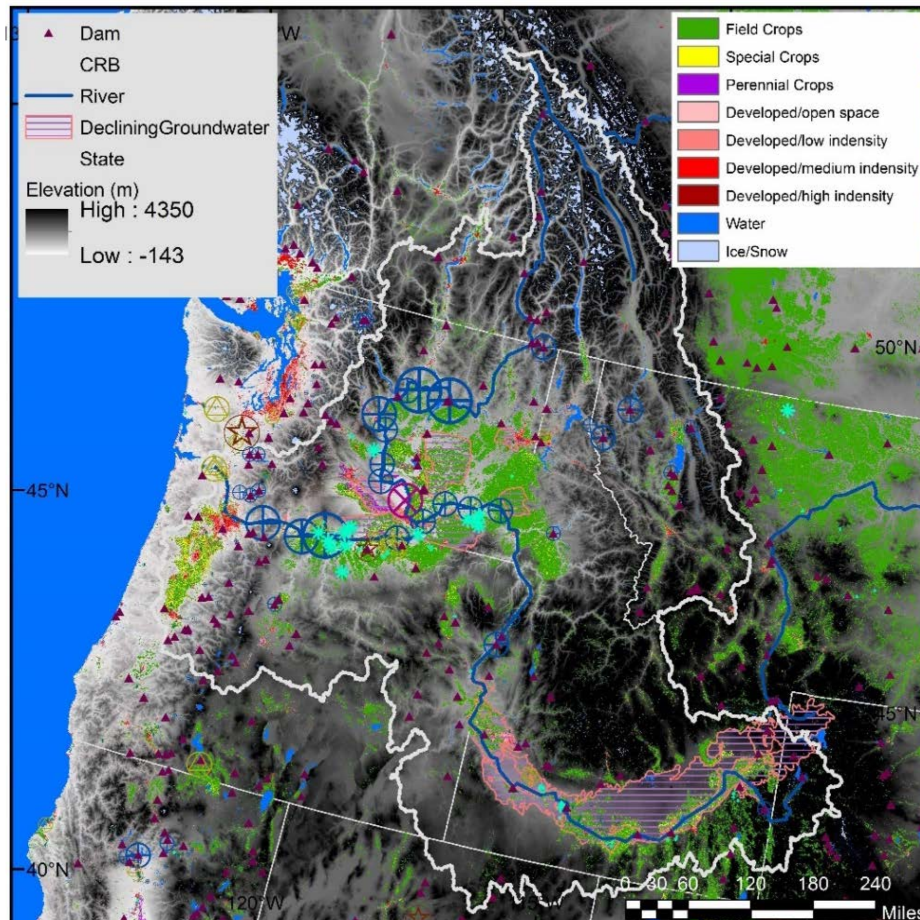


Overarching Goal and Hypothesis

- *Goal*: To identify and examine effective strategies to co-balance benefits among FEW sectors, and increase resilience across the integrated system

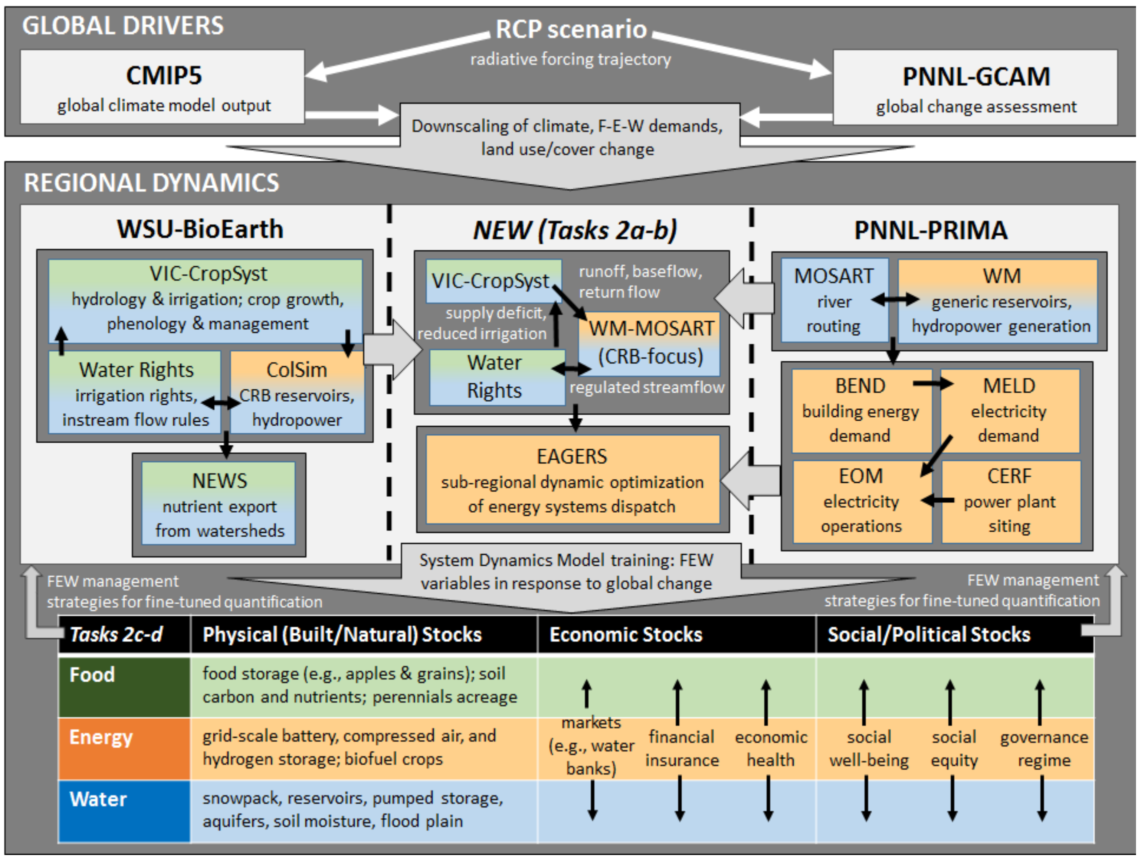
- *Central Hypothesis:* coordinated management of physical and non-physical storage systems across the three sectors can increase FEW system resilience

- Coordination increases *effective* storage of the overall system and enhances its buffering capacity to disturbance at multiple scales



Overview of Approach

- **Develop, evaluate, and iteratively apply a framework spanning theory through implementation to:**

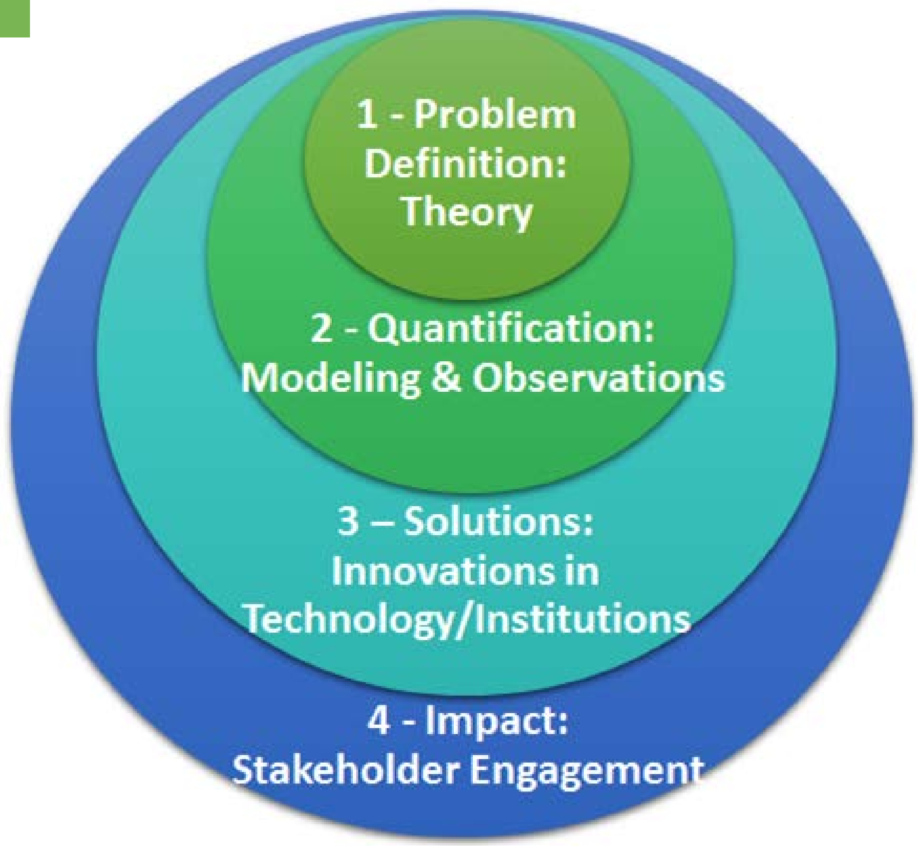


- Understand FEW linkages
- quantify innovative solutions across the FEW sectors
- remove barriers to the adoption of solutions, and
- increase system-wide resilience to global change

Specific Aims

Purely theoretical study of system interactions

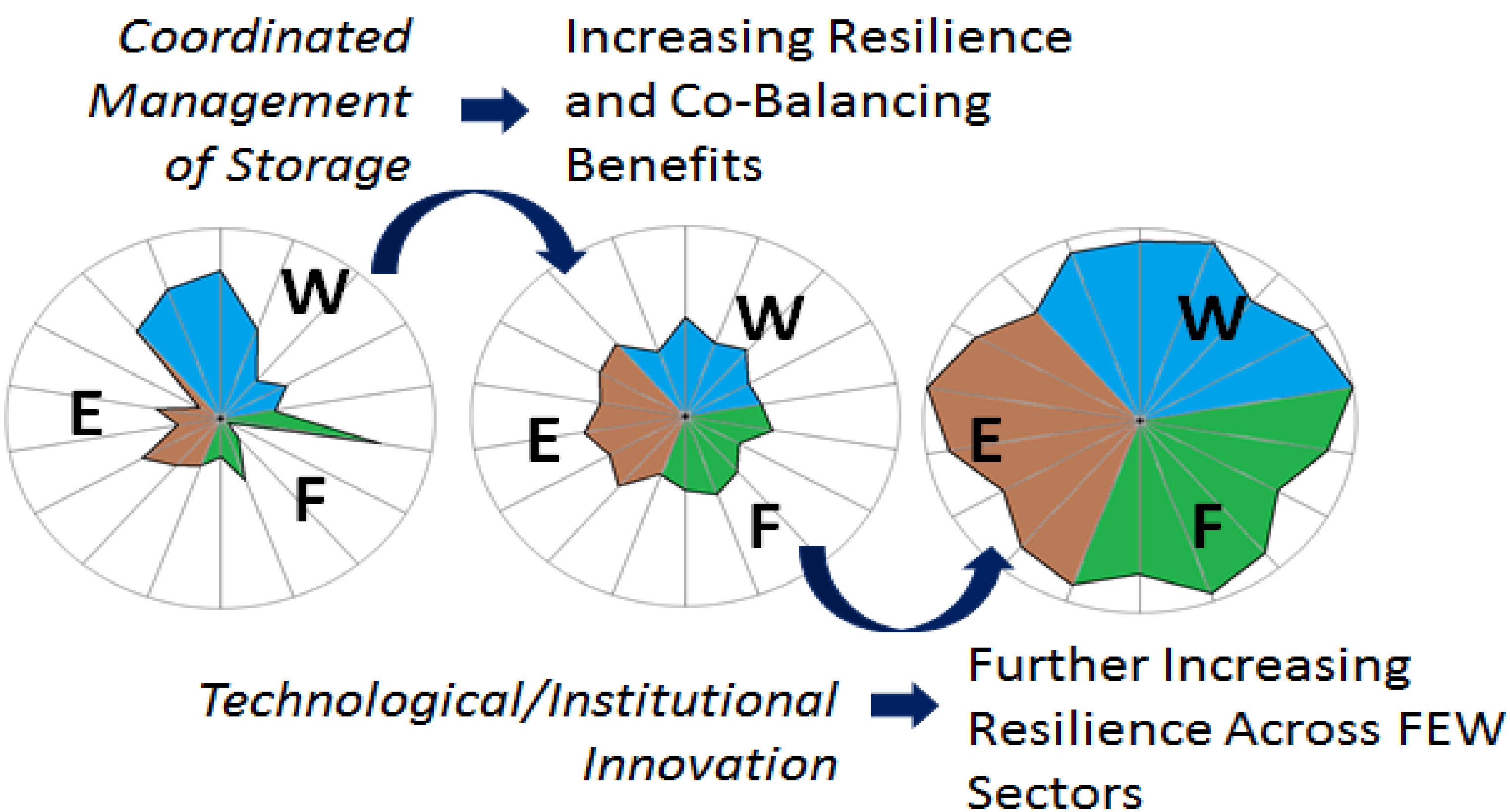
Targeted decision-support tool for one



Ultimately, INFEWS research seeks to advance understanding of how FEW sectors interact. This knowledge has potential to inform decisions at multiple scales and sectors.

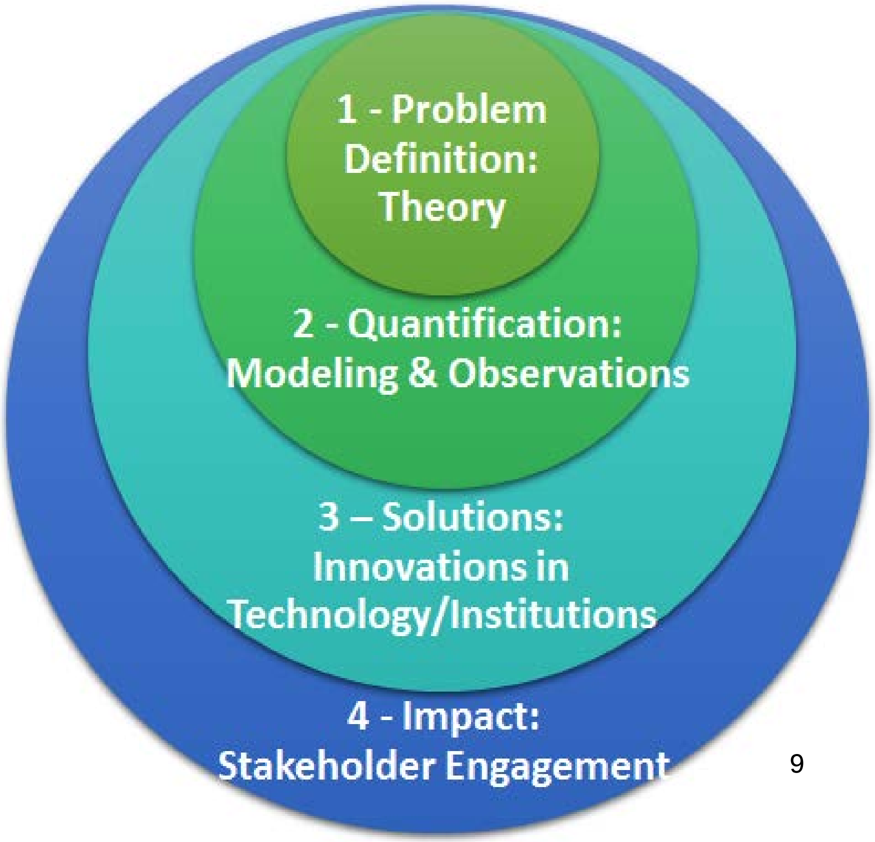
Evaluate FEW Solutions: The "FEW Resilience Calculator"

Resilience Indicators: Economic, Environmental, Social Equity Indicators specific to Food, Energy, and Water Systems



Specific Aims

- Aim 1: develop theoretical foundation characterizing our region's FEW system that is generalizable to national and global scales
- Aim 2: integrate state-of-the-science computational models to capture FEW system interactions
- Aim 3: evaluate benefits/impacts of FEW technological and institutional solutions using the modeling platforms
- Aim 4a: convene multi-disciplinary resilience workshops
- Aim 4b: engage stakeholders to develop new strategies and remove barriers to adoption

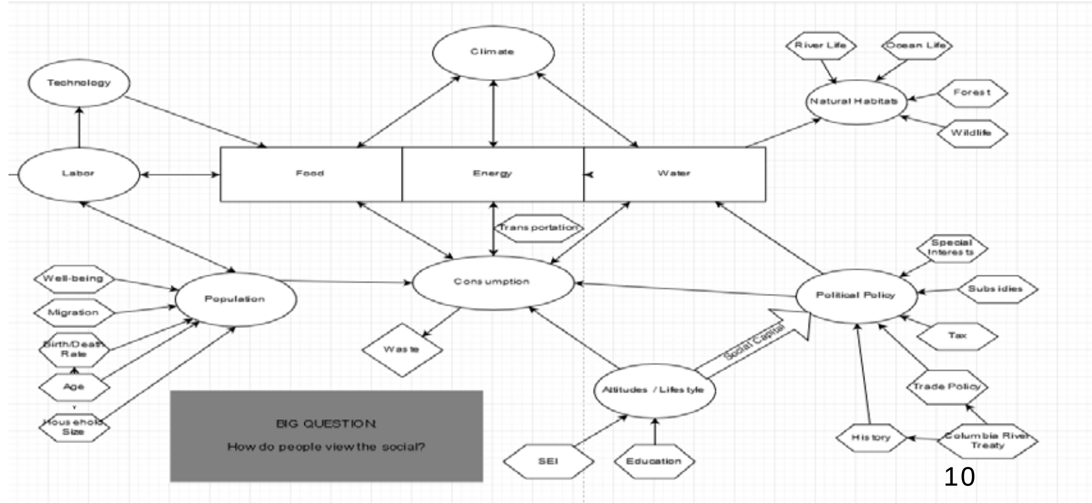


Systems Dynamics (SD) modeling

"Stock and flow" models informed by mechanistic, integrated model output (BioEarth + Prima)

- conceptual models of an integrated food, energy, water, and social system
- develop frameworks for translating process model output to SD relationships and vice versa

Conceptual models act as a foundation for identifying key drivers, parameters, time steps, and variables of importance to build/improve existing systems dynamic and biophysical models.



Aim 3: Modeling FEW Solutions

- **Identify existing and future *friction points***
  - Historical climate and future climate change
  - Management status quo
  - Societal acceptance

What are FEW *friction points?*
Key barriers to jointly managing food, energy and water.

- **Examine potential range of FEW *innovations***
  - Changes in institutions and/or technology
  - How will innovation reduce friction points?

What are FEW *innovations*?
Strategies for reducing barriers to adopting solutions.

Disturbances
Shocks: heat waves, droughts, floods, rapid shifts in commodity prices, etc.
Pressures: shift in snowmelt timing, growing/changing population, etc.

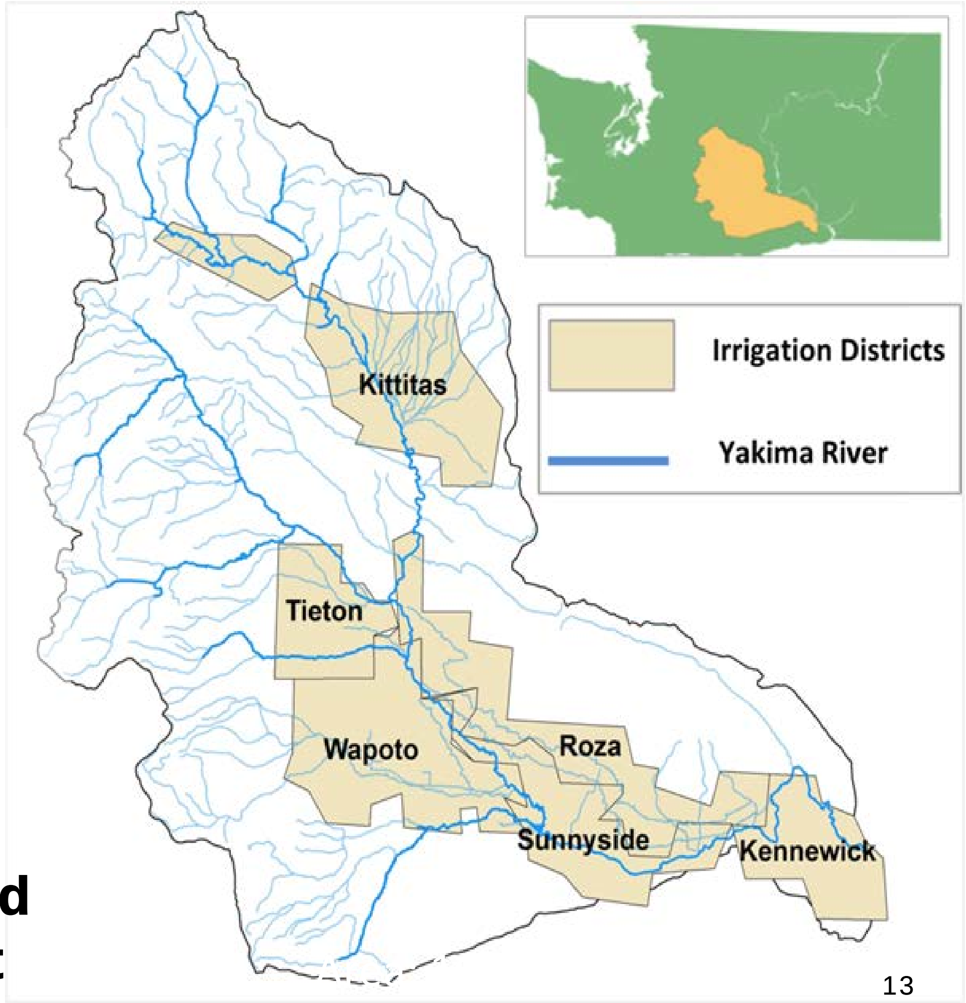
Innovation Examples

LEDs for sunlight	Drip Irrigation	Household capture/ reuse
Exempt well overhaul	Water markets/ water trading	Consumptive use-based water law
PS vs NPS distinction	Wind & solar energy	Smart metering
Efficient plant varieties	Demand reduction	Floodplain storage
Grid-scale storage	Precision agriculture	Improved adjudication

Primarily **technological** or **institutional** innovations?

Yakima River Basin- FEW Case Study

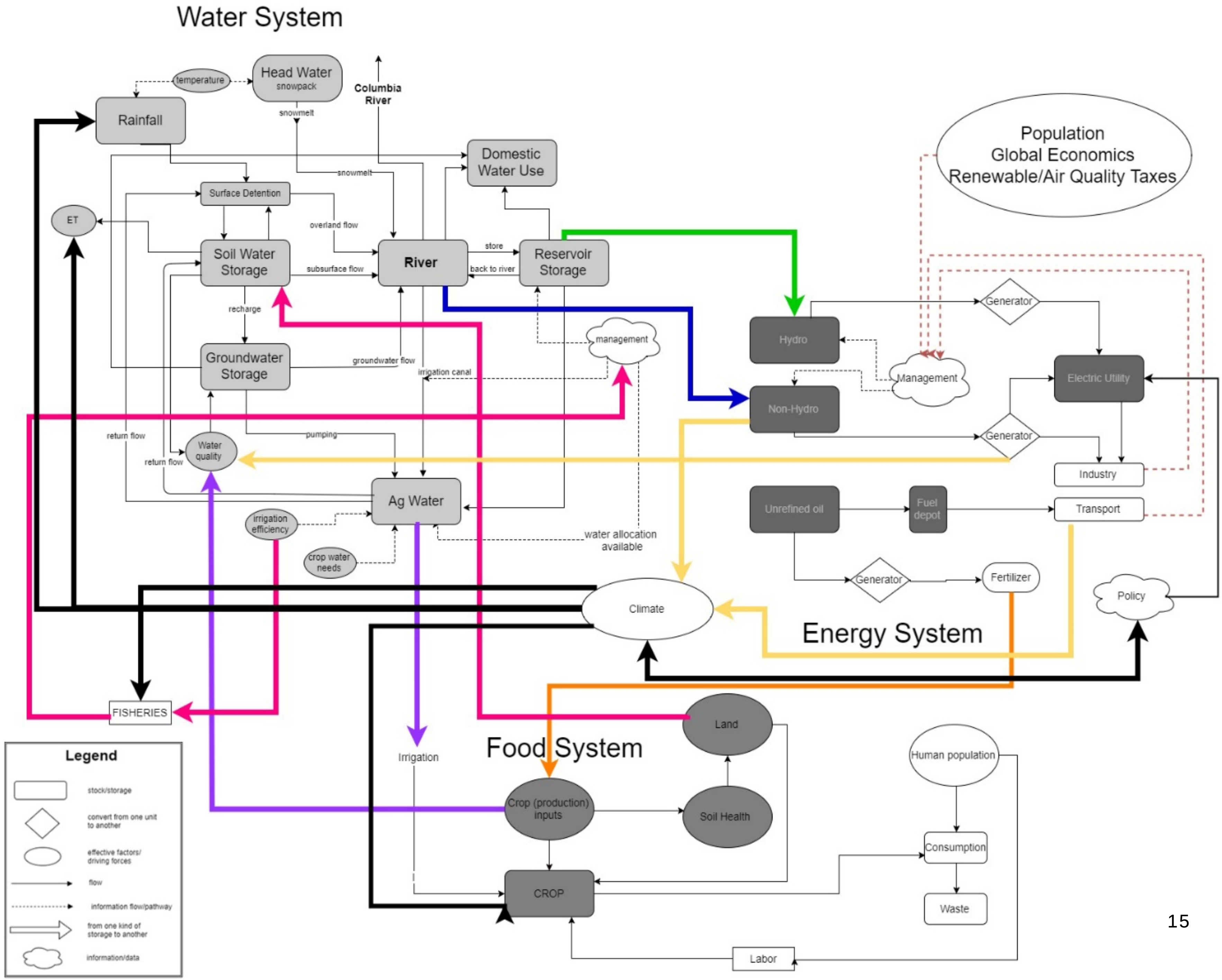
- Semi-arid climate: (206 mm/year rainfall)
- Ranked 1st in US in many agricultural products (USDA, 2007)
- 10% employment in agriculture (USBR, 2002)
- Irrigated crop income: $1.3B (USDA, 2007)
- Low irrigation efficiency (>70% surface and inefficient sprinklers)
- **Increased droughts lead to seasonal curtailment**



Slides by K. Malek

Innovation in the FEW nexus- Yakima River Case Study (K. Malek)

- Detailed case study on irrigation
  1. Conceptual mapping to identify where FEW interlinkages exist
  2. Identify friction points and innovations related to irrigation technology improvements
  3. Apply in biophysical, mechanistic models to evaluate effectiveness of, and trade-offs between, innovations

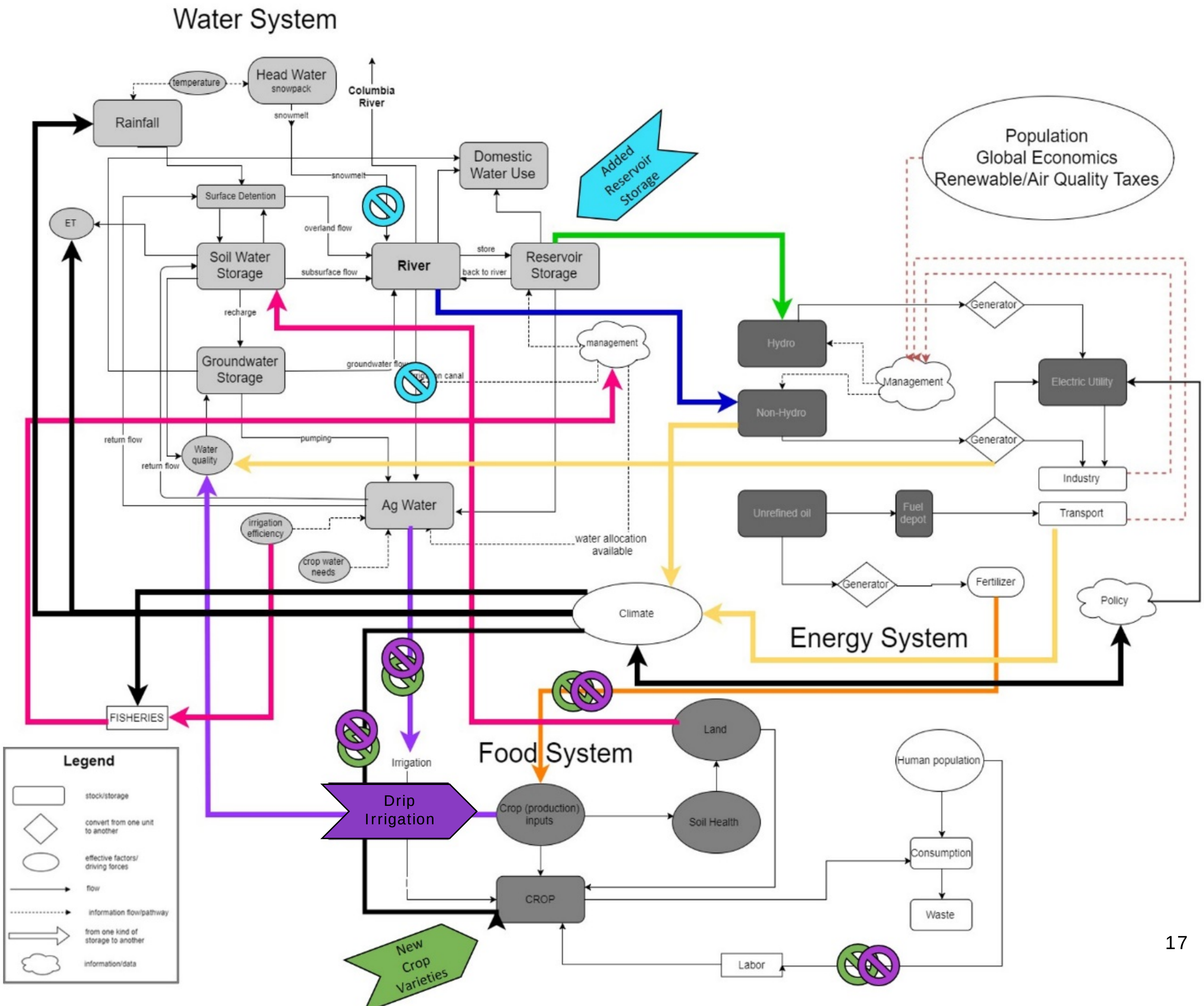


Water System
temperature
Head Water
snowpack
snowmelt
Columbia River
Rainfall
Domestic Water Use
snowmelt
Surface Detention
ET
overland flow
Soil Water Storage
River
store
Reservoir Storage
subsurface flow
back to river
recharge
management
Groundwater Storage
groundwater flow
irrigation canal
return flow
pumping
Water quality
return flow
Ag Water
irrigation efficiency
crop water needs
water allocation available
Population
Global Economics
Renewable/Air Quality Taxes
Generator
Hydro
Management
Electric Utility
Non-Hydro
Generator
Industry
Unrefined oil
Fuel depot
Transport
Generator
Fertilizer
Climate
Policy
Energy System
FISHERIES
Land
Irrigation
Food System
Crop (production) inputs
Soil Health
Human population
Consumption
CROP
Waste
Labor
Legend
stock/storage
convert from one unit to another
effective factors/ driving forces
flow
information flow/pathway
from one kind of storage to another
information/data

Innovations in irrigated agriculture

- According to past studies in a sub-basin of the Columbia River (the Yakima River Basin), more water-conserving irrigation systems at the farm level could potentially ameliorate the negative effects of increases in droughts, improving the overall agricultural economy of the basin.

- Innovations Modeled in Yakima River Basin:
  1. Increased reservoir storage
  2. Use of drip irrigation technology
  3. Introduction of climate-adapted crop varieties



Water System
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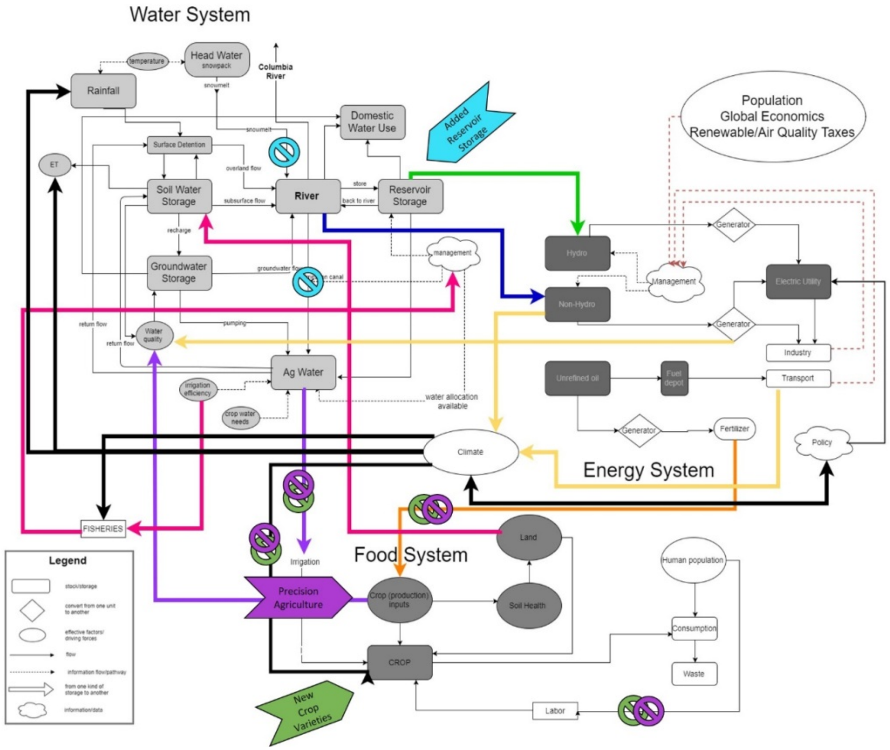
groundwater flow
irrigation canal
Non-Hydro
return flow
Water quality
pumping
Generator
Industry
Ag Water
Unrefined oil
Fuel depot
Transport
irrigation efficiency
water allocation available
crop water needs
Generator
Fertilizer
Climate
Policy
Energy System
FISHERIES
Land
Legend
stock/storage
convert from one unit to another
effective factors/ driving forces
flow
information flow/pathway
from one kind of storage to another
information/data
Irrigation
Food System
Human population
Drip Irrigation
Crop (production) inputs
Soil Health
Consumption
CROP
Waste
New Crop Varieties
Labor



Any given innovation can address multiple existing friction points, and more than one innovation can act to relieve a given friction point (e.g., Innovations 2 & 3).

The modeling framework will evaluate trade-offs between innovations.

Innovations Addressing Friction Points:

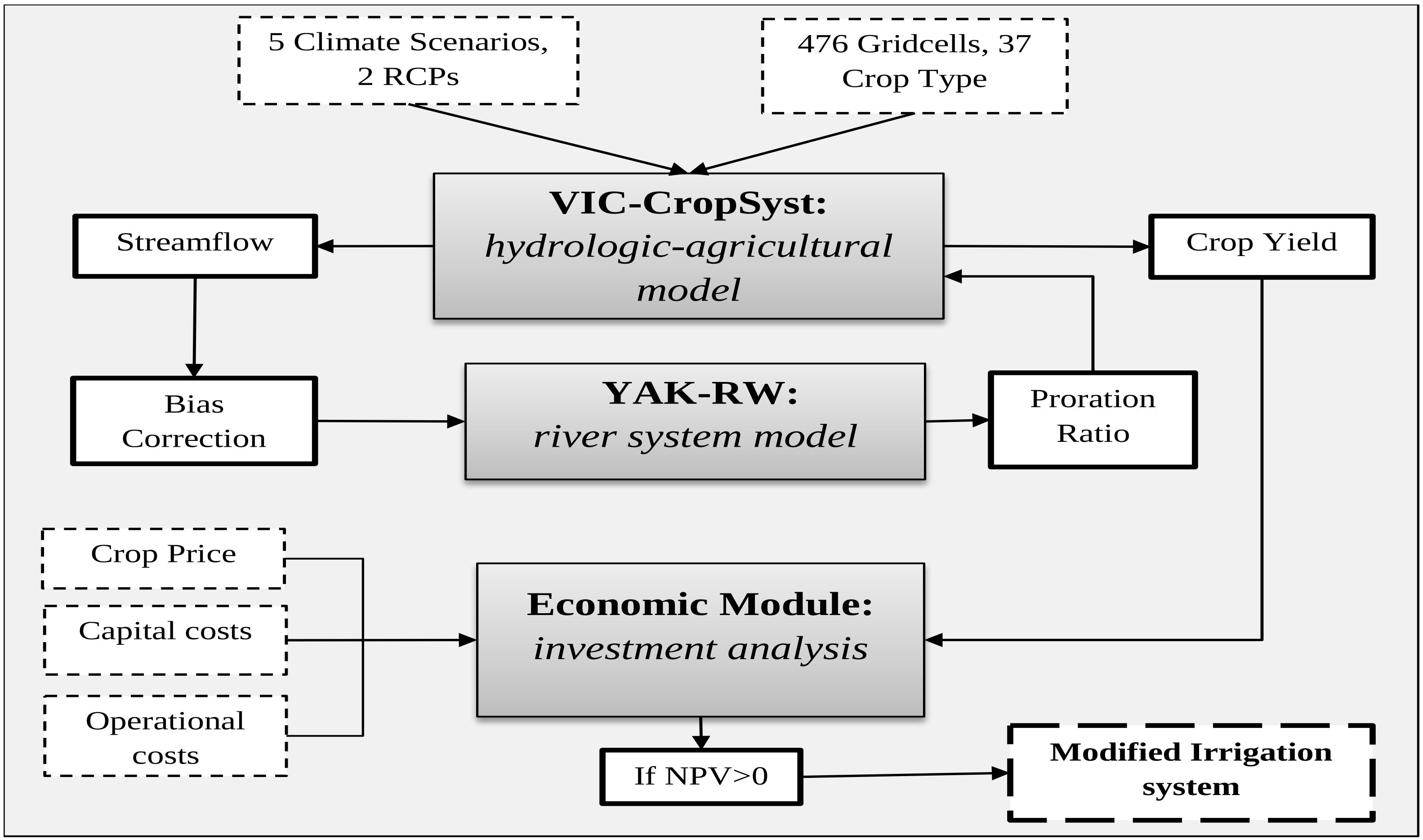
1) *Additional Reservoir Storage Capacity*
   - Decreasing snowpack limits water availability in receiving streams
   - Increased frequency and severity of droughts requires curtailment

2) *Use of Drip Irrigation Technology*

&

3) *Switch to Better Adapted Crop Varieties*
   - Warmer growing season
   - High labor costs
   - Over-application of nutrients
   - Decreased irrigation water available

Agricultural Spatial Economic Analysis Platform (ASEAP)



Slides by K. Malek

Emerging Results (K. Malek, J. Yoder)

For Drip Irrigation Innovation:

- Climate change produce more frequent and more severe droughts -> irrigation demands will increase
- Less curtailment with efficient irrigation (↓ irrigation demands, ↓ return flows)
- Drop in demand reduces return flows and need for power → hydropower generation declines.

Emerging Results (K. Malek, J. Yoder)

For Drip Irrigation Innovation:

- New irrigation (automated) technologies will reduce labor demand in the agricultural sector.
- Impact depends on producers' willingness and ability to invest in new infrastructure.

Less return flow due to more-efficient systems➔ may have some negative impacts on basin-wide agricultural economy

Conclusions

- Still much work to do, but…
  - Conceptual models useful for identifying where key interdependencies exist.
  - Maps help identify key drivers, parameters, time steps, and variables of importance to build and improve existing CRB systems dynamic and biophysical models.
  - Identifying stress and opportunity points with the system can improve understanding of how new innovations may impact system-wide resilience to regional and global change.

Thank you!

Societal acceptance of new technology, management practices and hidden cost transfers

- Thursday Dec 7, 1-1:30pm
- 20-25m so there's 5-10m for questions
- **Increasing Resilience Across the Food, Energy, and Water Sectors in the Columbia River Basin**
- Food-Energy-Water (FEW) security is reliant in part by our ability to understand the interdependencies within FEW systems. Our NSF-INFEWS project examines how coordinated management of physical (e.g., reservoirs, aquifers, and batteries) and non-physical (e.g., water markets, social capital, and insurance markets) storage systems across FEW sectors promotes overall system resilience. Focusing on the Columbia River Basin (CRB) in the northwestern part of the United States, our NSF-INFEWS project uses an integrated approach to understand FEW linkages. To understand where and how FEW systems interlink, we created detailed conceptual models of the food, energy, water, and social systems to identify where key interdependencies (i.e., overlaps, stocks, and flows) exist within and between systems. These maps allow us to identify key drivers, parameters, time steps, and variables of importance to build and improve existing CRB systems dynamic and biophysical models. From these maps we can also identify stress and opportunity points with the system, and test how new innovations may impact system-wide resilience to regional and global change.

Aim 3: Modeling FEW Solutions

- Historical Climate
  - What pressure points already exist?
- Future Climate
  - Management status quo – how will climate change exacerbate or create new pressure points?
  - Innovations in institutions and/or technology – how will innovation reduce pressure points?

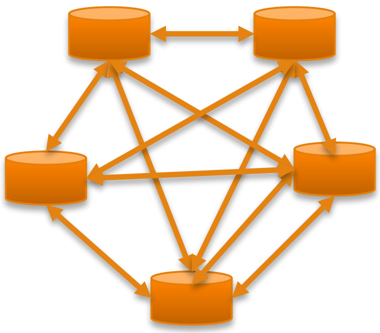
Disturbances

Shocks: heat waves, droughts, floods, rapid shifts in commodity prices, etc.

Pressures: shift in snowmelt timing, growing/changing population, etc.

Multiple independently-managed storage systems

or



Coordinated management of a distributed storage system

Aim 1: Theoretical Foundation

- Identify critical characteristics of a FEW system
  - Which characteristics are specific to our region?
- Identify critical connections between food, energy, and water systems
- Identify critical drivers of FEW resilience
- Use this information to classify FEW problems; this aids in the transferability of our theoretical foundation to other regions and scales

Aim 2: Quantitative Frameworks

- An integrated modeling (IM) platform: combining two existing platforms (BioEarth and PRIMA)
- A system dynamics ("stock and flow") model that can include more components of the FEW system in a highly flexibly framework.

IM Platform

- Strength:
  Mechanistic
- Weaknesses:
  Computationally-intensive
  Not all "stocks" and "flows" represented

→ Calibration of relationships between stocks

← Inform scenarios

SD Platform

- Strengths:
  Ease of capturing "stocks" and "flows"
  Computationally efficient
- Weakness:
  Lacks mechanisms

Quantitative Frameworks: The WSU BioEarth Project (food-water-environment)

Example Management Scenarios

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

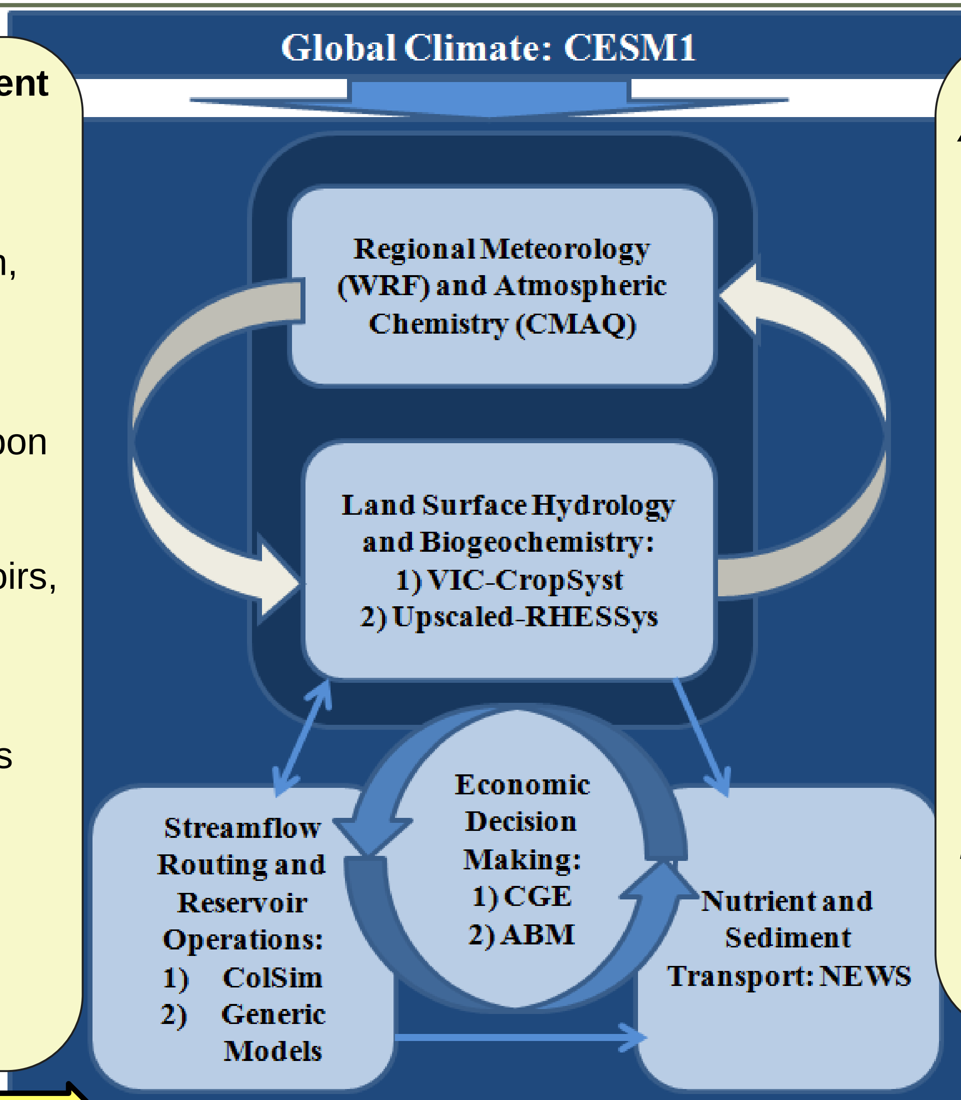
Rangeland: grazing, restoration

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

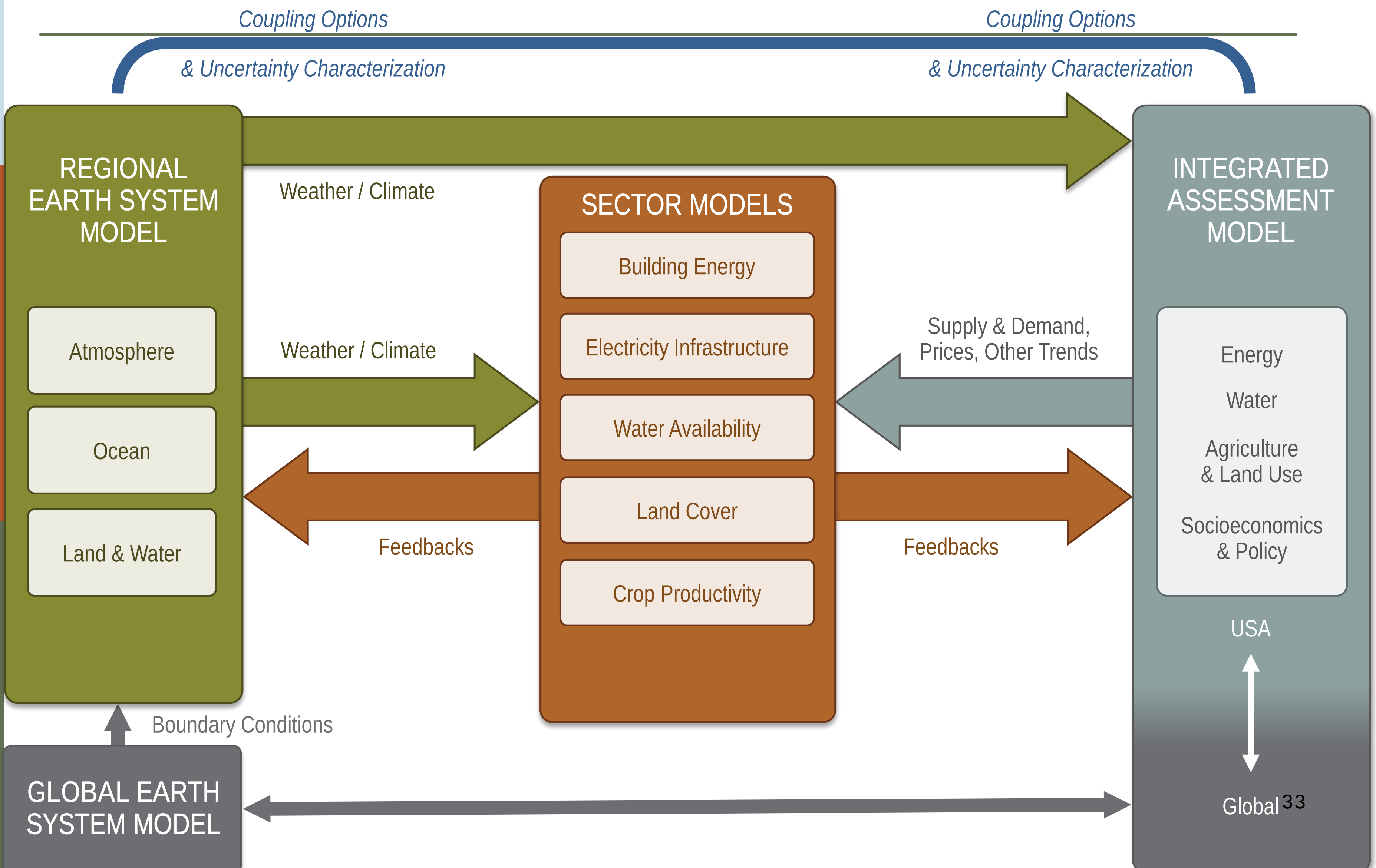
Water quantity and deficit: soil moisture, rivers, reservoirs, unmet demand

Water quality: dissolved inorganic/organic nitrogen and carbon

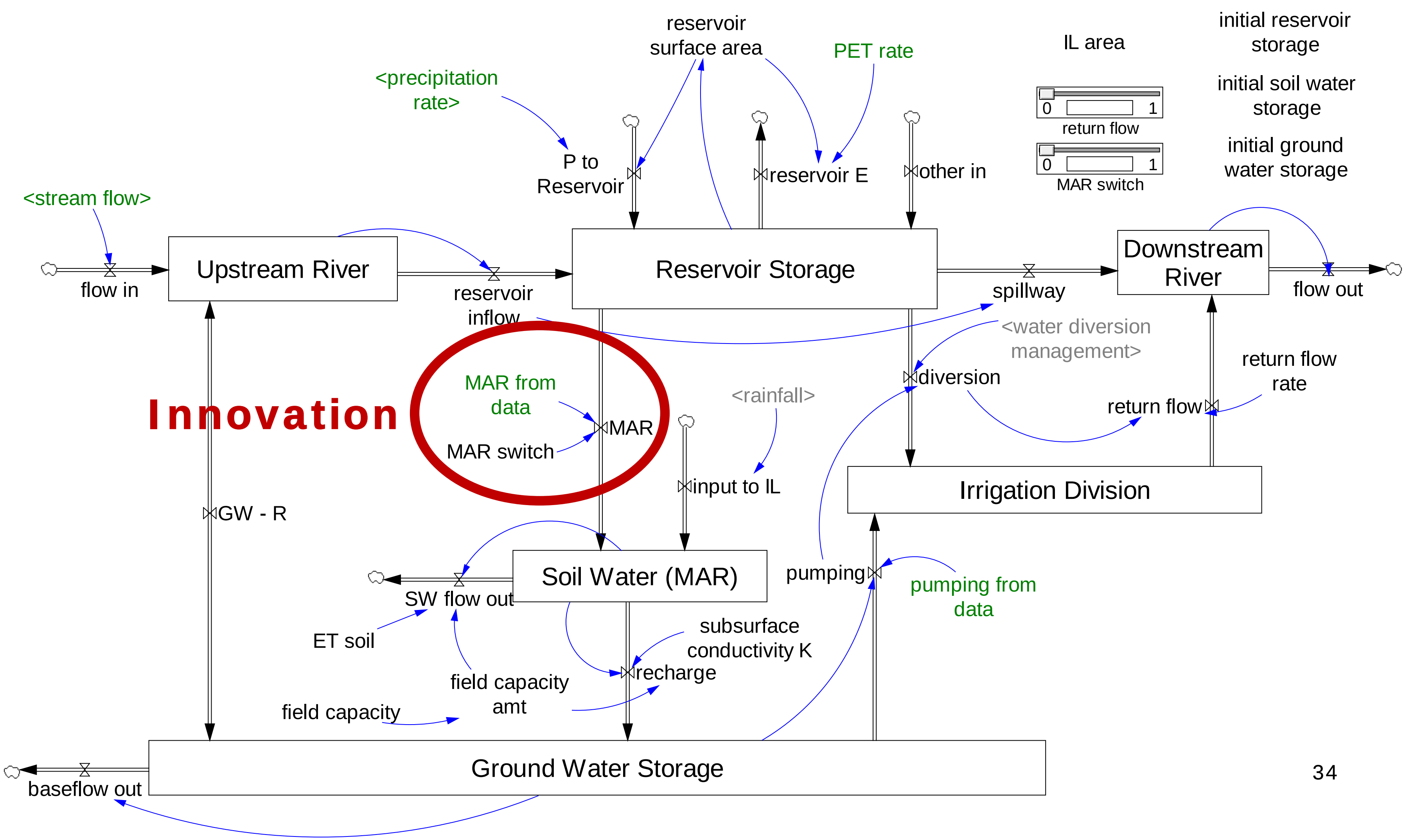
Terrestrial ecosystem health: species composition, net primary productivity, water stress, nutrient limitations

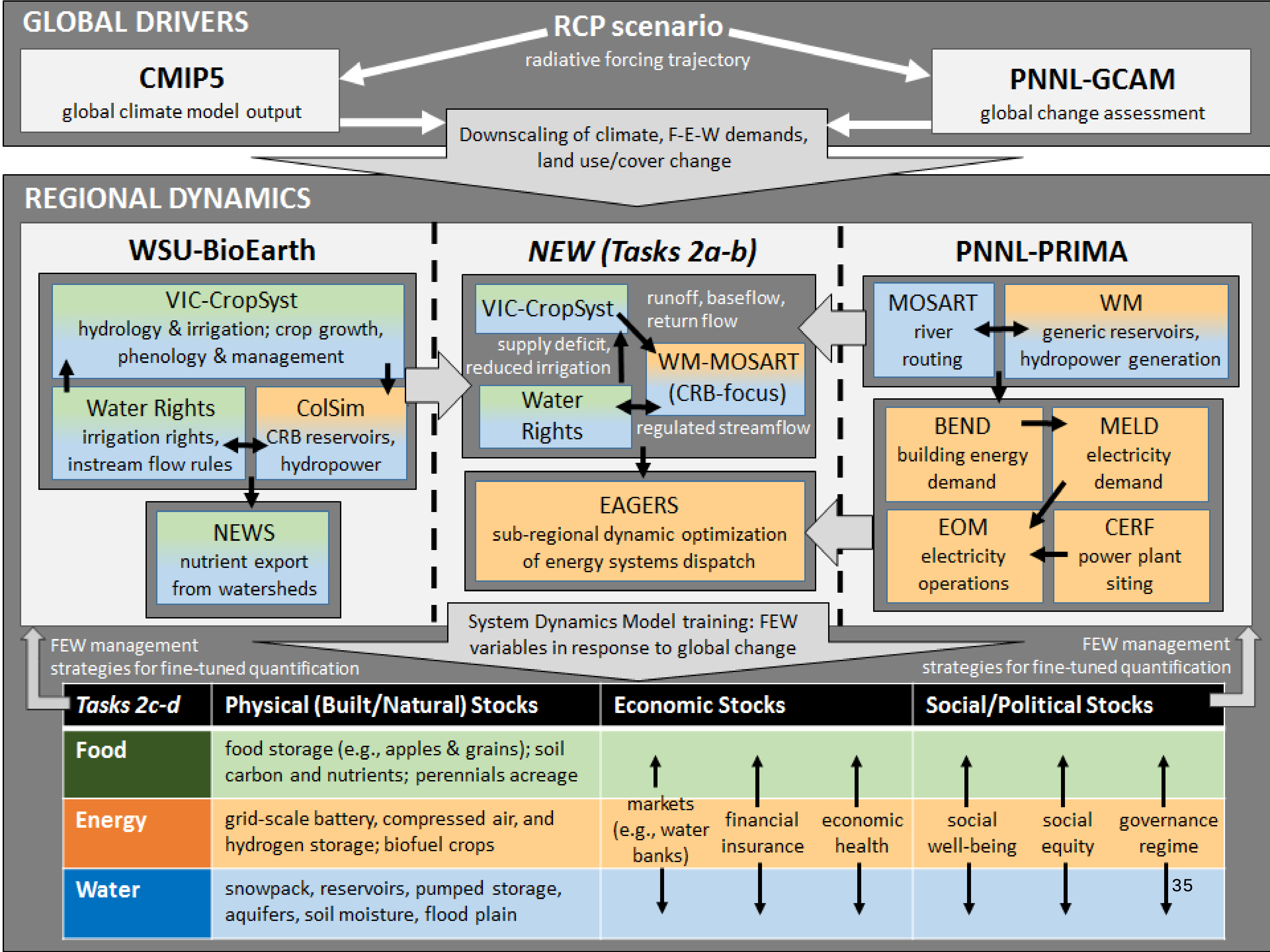
Economic: crop yield, forest/range productivity, hydropower generation, carbon mitigation

Quantitative Framework: The PNNL PRIMA Project (water-energy)



Quantitative Framework: Our Generic System Dynamics Model

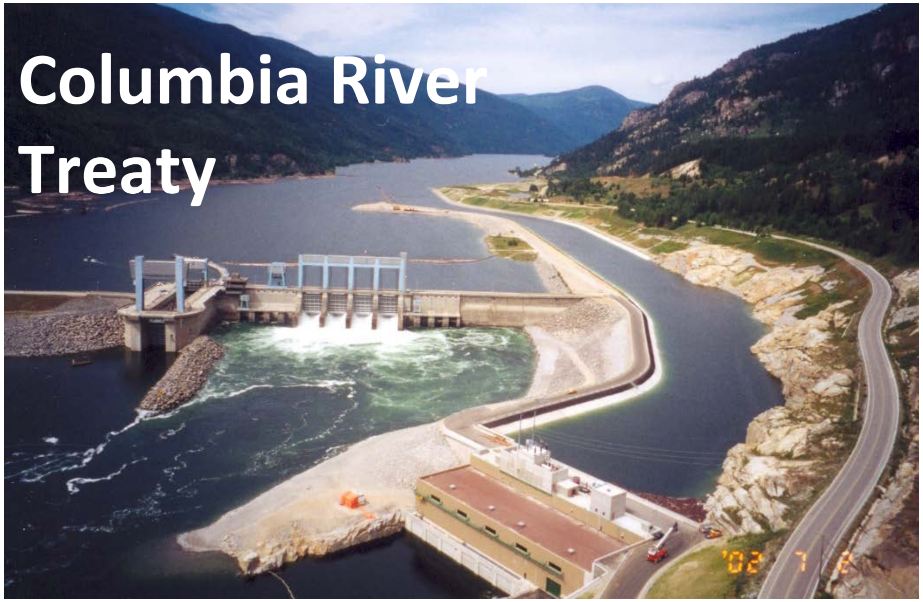


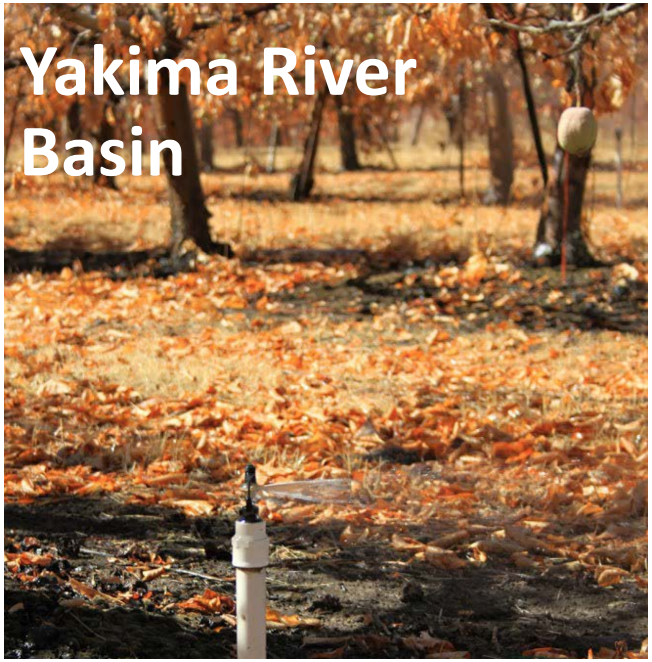

GLOBAL DRIVERS
RCP scenario
radiative forcing trajectory
CMIP5
global climate model output
PNNL-GCAM
global change assessment
Downscaling of climate, F-E-W demands, land use/cover change
REGIONAL DYNAMICS
WSU-BioEarth
NEW (Tasks 2a-b)
PNNL-PRIMA
VIC-CropSyst
hydrology & irrigation; crop growth, phenology & management
Water Rights
irrigation rights, instream flow rules
ColSim
CRB reservoirs, hydropower
NEWS
nutrient export from watersheds
VIC-CropSyst
runoff, baseflow, return flow
supply deficit, reduced irrigation
WM-MOSART (CRB-focus)
Water Rights
regulated streamflow
EAGERS
sub-regional dynamic optimization of energy systems dispatch
MOSART
river routing
WM
generic reservoirs, hydropower generation
BEND
building energy demand
MELD
electricity demand
EOM
electricity operations
CERF
power plant siting
System Dynamics Model training: FEW variables in response to global change
FEW management strategies for fine-tuned quantification
FEW management strategies for fine-tuned quantification
Tasks 2c-d
Physical (Built/Natural) Stocks
Economic Stocks
Social/Political Stocks
Food
food storage (e.g., apples & grains); soil carbon and nutrients; perennials acreage
Energy
grid-scale battery, compressed air, and hydrogen storage; biofuel crops
Water
snowpack, reservoirs, pumped storage, aquifers, soil moisture, flood plain
markets (e.g., water banks)
financial insurance
economic health
social well-being
social equity
governance regime

Aim 4: Broader Engagement

- Broader scientific community: resilience workshops
- Stakeholders: core stakeholder advisory group (SAG) and case study-specific workshops

Initial Case Studies





Others being considered:

- MAR/ASR
- Pumped hydro
- Wine industry
- Water markets
- etc.

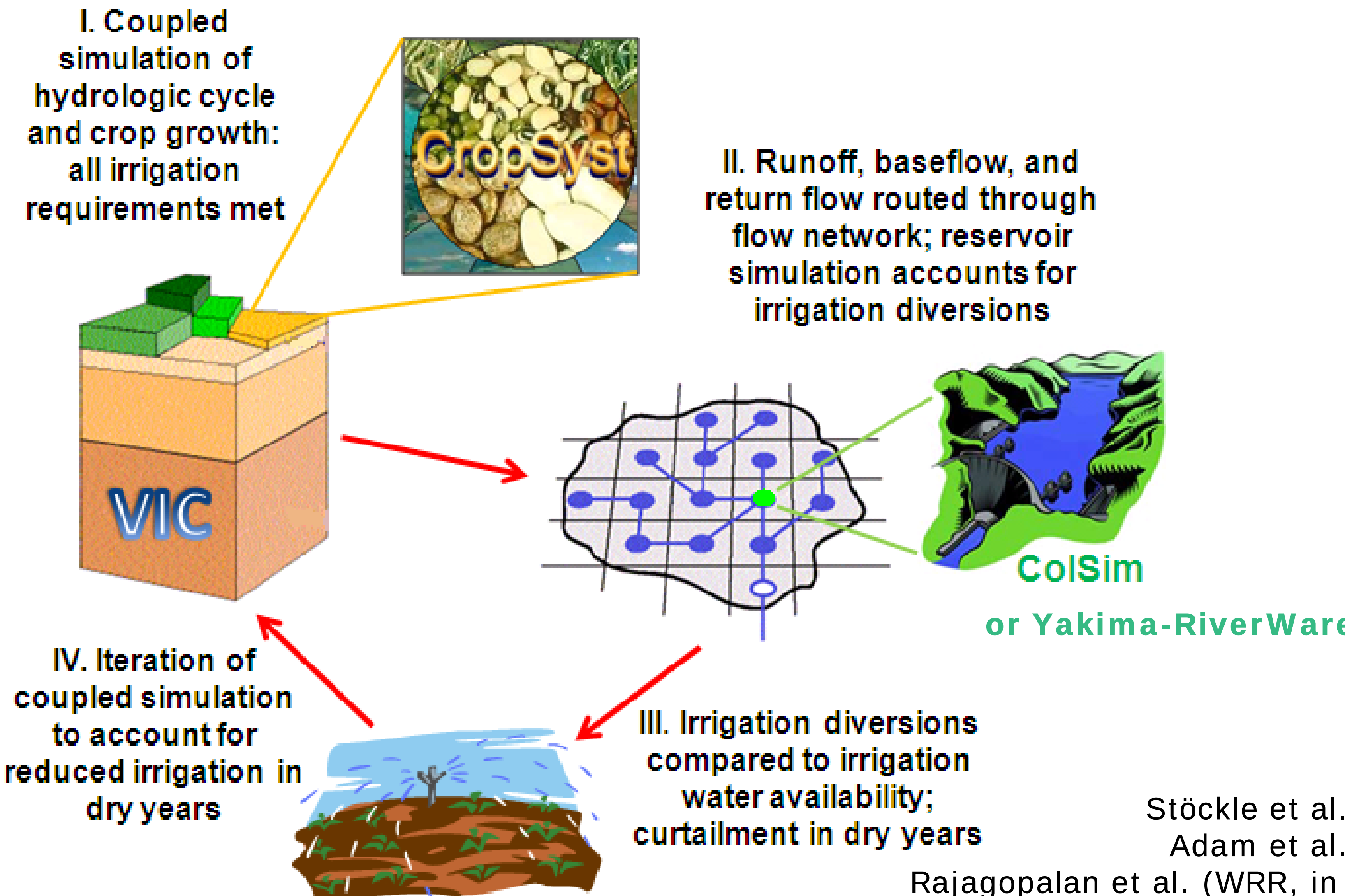
Expected Outcomes

- Our theoretical work and multidisciplinary workshops will result in operational definitions of resilience for modeling the FEW nexus, and mechanistic understanding of connections across FEW systems
- Dramatic improvement of understanding of the interactions within and between FEW sectors at the regional scale
- A generalizable approach that can be applied over other regions and scales, including new computational modeling frameworks to evaluate strategies that both co-balance benefits and increase resilience, while considering constraints and long-term sustainability
- Enabled quantification of the extent to which specific technological and institutional innovations would be most effective in fostering a resilient FEW system; this information can be used to formulate policy that would incentivize development or use of such technologies

Part 2

- How will climate change impact CRB water availability and irrigation demand?
- What are the impacts on irrigated agriculture?

Integrated Hydrology, Cropping Systems, and Water Management

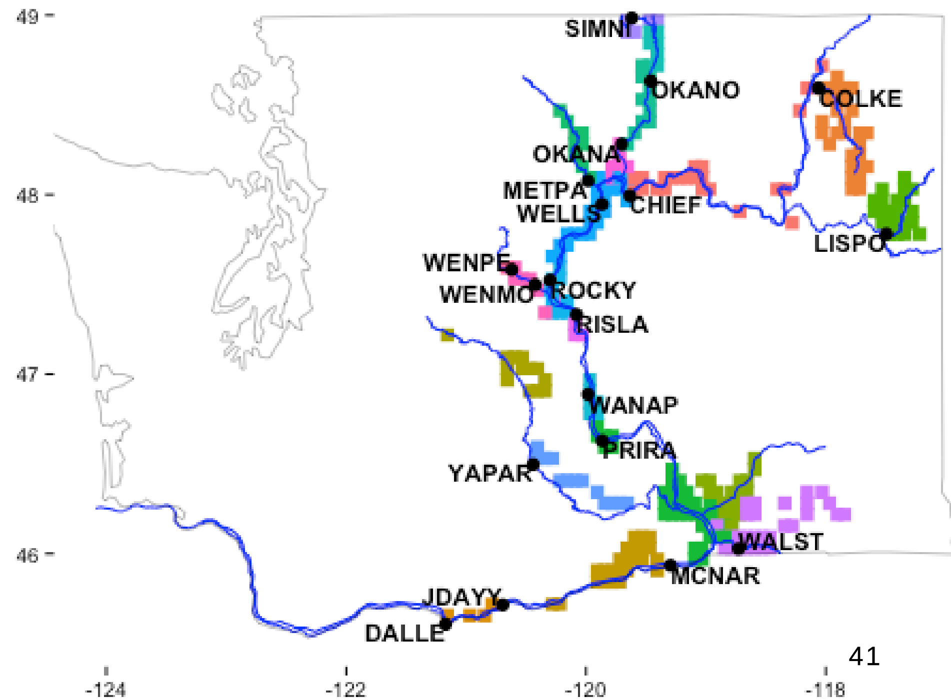


Stöckle et al. (2014)
Adam et al. (2014)
Rajagopalan et al. (WRR, in review)

Types of Water Rights Curtailment

- Columbia River Mainstem – interruptibles
  - captured
- Yakima River Basin – prorationing
  - captured
- Non-Yakima tributaries – interruptibles
  - captured
- *Non-Yakima tributaries – non-interruptibles*
  - *Not captured*

Eastern Washington Interruptible Rights



Courtesy Kirti Rajagopalan, WSU

Crops Modeled

Major Crops

- Winter Wheat
- Spring Wheat
- Alfalfa
- Barley
- Potato
- Corn
- Corn, Sweet
- Pasture
- Apple
- Cherry
- Lentil
- Mint
- Hops
- Grape, Juice
- Grape, Wine
- Pea, Green
- Pea, Dry
- Sugarbeet
- Canola

Vegetables

- Onions
- Asparagus
- Carrots
- Squash
- Garlic
- Spinach

Other Pastures

- Grass hay
- Bluegrass
- Hay
- Rye grass

Other Lentil / Wheat Type

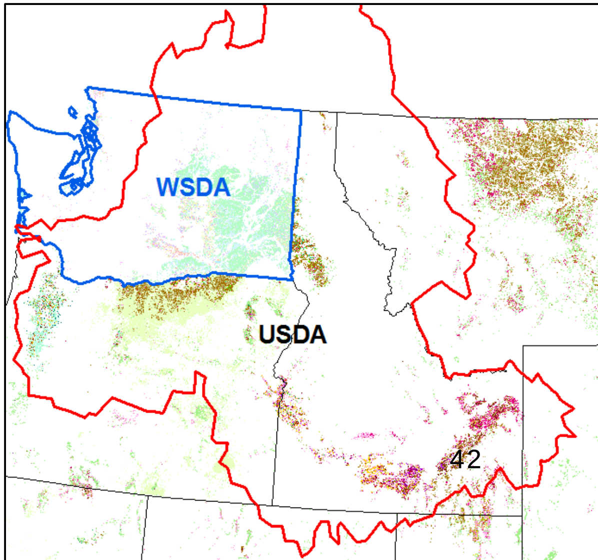
- Oats
- Bean, green
- Rye
- Barley
- Bean, dry
- Bean, green

Berries

- Caneberry
- Blueberry
- Cranberry

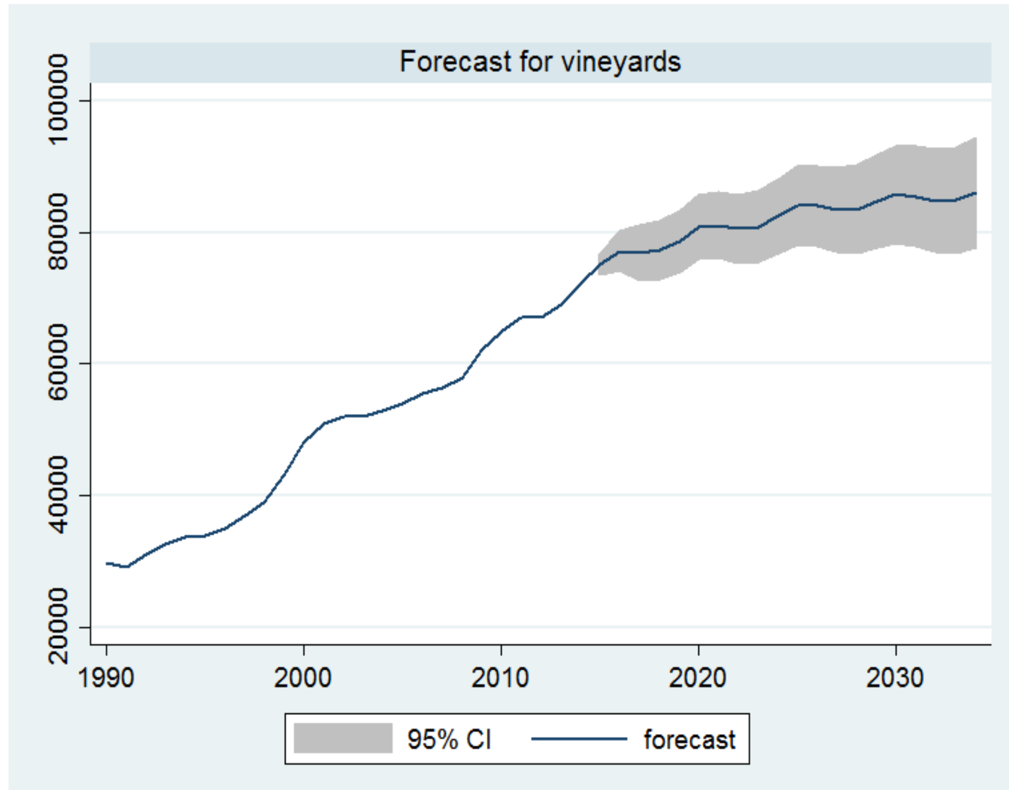
Other Tree Fruits

- Pear
- Peaches



Economic Modeling: Forecasting Future Crop Mix

- Changes in crop mix can affect overall water demand due to differences in crop water requirements.
- Data on recent trends in the irrigated crop mix in Eastern Washington were used in a statistical model to forecast future crop mix.



- This approach has been shown to produce more accurate forecasts than complex economic models.

Courtesy Michael Brady, WSU

Summary of Changes in CRB Water Supply and Demand (2030s Ensemble Mean)

Supply:

- Average annual increase: +14.6% (+/-8.3%)
- Average shift in seasonality:
  - ↓ -10.3% (+/-7.9%) between June and October
  - ↑ 30.8% (+/-9.4%) between November and May

Demand:

- Average decrease in eastern WA irrigation demand:
  - -5.1% (+/-1.0%) (historical crop mix)
  - -6.9% (+/-1.0%) (future crop mix)
- Average shift in seasonality (future crop mix):
  - ↑ 5.7% between March and June
  - ↓ -13.3% between July and October

Hall et al. 2016

Causes of 2030s Projected Decrease in Irrigation Demand

In Response to Climate Change

- Water Supply: Springs are getting wetter
- Water Demand: Shifting of irrigation requirements earlier in the season
  - Earlier planting and shorter irrigation season for most crops
  - Higher water-use efficiencies due to increases in CO_2

In Response to Economic Drivers

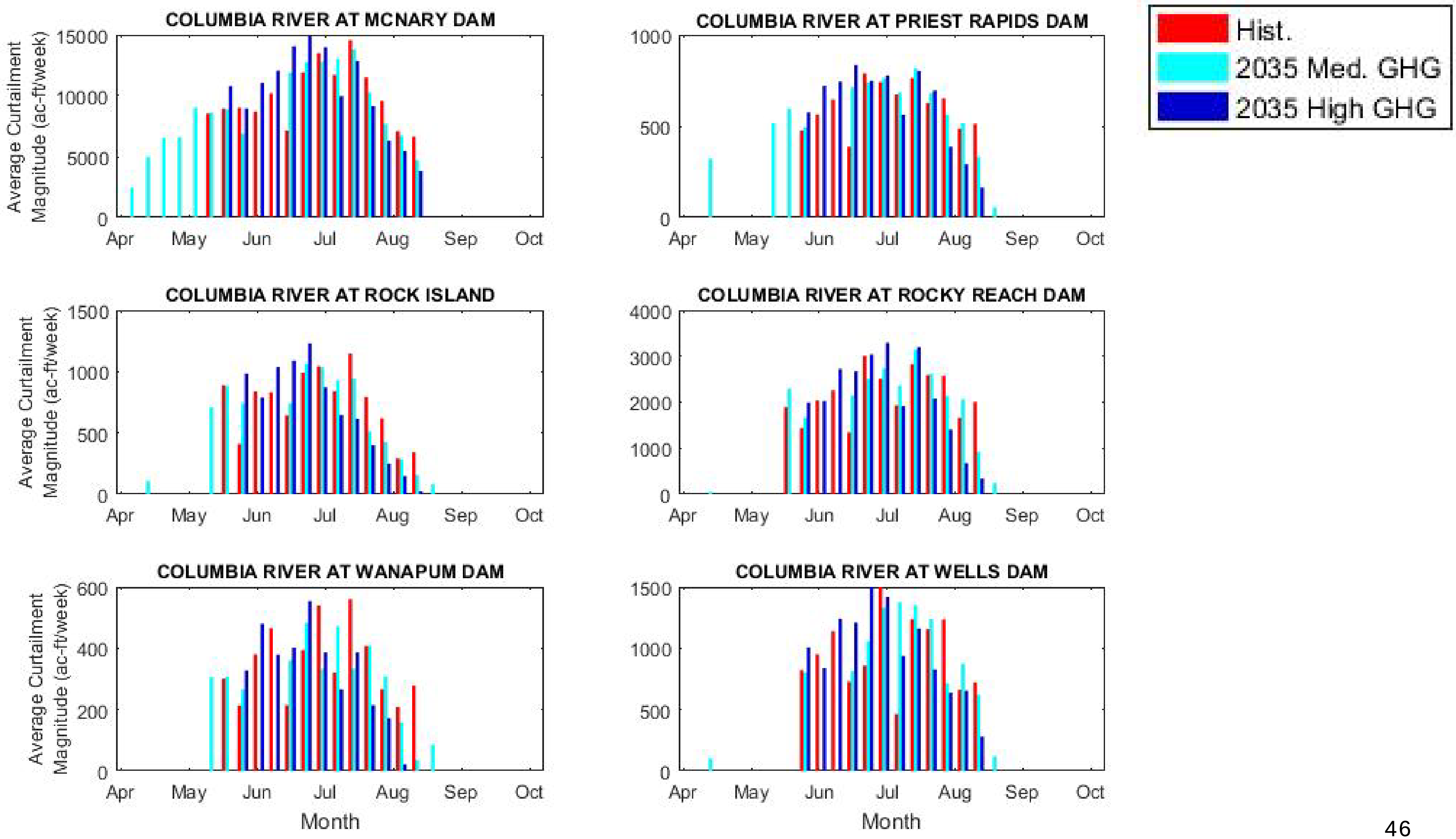
- Shift towards more water-use efficient crops

Note that many adaptive actions were not considered

- Increases in double/cover cropping
- More slowly-maturing crop varieties (e.g., corn)
- Expanded irrigated acreage
- Changes in irrigation technology/management

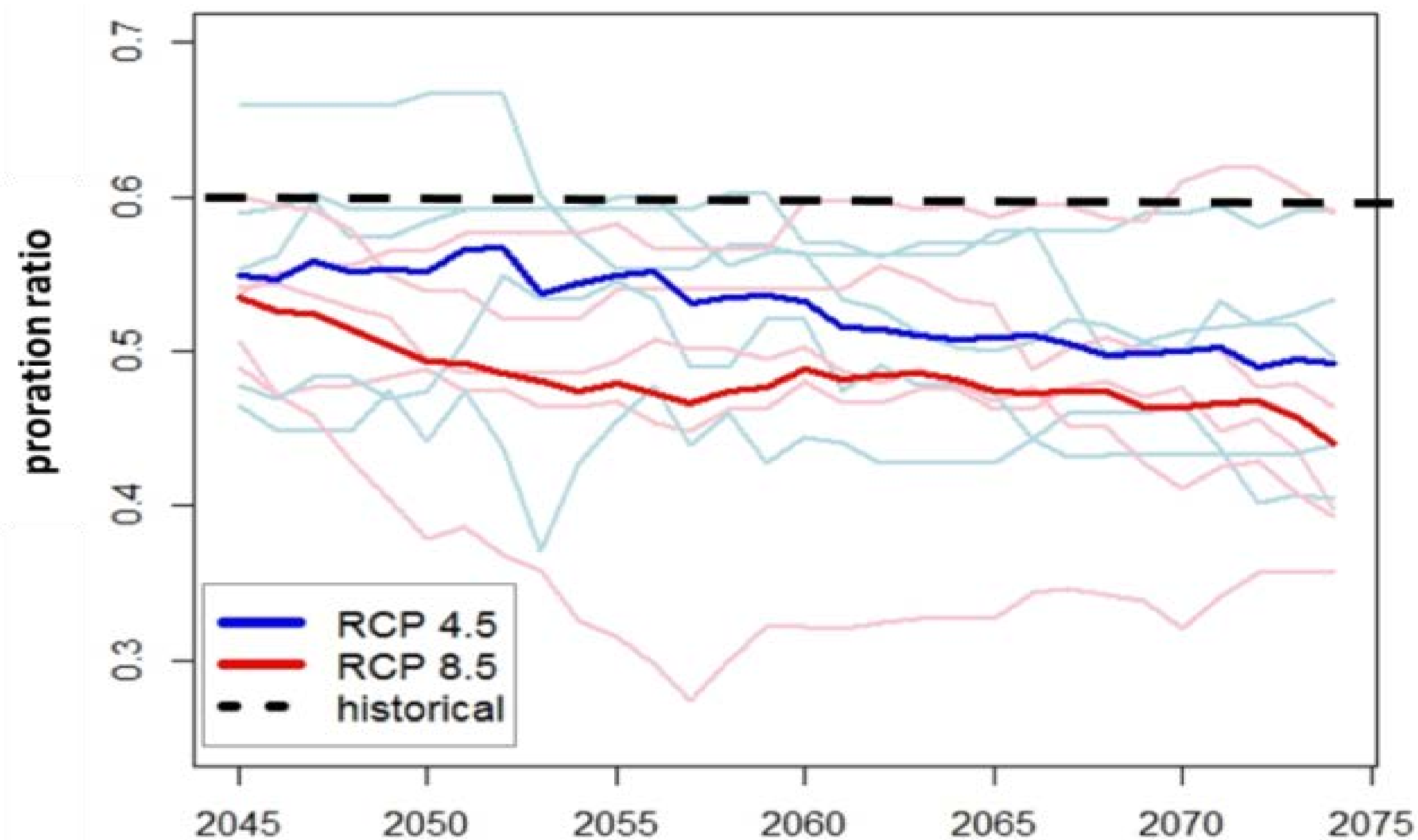
Hall et al. 2016

2030s Columbia Mainstem Water Rights Curtailment



Hall et al. 2016

Impacts on Proration Ratios in the Yakima River Basin



Proration Ratio = Percent of Water Right Allowed for Irrigation Season

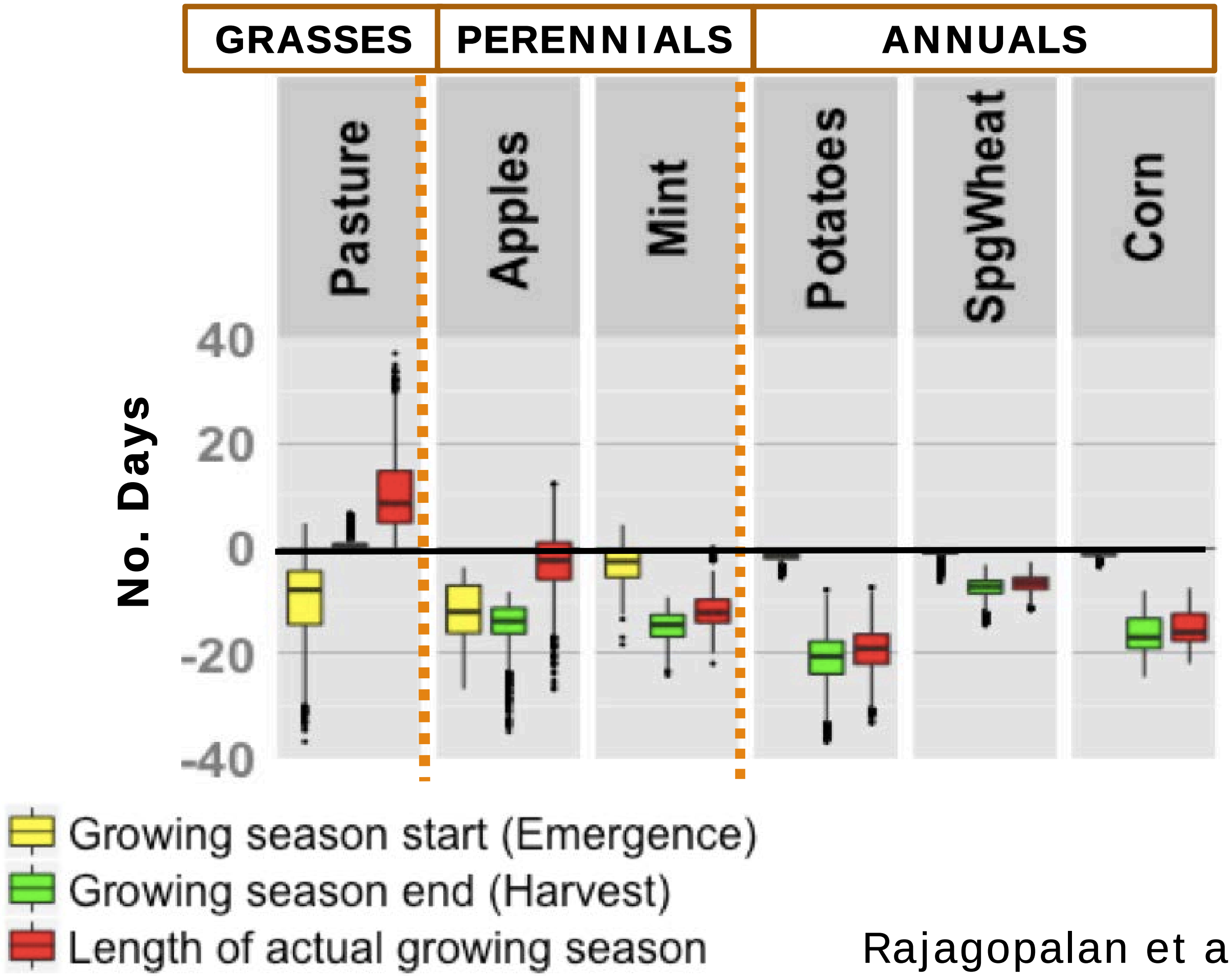
Malek et al. (WRR, in prep.)

Crop Yield Impacts

- **Direct impacts** of near-term (20-year) changes on crop yields
  - CO_2
  - precipitation
  - temperature

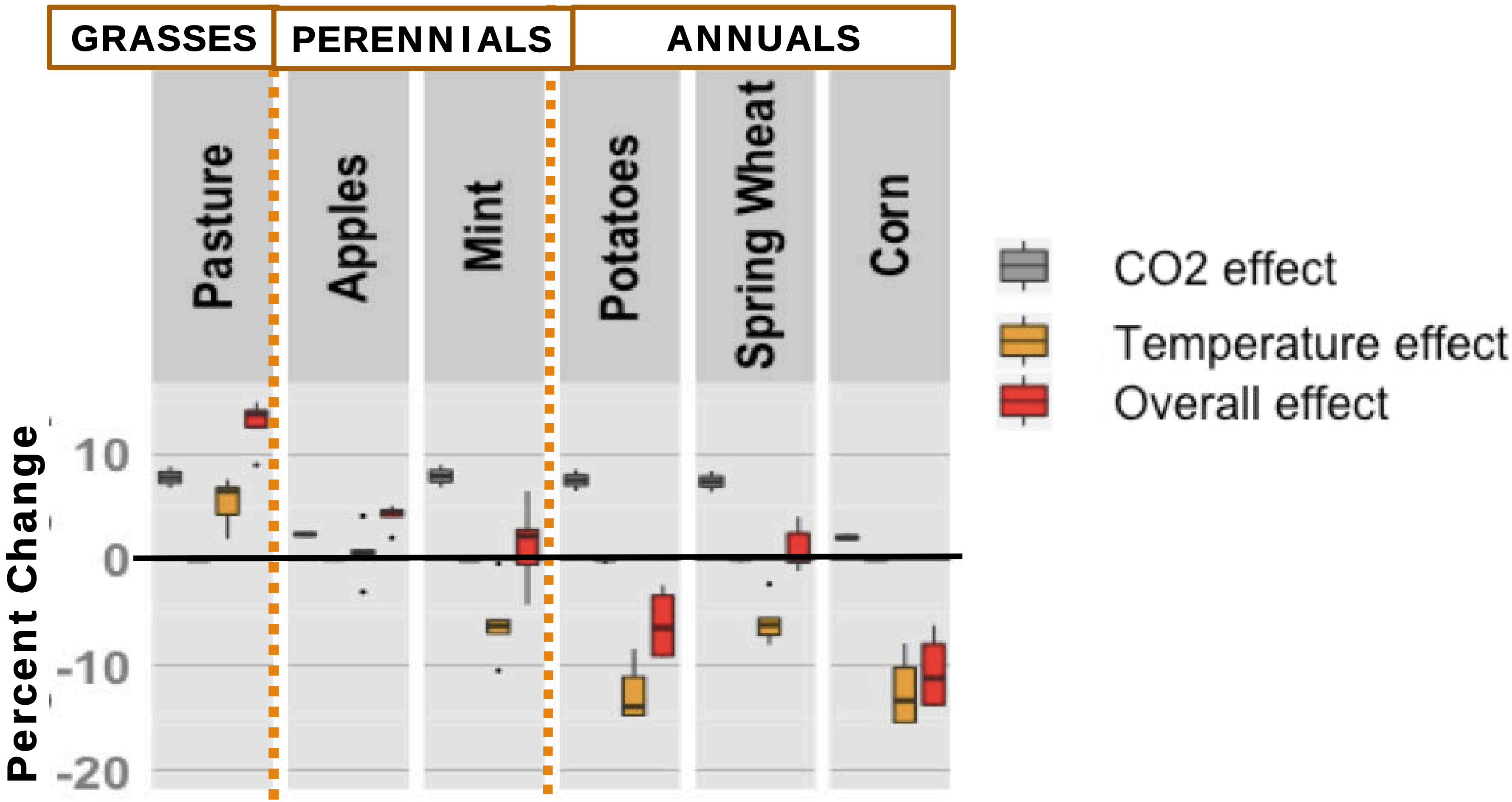
- **Indirect impact** of near-term (20-year) changes on crop yields
  - water rights curtailment

Direct Impacts: Growing Season Length (2030s)



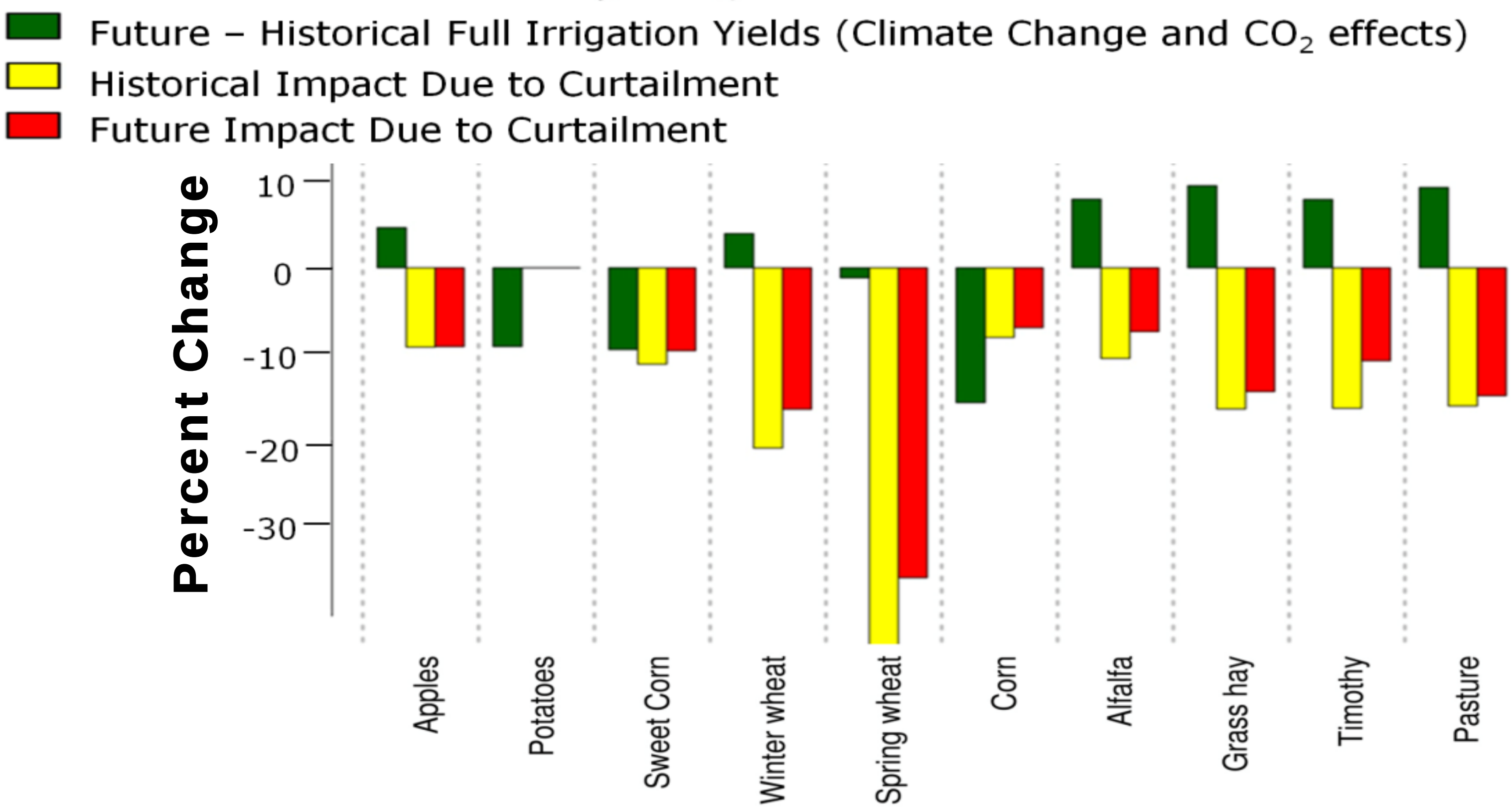
Rajagopalan et al. (in revision)

Direct Impacts: Irrigated Crop Yield (2030s)



Rajagopalan et al. (in revision)

Indirect Impacts: Irrigated Crop Yield
(in eastern WA with interruptible water rights)



- Although curtailments are higher in the 2030s, impacts of curtailment on yields may be smaller than historical
- This is not likely to be the case
  - for longer projections
  - if certain adaptive actions are taken by irrigators

Rajagopalan et al. (in prep)

Some Key Uncertainties and Data Gaps (not comprehensive)

Current Conditions

- Extent of current double and cover cropping
- Limitations with water rights information; not all categories of water rights were modeled
- Treatment of areas with declining groundwater levels

Future Conditions

- Response of crops to CO_2 fertilization, esp. tree fruit
- New water rights being granted – expansion of irrigated extent
- Future areas with declining groundwater levels
- Adaptive actions that may either alleviate or exacerbate water constraints

Summary of Impacts

- *Climate Change:* Climate change is associated with warming, changes in precipitation seasonality, changes in the frequency of extreme events, and increases in CO_2
- *Water Supply:* While changes in annual water availability is uncertain, availability will decrease during the later stages of the growing season without adequate reservoir storage
- *Water Demand:* Irrigation water demand may increase or decrease depending on producer actions taken; it will also shift earlier in the growing season
- *Agriculture:* Irrigated crop yields are impacted by these changes
  - Warming: mixed effects
  - CO_2 fertilization: increases
  - Curtailment: decreases but future decreases may be less than expected, at least in the near-term
- *Uncertainties:* Adaptation actions may alleviate impacts for some users at the expense of other users

Thank you!