Water and Forests: Sensitive (and not so sensitive) interactions in changing climate

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University of California, Santa Barbara
What really are process-based models and why do we use them?

- Mechanistic representation of key interactions among climate, hydrology, plant and soil C and N

- Models are dependent largely on historic understanding of physiologic controls – but key point is that they –

- Account for non-linear and spatially varying responses related to shifts in the dominant controls – temperature, light, water, nutrients

**BALANCE:**

WATER, ENERGY, CARBON, NUTRIENTS
Regional Hydro-Ecologic Simulation System (RHESSys)
Vertical drainage
Lateral drainage
Carbon and Nitrogen cycling in RHESSys
Modeling the Urban landscape
Spatial Hierarchy

- Basin
- Hillslope (within basin) Drainage Organization
- Zone (within hillslope) Meteorology & Energy
- Patch (within zone) Soil & Litter
- Strata (vertical within patch) Vegetation
- overstory
- understory
Parameter Files
Library of parameters:
- Vegetation
- Soils
- Zone processes
- Land use

Time Series Files
Required:
- Temperature/Precipitation
  - Single station interpolation
  - Gridded climate data
Optional – many additional

Output (~100 store/flux variables)
- Daily, monthly, yearly
- BGC, Hydro
- Basin, Hillslope, Zone, Patch, Stratum
# RHESSys outputs

<table>
<thead>
<tr>
<th></th>
<th>Daily</th>
<th>Daily Growth</th>
<th>Monthly</th>
<th>Yearly</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basin</strong></td>
<td>Streamflow</td>
<td>GPSN</td>
<td>Streamflow</td>
<td>GPSN</td>
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<tr>
<td></td>
<td>Saturation Deficit</td>
<td>Plant/Soil Respiration</td>
<td>DOC/DON</td>
<td>Plant Respiration</td>
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<tr>
<td></td>
<td>Evap/Trans LAI</td>
<td>Plant/Litter/Soil C&amp;N Nitrification/Denitrif</td>
<td>LAI PSN ET</td>
<td>New Carbon</td>
</tr>
<tr>
<td></td>
<td>Snowpack</td>
<td>LAI</td>
<td>Vegetation N uptake</td>
<td>Denitrification</td>
</tr>
<tr>
<td><strong>Hillslope</strong></td>
<td>Saturation Deficit</td>
<td>Maintenance Resp</td>
<td>Streamflow</td>
<td>Nitrate to Stream</td>
</tr>
<tr>
<td></td>
<td>Total Stream Outflow</td>
<td>Plant/Litter/Soil C&amp;N</td>
<td>DOC/DON</td>
<td>Organic C&amp;N loss</td>
</tr>
<tr>
<td></td>
<td>LAI PSN Evap/Trans Groundwater</td>
<td>Mineralized N</td>
<td>LAI PSN ET</td>
<td>ET NPSN</td>
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<tr>
<td><strong>Zone</strong></td>
<td>Rainfall/Snowfall</td>
<td>LAI PSN</td>
<td>Soil Moisture</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>Evap/Trans</td>
<td>Net Nitrate Flux</td>
<td></td>
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<tr>
<td></td>
<td>VPD</td>
<td>PSN</td>
<td>ET LAI NPSN</td>
<td>N/A</td>
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<tr>
<td></td>
<td>Radiation</td>
<td>Subsurface flow</td>
<td>Vegetation N Uptake</td>
<td></td>
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<tr>
<td><strong>Patch</strong></td>
<td>Soil Moisture</td>
<td>LAI PSN</td>
<td>Soil Moisture</td>
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<td></td>
<td>Evap/Trans PSN</td>
<td>Plant/Soil Respiration</td>
<td>Net Nitrate Flux</td>
<td></td>
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<tr>
<td></td>
<td>Subsurface flow</td>
<td>Plant/Litter/Soil Carbon</td>
<td>ET LAI NPSN</td>
<td>ET NPSN MaxLAI</td>
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<tr>
<td><strong>Stratum</strong></td>
<td>LAI NPSN Radiation</td>
<td>Leaf/Root/Stem C</td>
<td>Soil Moisture</td>
<td>Organic C&amp;N loss</td>
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<tr>
<td></td>
<td>Rain/Snow Interception Conductance</td>
<td>Maint/Growth Resp</td>
<td>Net Nitrate Flux</td>
<td></td>
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<tr>
<td></td>
<td>LAI PSN Coarse Woody Debris C</td>
<td>Leaf Water Potential</td>
<td>ET LAI NPSN</td>
<td>Leaf Water Potential</td>
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<tr>
<td></td>
<td>Leaf Water Potential</td>
<td>NPSN</td>
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Figuring out where and when an increase or decrease in water supply and demand by forests will occur in snow-dominated regions:

A good job for a coupled model of eco-hydrologic processes

Two parts

1. Parameterizing and testing (quantifying uncertainty)

2. Using the model to look at forest water use responses
   - short-term (no change in forest structure)
   - medium term (change in productivity, disturbance events)
   - long term (dieback, species change responses)
Classic hydrology parameterization-evaluation
RHESSys hydrologic model performance – post calibration
Streamflow (1960-2000)

- NSE (monthly) 0.7
- NSE (log transformed daily) 0.75
- Annual total $R^2 = 0.95$

CC related flow metrics
- Timing of Center of Mass of Streamflow (Bias -3 day, $R^2=0.92$, $RMSE=5$)
- Minimum 7 day flow ($R^2=0.7$, $RMSE=6\text{mm}$)
Other sources for multi-criteria eco-hydrologic model evaluation

RHESSys estimates of annual NPP and tree ring increment for a high elevation mixed Douglas fir (PSME), Engelmann spruce (PIEN), and Ponderosa pine (PIPO) stand in the Santa Fe water supply catchment (Dugger et al., in prep)

SNOW:
Remote sensing snow depletion trajectories, snow pillows (Sierra Critical Zone Observatory)

TREE WATER USE, NPP:
Sap-flow and flux tower timing of summer water stress stomatal closure differences between riparian and upslope locations (Tague et al., ); topographic patterns (Sierra Critical Zone observatory)
(Son et al., in prep)

TREE DEATH:
Spatial gradients in drought related mortality
(Tague et al, in review)
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
McDowell et al. (2009) – 3 plots of Ponderosa pine in Bandelier National Park

- BAI measurements since 1990
- During 2000 drought, low elevation trees died, upper did not
- Within 10km, elevation range (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"
Allocation to and use of non-structural carbohydrate storage (NSC)
Two new parameters:
(NSC/NPP proportion of NPP allocation to NSC; minL/ABC)
RHESSys estimates capture cross-site differences in productivity

<table>
<thead>
<tr>
<th>Elev (m)</th>
<th>Precip scalar</th>
<th>Soil maximum saturated hydraulic conductivity (m/day)</th>
<th>Soil decay of saturated hydraulic conductivity with depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>2767</td>
<td>1.27</td>
<td>764</td>
</tr>
<tr>
<td>Mid</td>
<td>2308</td>
<td>1.03</td>
<td>1500</td>
</tr>
<tr>
<td>Low</td>
<td>2002</td>
<td>0.85</td>
<td>3667</td>
</tr>
</tbody>
</table>

NPP vs BAI correlations > 0.5 for all sites – and for all values of NSC parameters
Non-Structural carbohydrate storage falls near zero for low elevation site- consistent with mortality due to carbon starvation

Mortality risk – minimum NSC
(Tague, McDowell, Allen. *in review*)
Spatial patterns of snow – changes in % basin cover and depletion trajectories (comparison with remote sensing estimates?) at Big Thompson, CO 23-yr Data Set
How good do parameters/inputs have to be? Analysis of downscaling/upscaling temperature/precipitation data

50m gridded temperature PRISM data (Daly 2009)

Versus

Standard adiabatic lapse rates, Point station measurements

HJA
64 km² watershed in western Oregon
Uniform pseudo adiabatic lapse rate of 6.5°C/km

- Min and Max daily temperature lapse rates as climate input using data from two met stations (as demonstrated in Daly et al., 2009)
- Spatial grids of monthly tmax and tmin (PRISM) – to adjust daily met data
Slightly Improved long-term streamflow estimates

**Daily Rate**

Constant 0.71

Daily 0.83

Gridded 0.82
Different climate produced by downscaling/upscaling (models about within watershed air-temperature lapse rates) produces substantially different estimates of basin-averaged summer transpiration
Figuring out where and when an increase or decrease in water supply and demand by forests will occur in snow-dominated regions:

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Broader context of climate change in snow-dominated regions: Focus on mountainous Western US - Forests and Water?

What happens to water availability (supply) for and water use (demand) by forests in a warming climate?

How do changes in supply and demand impact forest productivity and sensitivity to disturbance (fire, disease, drought related dieback)?

Do these changes have implications for streamflow timing and magnitude?

Relevance for *Northwatch*:
large topographic-temperature moisture gradient (representing a diversity of climate conditions) – Water stress increasing issues in other Northern regions (boreal aspen drought response e.g Barr et al., 2007, GCB)
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 $C_i$ (concentration of carbon in leaves) which depends on $g_s$

Stomatal Conductance (Jarvis Model)

$$g_s = f(T_{max}, T_{min}, LWP, \text{atm C02, Radiation, VPD})$$

$$g_s \text{ _canopy} = g_s \times \text{LAI}$$

LWP (leaf water potential)

related to soil water availability

linked with distributed hydrologic model and it’s parameterization
Gross PSN \( f(\text{light, nutrient availability, conductance, leaf area}) \)

Respiration \( f(T, N \text{ and biomass}) \) varies with type and size of plant components

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

Potentially 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; suggests that carbon cycling (rather than structural or some other mechanism) can explain growth and equilibrium size of stands
Broader context of climate change in mountainous Western US?

Summer drought (both ecologically and hydrologically) is common

A: Warmer temperature (increased PET) DEMAND

B: With change in timing of inputs (with shifts from snow to rain and earlier melt), more summer drought stress SUPPLY

Net effect (assuming no change in vegetation – so short term) becomes:

IS A-B + or -

Tague et al., (2010) *Ecohydrology*
Study sites

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)

http://sagehen.ucnrs.org/Photos/scenics/index.html
Watershed scale ET highly variable: both temperature and water limited conditions – Also interesting departures from a general
Watershed scale ET highly variable: both temperature and water limited conditions – Also interesting departures from a general pattern in AET/PET or AET versus P.
Scatter in ET/P relationship is due to the timing of when that precipitation became recharge – and the synchronicity of the recharge with forest water demand.
Scatter in ET/P relationship is due to the timing of when that precipitation became recharge – and the synchronicity of the recharge with forest water demand and overall amount of precipitation.
At plot scale, similarly, scatter is significant.

Higher elevations: lower biomass

Much scatter for years when P is > 1000m – it is as great as difference in ET due to precipitation variation < 1000m

Scatter in ET/P relationship is due to the timing of when that precipitation became recharge.
Scatter in ET/P relationship is due to the timing of when that precipitation became recharge – and the synchronicity of the recharge with forest water demand

The timing of recharge – that relates a lot to the timing of snowmelt

Years where more rain falls as snow – shifts the timing of recharge to earlier in the year – SENSITIVE TO WARMING
So, with a warmer climate (+3°C) and no change in precipitation – we get increased demand (ET should stay the same or go down) – but also a shift in timing (ET should go up)

Note that the effect of timing occurs across all P, but is greater in wetter years, but also biggest increases occur in the wettest years
Mean watershed change is small (< 1% as increases balance decreases; although individual years show declines ~15%)

Left skewed distribution – for some patches, in some years quite large declines in ET (and NPP estimates), more but smaller increases
What is the role of lateral moisture redistribution? Sensitivity to non-local conditions (often ignored in larger scale analysis)

- Snowmelt
- Rooting Zone (vertical drainage)
- Transpiration
- Snowmelt
- Travel Times (lateral drainage)
- Atmospheric Drivers

Parameter Uncertainty

Water Stress

Note that the effect of timing occurs across all P, but is greater in wetter years, but also biggest increases occur in the wettest years.
Contribution of lateral redistribution of water

All else being equal, mean watershed ET when lateral redistribution is included is 33% higher than when watershed is run assuming no-lateral redistribution.
As we might expect – with lateral redistribution included = similar shape but more large declines AND increases in ET

![Change in ET with +3C](image)

Similar, slightly greater large declines in ET,
Including re-distribution increases spatial CV but also accentuates relationship with precipitation, particularly under warming scenarios – maximum spatial variance at intermediate wetness.

Similar, slightly greater large declines in ET,
Stomatal closure - Transpiration reduction due to water stress (daily/hourly)

Threshold related to magnitude (on/off)
- LWP stomatal closure wilting point

Decline in productivity due to drought or increases due to growing season length (seasonal)

Temperature versus water limited productivity

Drought stress mortality (annual-multi year)

Tipping point type threshold
Not enough non-structural carbohydrate storage (McDowell et al., 2011)

Thresholds in Eco-hydrology (hierarchy)
How does a warming climate influence the likelihood of crossing these thresholds?

How do soil/rooting and drainage characteristics impact this relationship?

Decline in Transpiration

Temperature vs. water limited productivity

Drought stress mortality
Total Watershed Scale Transpiration

With warming:
some years - T limited; Others - strongly water-limited.

Cause of this threshold:
some relationship with P – but more with the timing of effective water input
Largest declines occur in lower snow years with early melt and large differences in SWE with warming.

Threshold of when increased T leads to declines in transpiration - depends on timing of water inputs (as much as magnitude)
Drought stress mortality potential is much more sensitive to temperature and demonstrates a less clear relationship with precipitation (multi-year process).
Are there warming thresholds that impact the 50-year mean response?

Soil Parameter Effect:
- More important for water use
- Less critical for mortality thresholds
Effect of *soil/rooting storage uncertainty/variability* is greater than CC effect for NPP and ET but reverses for mortality estimates.
What about multi-year drought timing?
Vegetation growth (and water stress mortality) risk are multi-year time scale phenomena and as such are influenced by timing of “wet” (good) and “dry” (stress) years

SCENARIO: Same total precipitation: 10 years (5 wettest, 5 driest from 50 year record) ; 5 wet, followed by 5 dry, 5 dry followed by 5 wet, alternating
Reduced capacity following dry period (leaf drop, low NPP) reduces capacity in subsequent wet years (by a lot!) leading to lower mean NPP (almost ½).
Vegetation growth (and water stress mortality) risk are multi-year time scale phenomena and as such are influenced by timing of “wet” (good) and “dry” (stress) years.

For drier, (mid and low elevation sites), mortality risk is greater for BOTH, wet to dry, and dry-wet, relative to alternating.

Similar to Westerling et al () who show fire risk greatest with wet years following dry years.
Classifications based on mean annual supply vs. demand (Budyko Curve) give a general sense of shifts between temperature and water limited forests.

Patch-watershed vegetation scale water use in SDS often shift between the two from year to year.

Year to year variation and CC can alter the temporal synchronicity of recharge, leading to departures from annual curves.

Greatest sensitivity to timing shifts with warming occurs in intermediately wet patches/years but both +-. Basin scale responses can balance increases (due to longer growing season) with declines due to shifts in timing.
Classifications based on mean annual supply vs. demand (Budyko Curve) give a general sense of shifts between temperature and water limited forests.

Patch-watershed vegetation scale water use in SDS often shift between the two from year to year.

Year to year variation and CC can alter the temporal synchronicity of recharge, leading to departures from annual curves.

Greatest sensitivity to timing shifts with warming occurs in intermediately wet patches/years but both +-. Shifts in the timing of recharge tend to lower ET in intermediately wetter years.
- Lateral redistribution overall enhances forest water use

- Surprisingly locations with lateral subsidy can sometimes show greater declines in forest water use (relative to those that do not)

- As drought increases spatial variation in ET reduces – only in +3C warming scenario for Sagehen

- Multi-year timing also matters – with persistent drought (and particularly drought following wet years) increases drought stress mortality risk
Conceptual Model

Climate inputs

Static vegetation

Dynamic vegetation

Disturbance

Carbon flux

Water flux
Impact of streamflow and NPP dynamics

The dynamic vegetation model improved streamflow predictions during drought years, shifting the mean annual streamflow percent error from 20% to 10%.
Scenario Results:
Annual streamflow declines

Percent Change in Annual Streamflow

Warming Effects

7% decrease on average

15% decrease on average

27% decrease on average
Forest NPP responses to water availability alter water demand (at short and long time scales) to more closely match that water availability – “Eco-optimality” for water limited environments.

This tends to buffer streamflow responses.

However, responses to multi-year climate forcing patterns – and particularly increases in extremes – can reduce the efficiency of long-term vegetation water use – and are most likely to lead to drought-related disturbances.

Which exacerbate streamflow response.
Tague and Dugger (2010) Ecohydrology and Climate Change in the Mountains of the Western USA – A Review of Research and Opportunities. Geography Compass 4(11): 1648-1663
Modeling the Urban landscape
Calibrated soil drainage parameters

\[ K_z = K_0 e^{-z/m} \]

- \( K_0 \): Surface litter (O horizon)
- \( K_0 \): Topsoil (A horizon)
- \( K_0 \): Leaching zone (E horizon)
- \( K_0 \): Subsoil (B horizon)
- \( K_0 \): Parent material (C horizon)
- \( K_0 \): Bedrock

- \( \psi \): Air entry
- Pore size index
- Macropore
- Root Depth
- Deeper Groundwater
- \( gw_1 \)
- \( gw_2 \)