Interacting controls on eco-hydrologic responses to warming in mountain ecosystems

Implications of hillslope-scale climate variation for estimating eco-hydrologic responses to warming

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Coupled eco-hydrologic responses to climate change

- Estimate whether vegetation response to warming (directly and indirectly via disturbance influence) are likely to be a “big” or “small” influence on streamflow responses.

- Improve understanding and ability to predict how vegetation will respond to climate driven changes in hydrology (precip, snowmelt, soil moisture, vpd) and implications for productivity, disturbance, vulnerability to disease and mortality.

http://westernmountains.org/

Western Mountain Initiative

Southern Sierra Critical Zone Observatory

https://snri.ucmerced.edu/CZO
Empirical analysis is used to improve process representation in mechanistic models.

We use multiple data sources for model parameterization, performance verification, data assimilation.

Spatially-distributed, dynamic models of coupled eco-met-geo-hydro processes.

Models generalize understanding gained from field-based approaches to other watersheds.

Models are coupled with downscaled GCM projections to develop future scenarios.
Can we model these types of responses using coupled mechanistic hillslope hydro-carbon cycling models

RHESSys is a GIS-based, hydro-ecological modelling framework designed to simulate carbon, water, and nutrient fluxes. By combining a set of physically-based process models and a methodology for partitioning and parameterizing the landscape, RHESSys is capable of modeling the spatial distribution and spatio-temporal interactions between different processes at the watershed scale.

http://fiesta.bren.ucsb.edu/~rhessys/
Tague and Band, 2004
Carbon and Nitrogen Cycling in RHESSys
Transpiration (Penman-Monteith)

\[ LE = \frac{s(Rn + S) + \rho C_p (e_s - e_a) * g_a}{s + \gamma \left( 1 + \frac{g_a}{g_s} \right)} \]

Photosynthesis (Farquhar)
\( F(Ac, Aj) \) - both of which include \( Ci \) (concentration of carbon in leaves) which depends on \( gs \)

Stomatal Conductance (Jarvis Model)

\( gs = f(T_{max}, T_{min}, LWP, atm\ C02, Radiation, VPD) \)
\( gs_{canopy} = gs \times LAI \)

LWP - related to soil water availability
Linked with distributed hydrologic model and its parameterization
Respiration: maintenance, and growth \( f(T, N \text{ and biomass}) \) varies with type and size of plant components

Gross PSN - \( f(\text{light, nutrient availability, conductance), and leaf area} \)

NPP - Allocated to leaves, stems and roots; which impact photosynthetic capacity and respiration costs

Potential complex dynamics because you have a system with feedbacks and multiple controls

That carbon cycling models give you “reasonable” forest biomass for particular sites is not trivial; suggest that carbon cycling (rather than structural or some other mechanism) can explain growth and equilibrium size of stands
How will climate change alter vegetation water use in snow-melt dominated mountain environments of the Western US?

- **Tree Ring Analysis**
  - Higher elevations temperature
  - Transitioning to water-limited at lower elevations
    (Natawakaski and Peterson, 2006)

- **Climate effects on growth** - likely also on water use

- **Evidence of widespread drought stress related forest mortality**
  (Allen et al., 2010)

- **At what scales do we see spatial differences in response**
Map of study site (Christensen et al., 2007)
Calibrated model captures major trends in:
- Streamflow
- Snow accumulation and melt
Consider a uniform temperature increase, +2ºC to +8ºC (beyond the upper bound of current GCM for California 2100)
For a given precipitation input – greatest sensitivity of vegetation water use occurs at mid elevations where greatest change in SWE occurs and plants are water limited – consistent with empirical studies of SWE and tree ring growth.

- BAI measurements since 1990
- During 2000 drought, low elevation trees died, upper did not
- Within 10km, elevation (2700, 2300, 2000m)

Can eco-hydrologic model capture

- pre-drought difference in LAI and annual basal area increment (productivity) between high, mid and low elevation sites
- Reduced carbon-sequestration leading to death by “carbon starvation”
RHESSys estimates capture cross-site differences in productivity.
RHESSys estimates of stem biomass vs. measured BAI

- Pearson Cor High: 0.50
- Pearson Cor Mid: 0.66
- Pearson Cor Low: 0.55
Carbon-cycling model predicts critical LAI loss during 2004 drought for low but not mid-high sites.
Carbohydrate Storage?:
Reserve for use in “bad” years; benefit is resilience to drought; cost is less production of useful biomass (leaves, stems, roots) in good year

Q: Could carbohydrate storage be an important variable to consider in thinking about carbon starvation mortality)?

Q: Would accounting for carbohydrate storage change modelled response of Ponderosa Pines to climate variation at Frijoles site?

Note: we know even less about carbohydrate storage then we do about allocation to roots, stems, leaves (Sala et al., and McDowell, New Pythologist 2010)
Assumptions about carbohydrate storage do not impact mortality in low elevation site but do control whether mid site would withstand drought.
Scaling UP: Bandelier National Park
Use RHESSys estimates to scale to larger Bandelier National –
distribution of Peak SWE with elevation

Peak SWE - Interannual Variation 1980-200

Peak SWE (mm)

0 50 150 250

Elev 100ms

18 20 22 24 26 28 30
Peak Snow water equivalent depth for 50 years, all elevations

Warming scenarios +2, +4
RHESSys estimates of NPP for Ponderosa Pine
yellow = high probability of mortality
What do spatial variation in energy, moisture drivers + hydrologic connection tell us about spatial variation in climate sensitivity?
Study Site: Sagehen Experimental Watershed (UC Berkley Field Station)

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

http://sagehen.ucnrs.org/Photos/scenics/index.html
RHESSys hydrologic model Performance –
post-calibration
Streamflow (1960-2000)

- NSE (monthly) 0.77
- NSE (log transformed daily) 0.66
- Min 7 day streamflow R2 (0.86)

4 Drainage Parameters

- K - saturated hydraulic conductivity
- M - decay with depth
- Pa - water potential at air entry
- Po - pore size index
Ecological Recession:

- Day of Water Year (Nov. 1 to Oct. 31) at which 7 day moving average of transpiration goes to 50% of peak growing season value (T on cloudy days removed)

- Timing of ecological recession – can be compared with sap-flow estimates (without necessarily having to scale to whole tree transpiration) (Tague, 2009, Hydrologic processes)

Note at PET does not Reach 50% of its peak

For riparian patch, a 2°C temperature increase results, on average of 20 years, a 1 week earlier timing of water stress recession.

For a patch with same local conditions and LAI, but disconnected from upslope drainage area, a 2°C temperature increase results in a 2 week earlier timing of water stress recession.
Sensitivity of Floodplain vs Hillslope water stress to soil drainage parameters
Parameters that match both streamflow and sap flow produces slightly more efficient basin scale water use.
But conversely show greater sensitivity of forest transpiration to 2C warming, particularly for floodplain patch.
2C Warming Scenarios – change in ET across elevation

**Dry Year**

**Avg. Year**

**Wet Year**

Mean Annual ET (mm/yr)

Elevation (m)
Relationship between modeled snowpack (water year max 15-day average) and observed August streamflow

Conclusion: spatial (between watershed) differences in subsurface drainage rates leads to significant and substantial differences in the sensitivity of summer low flow to a change in snow-melt recharge

Conclusion:

- Climate change impacts on vegetation water use and productivity depend upon the spatial co-variation of snowmelt (at scales of 100s m) and soil/deeper groundwater drainage rates (storage/connection).

- Efforts to improve/evaluate coupled carbon-hydro cycling can take advantage of:
  - Differences along elevational gradients, riparian and upland responses
  - Sap flow recession as an indicator of timing of summer water stress can be used in calibration of hydrologic models
  - These assessments contribute not only to estimates of forest responses to climate change but also more generally to the parameterization of hydrologic models (specifically uncertainty in subsurface drainage characteristics) (Tague 2009, Hydrologic Processes)

Next Steps and Key Challenges
NEXT STEPS
WMI Focus:
Modelling as synthesis
Watershed Sites, Comparison with tree ring, C13 isotope data
Combination of snow versus rain and total precip together control sensitivity of vegetation water use to precip variation.
Is the timing of modeled streamflow sensitive to seasonal variation in temperature lapse rates?

We explore this question, simulate two years in 64 km² HJA using:

1. Uniform pseudo-adiabatic lapse rate of 6.5 °C/km
2. Min & max daily temperature lapse rates as climate input using 2 met station data (as demonstrated in Daly et al 2009)
3. Spatially explicit monthly averages of Tmin and Tmax
Uniform Temp Lapse Rate = 6.5 °C/km; log(NSE) = 0.86

Temp Lapse Rate as Daily Climate Sequence: log(NSE) = 0.81

Gridded Tmin and Tmax: log(NSE) = 0.80
Spatial patterns of precip (how much snow falls at high elevations)

Initialization
- Landsat TM
- MODIS
- Other remote sensing products, including SNOW

Dynamic assimilation of Snow Remote Sensing products

LAI

LIDAR

RHESSys-Model of coupled hydrologic, and carbon cycling based ecosystem

Basin Output

Streamflow (mm)

Date

Oct  May  Oct  May
Key Uncertainty – Scaling of Precipitation with Elevation

\[ \text{Daily } P_i = \text{base station precip} \times (k \times (\text{elev}_i - \text{elev}_b) + 1.0) \]

- \( i \) = any model unit
- \( k \) = scale factor

Derived elevation scaling factor
0.0007
Key source of uncertainty – spatially distributed precip: Calibrate precip scale factor based on predicted streamflow bias:

Estimated scale factor 0.0007!!!
Multi-scale heterogeneity in controlling processes – accounting for very fine-scale heterogeneity in snow processes?
Within and between 1st order watershed (1km-10km) substantial spatial variation in climate (T,P, controls on snow) can be challenging to resolve.

Co-spatial variation of these climate drivers with vegetation structure and function and geology at these length scales can lead to non linear responses to climate variability and change.
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