Supporting Information

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Strategy. We used a regression-based space-for-time strategy to infer the possible effect of climate change on montane ET. Our analysis is subject to the weaknesses, shortcomings, and caveats inherent in the space-for-time approach (e.g., ref. 1). Our choice of strategy reflects the current state of understanding and modeling of Sierra Nevada evapotranspiration (ET), which is at the point where additional field observations are needed to guide the development of process-based models. Researchers are only beginning to understand the seasonality and phenology of montane plant activity, the effects of winter cold and summer moisture stress on montane plant activity, the relationship between elevation (climate) and ET, and the rates that ecosystem properties can change with climate variability (2–5). Process-based models that reliably simulate all these patterns are still being developed and tested, and field experiments to address these issues have not been attempted in the Sierra Nevada.

Ground-Based Measurements (Fig. 1A). Our ground-based measurements were described in detail previously (5, 6). We installed four eddy-covariance towers along a west to east transect at ~800-m altitude intervals in and around the upper Kings River basin. The sites were all on soil developed from granite, and had vegetation that was typical for the elevation and that had not been disturbed recently. The measurements were made from meteorological towers that extended 5–10 m above the trees. The half-hour eddy covariance fluxes of CO₂ (net ecosystem CO₂ exchange, NEE) and water vapor (ET) were calculated from observations of wind made with a sonic anemometer and CO₂ and water-vapor density made with a closed-path infraRed gas analyzer. Air temperature and other meteorological conditions were measured and averaged at half-hour intervals. Observations from six additional sites along a climate gradient in Southern California were used to establish a relationship between the Normalized Difference Vegetation Index (NDVI) and annual ET (Fig. S1).

Water and Cold Limitation in Local (Tower-Based) Observations (Fig. 2A). We used the seasonal patterns of gross ecosystem exchange (GEE; calculated by subtracting nocturnal whole-ecosystem respiration from NEE) to quantify the limitations imposed by summer moisture stress and winter cold on gross primary production (GPP; calculated by annually integrating GEE). We divided each year into three elevation-dependent intervals based on the half-hourly meteorological conditions and fluxes: (i) Winter: when soil moisture was abundant and temperatures were comparatively cold (for example, 10/27/08–4/24/09 at 2,015 m); (ii) Peak growing season: in spring and early summer, when soil moisture was abundant and temperatures were warm (for example, 4/24/09–8/22/09 at 2,015 m); and (iii) Late summer: when soil moisture was depleted and temperatures were warm (for example, 8/22/09–10/26/09 at 2,015 m).

We used the GEE observations during the peak growing season for each site and year to determine a best-fit rectangular hyperbola against light for periods that were neither cold- nor water-limited. We then ran the entire time series of observed light for that site and year through the corresponding peak growing season rectangular hyperbola to calculate a time series of GEE that would be expected in the absence of cold or moisture stress limitation (the unlimited GEE). We then summed unlimited GEE and also the observed GEE for the three intervals. Finally, we calculated the fractional reduction in GEE for each interval as the observed GEE divided by the unlimited GEE. We attributed the fractional GEE reduction in winter to cold limitation and the GEE reduction in late summer to water limitation.

Spatially Gridded Precipitation, ET, and P minus ET (Fig. 1). We extrapolated precipitation (P), ET, and P minus ET (P–ET) to the entire upper Kings River basin as described in ref. 5. The upper Kings River basin was demarcated by the US Geologic Survey 8 Digit Watershed Boundary Dataset (http://datagateway.nrcs.usda.gov; downloaded March 2013). Elevation was taken from the Shuttle Radar Topography Mission (SRTM) Final dataset (http://earthexplorer.usgs.gov; downloaded March 2013).

Gridded P was obtained for 1981–2010 at 30-arcsec (0.0083°) spatial resolution (7) (Parameter-elevation Regressions on Independent Slopes Model, PRISM, Climate Group, Oregon State University, http://prism.oregonstate.edu; downloaded March 2013). Gridded ET was calculated from NDVI measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite and averaged for snow- and cloud-free periods. MODIS NDVI for the Kings basin was obtained from the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (http://daac.ornl.gov/MODIS; MYD13Q1 Collection 5; downloaded March 2013) in geographic coordinates at 0.002083° resolution. NDVI observations were filtered to include only the highest quality data (pixel reliability = 0) for day of year (DOY) 0–201 and DOY 265–365, and a pixel reliability of 0 or 1 for DOY 201–265. NDVI data were then averaged for each water year, and ET was calculated using a regression between annual average NDVI and annual ET across 46 site years in 10 diverse California ecosystems, including the 4 in and around the Kings basin (Fig. S1) [ET(mm yr⁻¹) = 10.3247 × exp(2.8599 × NDVI); R² = 0.914]. Gridded P–ET was then calculated at 0.002083° resolution by subtraction. Finally, gridded P, ET, and P–ET were sorted into 100-m elevation bins and averaged.

Water and Cold Limitation in Basin-Wide (Remote-Sensing-Based) Observations (Fig. 2B). We analyzed the current spatial relationships between annual ET calculated from NDVI (Fig. S2) and the corresponding 30-yr climate normals to better understand the limits on ET (Fig. S4). This approach parallels that used by Nemani et al. (8) to partition the climate controls on plant primary production globally, and makes use of simple, universally accepted relationships between climate and primary production (9) and primary production and ET (10). We created a coregistered data stack of elevation, ET, and 30-yr normal maximum air T (Tmax) and P at 0.002083° resolution. We then analyzed the relationship between ET and Tmax for all pixels that were not P-limited (pixels with a P above 900 mm yr⁻¹) (Fig. S4B), and between ET and P for all pixels that were not T-limited (pixels with a Tmax above 12 °C) (Fig. S4A). We then fit separate sigmoidal regressions between ET and Tmax for the non-P-limited dataset [ET= 792.7/(1 + exp(–(Tmax – 9.36)/2.50))]; adjusted R² 0.697; n = 62,927], and ET and P for the non–T-limited dataset [ET= 677.7/(1 + exp(–(P – 284.2)/242.0)); adjusted R² 0.150; n = 45,558].

We used the resulting sigmoidal equations to separately calculate the ETs that would be expected for each pixel based on local P and Tmax climatology. We then estimated the ET for each pixel as the minimum ET from the two sigmoidal equations (Fig. S5) and compared the resulting values with those from the original NDVI approach (i.e., Fig. S5 vs. Fig. S2) [NDVI based ET (mm) = modeled ET (mm) × 1.037–13.0; adjusted R² 0.665;
We calculated the fraction of maximum ET that was realized for each pixel by subtracting the fractional water and cold limitation from 1. Finally, we binned all of the pixels at 100-m elevation intervals and averaged the fractional limitation imposed by P or $T_{\text{max}}$

We compared the mean NDVI as a function of elevation between warmer, more-xeric, southern-exposed slopes and cooler, more-mesic, northern-exposed slopes. We calculated the mean NDVI for each pixel using the same pixel reliability criteria used for the ET calculation. We calculated the slope and aspect of each pixel from the digital elevation model, and then excluded relatively flat locations with a slope less than 15°. We sorted the remaining pixels into locations facing south-southwest (aspect from 135° to 270°, where 360° is due north) and those facing north-northwest (315°–90°). Finally, we sorted the mean NDVIs into 100-m elevation intervals and averaged the NDVI within each bin (Fig. S6).

Climate Projections (Figs. 3 and 4A). We examined output from the Community Climate System Model Version 4 (CCSM-4) for the representative concentration pathways (RCP) and historic experiments in the Coupled Model Intercomparison Project Phase 5 (CMIP-5). We downloaded monthly near-surface air temperature, air temperature, geopotential height, and P for each of the five or six ensemble runs (www.earthsystemgrid.org/dataset/ucar.cgd.csm4.cmp5.output.html; downloaded May through July 2012). We then extracted the data for a 10-by-10 grid-cell region centered over California, and averaged the RCP run temperatures across 2085–2100, and the historic run temperatures across 1950–2005. We then output the projections for three grid cells in California’s Central Valley that were immediately upwind (west) of our study region (cells centered on 36.2827° N, 120° W; 37.2251° N, 121.25° W; 38.1675° N, 121.25° W). Finally, we averaged across the ensemble runs (Fig. S7), and interpolated the altitude-specific (11) 2085–2100 increase in air temperature over the historical mean for each 0.002083° resolution pixel in the Kings River basin. We also examined the RCP P output for grid cells in the Sierra Nevada. We combined the RCP temperature projections for each pixel in the Kings River basin with the T- and P-based sigmoidal regressions (i.e., Fig. S4) to estimate the effect of climate change on ET. We added the RCP-associated warming to the 1981–2010 Parameter-elevation Regressions on Independent Slopes Model (PRISM) temperature maximum normal for each pixel, and calculated the ET that would be expected as the minimum of the two sigmoidal regressions. We also calculated the P–ET for each pixel based on the 1981–2010 precipitation, and also assuming a 5% mean precipitation reduction. Finally, we binned the resulting ETs at 100-m elevation intervals and averaged, and also averaged across all pixels in the watershed.

We justify the direct extrapolation of upper-air temperatures over central California to near-surface temperature in the Kings River basin based on an examination of the relationship between the air temperatures measured at surface stations in the Sierra Nevada and the simultaneous air temperatures measured by radiosonde in coastal California. We compared the air temperature measured by radiosonde at the Vandenberg Air Force Base interpolated to 2050-m elevation with the simultaneous air temperature measured at the top of the 2015-m tower from September 2008 to July 2009 (Fig. S8). Vandenberg Air Force Base is ~260 km southwest of the tower site. The radiosonde observations were obtained from the University of Wyoming Atmospheric Soundings database (http://weather.uwyo.edu/upperair/sounding.html; downloaded July 2009).

We further justified our approach by examining the interannual 850-mb summer (June, July, and August) temperature anomalies reported for Marine Corps Air Station Miramar in the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC-B) dataset with the temperature anomalies reported for surface stations across the Sierra region by the California Climate Tracker website (Fig. S9). Miramar Air Station is 300–800 km south of the Sierra Nevada. The RATPAC-B dataset was obtained from the National Climate Data Center (www.ncdc.noaa.gov/oa/climate/ratpac/; downloaded August 2009). The California Climate Tracker dataset was obtained from the Western Regional Climate Center (www.wrcc.dri.edu/monitor/cal-mon/; downloaded August 2009).

Comparison Across River Basins (Fig. 4B). We compared the water balance for 11 large river basins draining the western slope of the Sierra Nevada with mean basin temperature. The historical monthly full natural flow was downloaded for each river basin from the California Data Exchange Center (http://cdec.water.ca.gov/; downloaded March 2013), and the flow summed annually and averaged for 1981–2010. The river basins were demarcated by the US Geological Survey 8-Digit Watershed Boundary Dataset (http://adata.gateway.nrcs.usda.gov/; downloaded March 2013). The location of the relevant long-term gauging station was determined for each basin, and the relevant eight digit subbasins were merged, such that a single polygon was created for each basin that corresponded to the watershed above the gauge. The river basin boundaries were then combined with the PRISM 1981–2010 $T_{\text{max}}$ and P normals and the SRTM elevation to calculate basin-wide means. Finally, the observed riverflow ($Q$) was normalized by basin area and subtracted from P to estimate the basin-average ET, which was then compared with the mean basin elevation and $T_{\text{max}}$. We also compared the 1981–2010 mean $Q - P$ for each basin with the corresponding NDVI-based annual ET for 2003–2012 (Fig. S3).

Fig. S1.  Annual total ET (mm yr\(^{-1}\)) across 10 sites and 46 site years as a function of annual mean NDVI (dimensionless). Figure is updated version of figure 2b from ref. 5. Ecosystem types are indicated by symbols and the water year of measurement is indicated by color. The year 2007 was much drier than normal and 2010 and 2011 were wetter than normal. The best-fit regression for all years was ET = 10.3247 \times \exp(2.8599 \times \text{NDVI}); adj \ R^2 = 0.914.

Fig. S2.  Relationship between elevation (meters above sea level) and ET (mm yr\(^{-1}\); 2003–2012 average) determined from MODIS NDVI for all pixels in the upper Kings River basin at 0.002083° resolution.

Fig. S3.  Relationship between elevation (meters above sea level) and ET (mm yr\(^{-1}\); 2003–2012 average) determined from MODIS NDVI for all pixels in the upper Kings River basin at 0.002083° resolution.
Fig. S3. Relationship between basin-average $P - Q$ and basin average NDVI-based ET for 11 major river basins on the western slope of the Sierra Nevada. $P - Q$ was calculated as the 1981–2010 mean $P$ for the basin based on the PRISM 30-y normal minus the corresponding annual mean full natural river flow for 1981–2010 divided by the area of the basin. NDVI-based ET is the mean annual NDVI for 2003–2012 calculated by averaging the results of the NDVI-base regression. The best-fit line is NDVI ET (mm yr$^{-1}$) = $-117 + 1.25$ ($R^2 = 0.75$), and the regression does not differ significantly from the 1:1 line.
Fig. S4. (A) Relationship between 30-y normal maximum air T ($T_{\text{max}}$; 1981–2010 normals from PRISM) and annual ET determined from MODIS NDVI for all pixels in the upper Kings River basin with a $P$ above 900 mm yr$^{-1}$ (i.e., pixels that are not considered water-limited). (B) Relationship between 30-y normal $P$ ($P$; 1971–2000 normals from PRISM) and annual ET determined from MODIS NDVI for all pixels in the upper Kings River basin with a $T_{\text{max}}$ above 12 °C (i.e., pixels that are not considered cold-limited). The sigmoidal regression between ET and $T_{\text{max}}$ for the non-$P$-limited dataset was $[ET = 792.6561/(1 + exp(\frac{T_{\text{max}} - 9.3567}{2.5029}))];$ adjusted $R^2 0.697$. The sigmoidal regression between ET and $P$ for the non-$T$-limited dataset was $[ET = 699.4783/(1 + exp(-\frac{P - 535.8093}{112.1342})] ;$ adjusted $R^2 0.194$.

Fig. S5. Relationship between elevation (meters above sea level) and ET predicted from the combined regressions in Fig. S4. The sigmoidal equations in Fig. S4 were used to separately calculate the ETs that would be expected for each pixel based on the local PRISM-based $P$ and $T_{\text{max}}$ climatology, and the predicted ET for each pixel determined as the minimum of the two values. A pixel-by-pixel comparison of the MODIS-based ET estimate (Fig. S2) and the regression-based estimate (Fig. S5) was $[\text{NDVI based ET (mm)} = \text{modeled ET (mm)} \times 1.033 - 9.9770; \text{adjusted } R^2 0.690]$. 

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Fig. S6. Relationship between mean NDVI (2003–2012 calculated using the same quality flags used for the NDVI-based ET calculation) and local aspect at 100-m elevation intervals for the upper Kings River basin. South-southwest pixels are those with a slope of at least 15° and an aspect from 135° to 270°, where 360° is north. North-northwest pixels are those with a slope of at least 15° and an aspect from 315° to 90°.

Fig. S7. Relationship between elevation (meters above sea level) and projected air warming based on output from the CCSM-4 prepared for the CMIP-5. Lines connect points that show the mean warming projected for 2085–2100 relative to the historical temperature modeled for 1950–2005 based on four RCP. Projections were averaged across five or six CCSM-4 ensemble runs and for three grid cells over California’s central valley and immediately upwind (west) of the Kings River basin.
Fig. S8. Time series from September 2008 to July 2009 of air temperature measured at the top of the 2,015-m tower (at an absolute elevation of ∼2,050 m) and air temperature simultaneously measured above Vandenberg Air Force Base using radiosondes for operational meteorological forecasting. Each Vandenberg sounding was interpolated linearly to an altitude of 2,050 m. Vandenberg Air Force Base is ∼260 km southwest of the 2015-m tower. The radiosonde observations are at 12- or 24-h intervals, and the tower data at 30-min intervals.

Fig. S9. Time series of mean summer (June, July, and August) air temperature anomaly based on surface meteorological observations across the Sierra Nevada (solid line connecting means values) and the 850-mB radiosonde temperatures reported for Marine Corps Air Station Miramar (dashed line connecting means). Miramar Air station is 300–800 km south of the Sierra Nevada. The surface anomaly observations were provided by the California Climate Tracker dataset from the Western Regional Climate Center. The Miramar radiosonde observations were taken from the RATPAC-B dataset.