# Climate Change Effects on Vegetation Water and Carbon Cycling and Species Composition in Yosemite National Park


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## Abstract

As part of the **Western Mountain Initiative**, this research explored potential climate change effects on vegetation productivity and drought stress in the Upper Merced River Basin, Yosemite National Park, Sierra Nevada, California. The RHESSys model was employed to analyze responses to simulated climate warming scenarios. Historical climate data for water years 1950 to 2000 was used as a baseline, and this data was forced with incremental 2ºC temperature increases (to a maximum of 8ºC), using both a baseline $CO_2$ of 322 ppm and an elevated $CO_2$ of 600 ppm. The responses of vegetation to modeled climate forcings were examined at the basin scale, and at mid and high elevations by examining leaf area index, net primary productivity, and evapotranspiration (ET). The results indicated that vegetation at higher elevations increases in productivity and growth with warming temperatures, but only up until a temperature 'tipping point' of 6ºC. After this point, vegetation becomes drought-stressed as the cost of respiration becomes higher than the gross photosynthetic capacity of the plant. Lower elevations are more water-limited and therefore immediately demonstrated a decrease in growth and productivity with warming temperatures of 2ºC. The response of basin vegetation to temperature was complicated by the interaction of $CO_2$, which creates a higher equilibrium of productivity for vegetation as plants become more water-efficient. However, temperature 'tipping points' were present even with higher $CO_2$. This research suggests potential decreases in vegetation productivity in the basin as plants become more drought-stressed, and these changes could impact net carbon storage in this ecosystem. Results also suggest that species composition of this conifer-dominated basin may change in response to increasing drought-stress. This was shown by comparing model estimates with Stephenson's (1998)[1] model of the relationship between actual ET and deficit as an indicator of species type for North American vegetation.


## Site Description

The study site was the Upper Merced River Basin (465 $km^2$) in Yosemite National Park, located in the Sierra Nevada, California.

Elevation: Lowest point at Happy Isles Bridge stream gage (1220 m); Highest point at Mt. Lyell (3997 m).

Snow-melt dominated basin, with snowmelt from April to June[2].

Annual average daily air temperatures from 1926 to 2003 are a minimum of 3.9ºC and a maximum of 20.2ºC (NCDC).

Vegetation is coniferous forest covering 68.5% of the basin consisting of pine, hemlock, Douglas fir, and juniper.


Map of study site (Christensen *et al*., 2007)

Yosemite Valley (K. Heyn, April 2008)

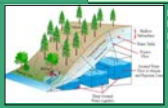
## RHESSys Model

The Regional Hydro-Ecologic Simulation System (RHESSys) model used for this analysis is a GIS based, terrestrial eco-hydrologic modeling framework designed to simulate carbon, water, and nutrient fluxes at the watershed scale (Tague and Band, 2004).

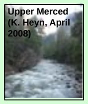
As with all hydrologic models, calibration is needed to define flow rates through critical zone soil and permeable bedrock layers. In RHESSys, we typically calibrate two shallow subsurface flow parameters:

*m* - decay of saturated hydraulic conductivity with depth

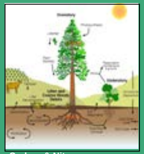
*K* - saturated hydraulic conductivity at the surface



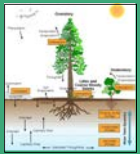
Lateral hydrological processing in RHESSys



Upper Merced (K. Heyn, April 2008)



Carbon & Nitrogen processing in RHESSys



Vertical hydrological processing in RHESSys

To support the use of this model, observed daily streamflow and observed annual basin snow cover were compared with RHESSys model estimates. Figures 1 and 2 demonstrate the level of model accuracy and validate the usefulness of applying this model to simulate eco-hydrologic patterns in the Upper Merced Basin.

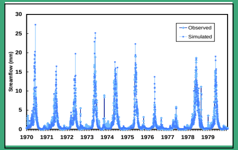



Figure 1: Daily simulated vs. observed streamflow (6% error) (Christensen *et al*., 2008)

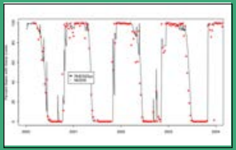


Figure 2: Annual simulated vs. observed basin snow cover

## Climate Change Scenarios

Scenarios were developed by applying uniform temperature increases to historical Yosemite climate data. Data from water years (October – September) 1950 to 2000 were used to simulate *fifty years of climate forcings.* We also examined effects of baseline (322 ppm) and elevated $CO_2$ (600 ppm). While we acknowledge that actual warming scenarios are likely to be more complex, scenarios comprising a uniform temperature increase allow us to focus on the impact of warming alone, rather than changes in timing and magnitude of precipitation inputs.

| Scenario | Temp increase (ºC) | CO2 concentration (ppm) |
|---|---|---|
| T | Baseline T | Baseline CO2 (322 ppm) |
| T2 | 2+ | Baseline CO2 (322 ppm) |
| T4 | 4+ | Baseline CO2 (322 ppm) |
| T6 | 6+ | Baseline CO2 (322 ppm) |
| T8 | 8+ | Baseline CO2 (322 ppm) |
| TC2 | Baseline T | Elevated CO2 (600 ppm) |
| T2C2 | 2+ | Elevated CO2 (600 ppm) |
| T4C2 | 4+ | Elevated CO2 (600 ppm) |
| T6C2 | 6+ | Elevated CO2 (600 ppm) |
| T8C2 | 8+ | Elevated CO2 (600 ppm) |

**Table 1: Climate scenarios used in RHESSys modeling**

## Seasonal Eco-hydrologic Changes

**Eco-hydrology:**
Model estimates show a decline in seasonal snowpacks and a shift in the timing of melt with warming (Figure 3). Evapotranspiration (ET) increases during the spring under warming scenarios (Figure 4). During the summer, ET declines and reflects an earlier summer drought driven "ecological recession" that can be linked with the shift in timing of water inputs from snowmelt.

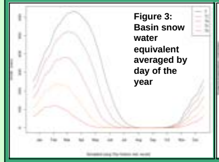


**Figure 3: Basin snow water equivalent averaged by day of the year**

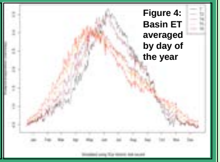


**Figure 4: Basin ET averaged by day of the year**

**Net primary productivity (NPP):**
Modeled NPP follows ET with increases during the spring and decreases during the summer as available soil moisture is depleted sooner under warmer scenarios (Figure 5). Declines in summer NPP also reflect increasing respiration rates with higher air temperatures. Model results from the elevated $CO_2$ scenario show a similar pattern of responses (Figure 6); however, overall NPP rates are higher, reflecting an increase in biomass due to an increase in plant water-use efficiency.

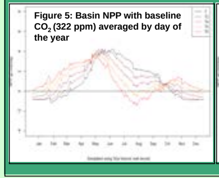


**Figure 5: Basin NPP with baseline $CO_2$ (322 ppm) averaged by day of the year**

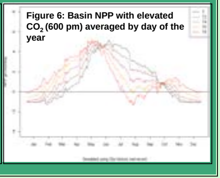


**Figure 6: Basin NPP with elevated $CO_2$ (600 pm) averaged by day of the year**

**Merced River, (K. Heyn, December 2007)**


**References:**
1. Stephenson, NL. 1998. Actual evapotranspiration and deficit: Biologically meaningful correlates of vegetation distribution across spatial scales. *Journal of Biogeography* 25: 855-870.
2. Christensen, L, Tague, CL, and Baron, JS. 2008. Spatial patterns of simulated transpiration response to climate variability in a snow dominated mountain ecosystem. *Hydrological Processes.*
3. Tague, CL, and Band, LE. 2004. Regional hydro-ecologic simulation system: An object-oriented approach to spatially distributed modeling of carbon, water and nutrient cycling. *Earth Interactions* 8: 1-42.


## Spatial Differences in Vegetation Response

Model estimates of mean basin biomass, illustrated as leaf area index (LAI), show negligible changes with warming. Two spatial "patches" in the basin were modeled to understand both smaller-scale vegetation responses and elevational differences to climate changes: a mid elevation patch (2453 m) and a high elevation patch (2634 m). Prior model estimates of ET suggest that, historically, mid elevation patches are water-limited while high elevation patches are temperature-limited (Christensen *et al*., 2008). RHESSys modeled results for this study indicate that the mid elevation patch biomass (LAI) gradually decreases with warming in response to decreasing water availability (Figure 7). In contrast, the high elevation patch vegetation responds positively to warming temperatures (Figure 8) up until a temperature **'tipping point'** of T6 (6ºC), above which point LAI drops severely, indicating possible plant **drought stress**. The effect of $CO_2$ on both patches is a higher equilibrium of biomass production through increased plant water-use efficiency, but temperature thresholds at which productivity declines are still present with elevated $CO_2$.

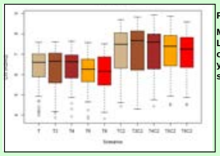


**Figure 7: Mid elevation LAI averaged over fifty years simulation**

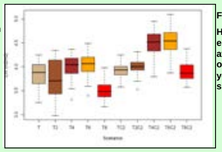


**Figure 8: High elevation LAI averaged over fifty years simulation**

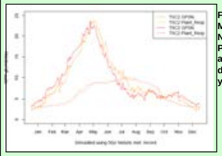


**Figure 9: Mid elevation NPP (GPSN – Plant_Resp) averaged by day of the year**

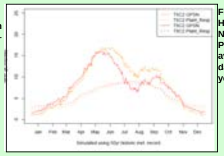


**Figure 10: High elevation NPP (GPSN-Plant_Resp) averaged by day of the year**

The spatial differences in plant responses can be explained by examining GPSN (gross photosynthesis) and respiration responses to the two highest temperature increases with elevated $CO_2$ (T6C2, T8C2). For both the mid elevation and high elevation patches (Figure 9 & 10), overall NPP declines with additional warming, and the decline is associated with lower late summer GPSN rather than increased respiration. However for the higher patch, GPSN is lower than at mid elevation, and the relative decrease in GPSN is greater, resulting in a greater reduction in NPP, and ultimately LAI.

## Potential Species Composition Changes

Model estimates of NPP, LAI and ET under warming suggest plant drought stress is likely to increase in response to warming. To examine potential changes to species composition in the basin due to drought stress, we use Stephenson's (1998) model associating species type with the relationship between ET and climatic water deficit (Figure 11). Figures 12 & 13 show RHESSys estimates of this relationship averaged across the Upper Merced Basin for both baseline and elevated $CO_2$. The trends indicate a notable shift toward greater deficit with warming climate. Comparing this with Stephenson's model may suggest a change in species from conifers to grassland or shrub. The mid elevation patch (Figures 14 & 15) shows an already greater deficit than the basin average (due to its water limitation), and this deficit increases with warming, indicating a greater sensitivity at this elevation. It therefore possible that mid elevation, water-limited patches will experience a species shift in response to growing deficit. The high elevation patch (Figures 16 & 17) starts out with a much lower deficit compared to either the basin or the mid elevation patch. The ET of this patch initially increases with warming, as plants respond positively to warmer temperatures. However, the temperature 'tipping point' at T6/T6C2 results in a drop in ET/productivity, and after this point the patch experiences increases in deficit and subsequent drought stress. Significant warming above 6ºC may therefore change the species composition of higher, more temperature-limited vegetation.

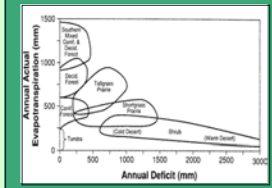



Figure 11: Stephenson's North American plant formations in response to annual deficit and annual ET (1998)

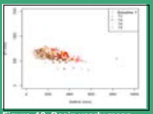


Figure 12: Basin yearly mean actual ET vs. deficit with baseline $CO_2$ over 50 yrs

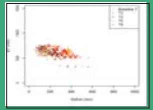


Figure 13: Basin yearly mean actual ET vs. deficit with elevated $CO_2$ over 50 yrs

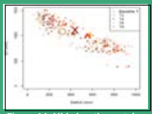


Figure 14: Mid elevation patch yearly mean actual ET vs. deficit with baseline $CO_2$ over 50 yrs

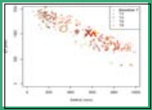


Figure 15: Mid elevation patch yearly mean actual ET vs. deficit with elevated $CO_2$ over 50 yrs

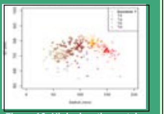


Figure 16: High elevation patch yearly mean actual ET vs. deficit with baseline $CO_2$ over 50 yrs

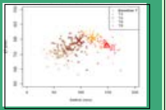


Figure 17: High elevation patch yearly mean actual ET vs. deficit with elevated $CO_2$ over 50 yrs

## Conclusion

Temperature warming in snow-melt dominated mountain ecosystems is likely to shift the magnitude and timing of summer water stress (primarily due to a shift in the timing of water inputs relative to energy inputs).

Productivity (NPP) and ultimately vegetation biomass (LAI) may increase in some locations with warming. However, RHESSys estimates suggest that for the Upper Merced Basin, even high elevations are likely to experience drought stress at the upper ranges of temperature increases predicted by current GCMs. Lower elevations are likely to see significant changes in vegetation productivity even with moderate warming.

Higher $CO_2$ does increase water-use efficiency, and model estimates suggest higher productivity and biomass, but there is still a drought stress response.

For mid elevations, increased drought stress may be great enough to lead to a shift to more drought-stressed vegetation and ecosystems in the basin.

Potential drought stress and changes to species composition suggest management implications for Yosemite Park Managers in terms of wildfire and natural resource management, and further research on vegetation responses to climate warming would be useful for future management planning.