The following supplement accompanies the article

Climate impacts on regional ecosystem services in the United States from CMIP3-based multimodel comparisons

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Supplement. The Supplement contains more detailed information on the TEM-Hydro model itself, the downscaling and bias-correction techniques, and the experimental design. Additional tables include a description of the TEM-Hydro calibration sites and results from the A1B experiment.

Methods

Model description

The Terrestrial Ecosystems Model version Hydro (TEM-Hydro) (Felzer et al. 2009, 2011) consists of multiple pools for vegetation carbon and nitrogen and a single pool for soil organic carbon and nitrogen, as well as a pool for inorganic nitrogen. The vegetation pools include leaves, active and inactive stem tissues (e.g. sapwood and heartwood), fine roots, and a labile pool for storage. Fluxes into and out of the pools include photosynthesis, nitrogen uptake, respiration, litterfall, and allocation. Allocation from the labile pool to the structural pools is determined from a nutrient optimization calculation based on resources available to the plant. Each compartment, with the exception of the labile pool, has a plant functional type (PFT)-dependent C:N ratio. The hydrology is based on a simple 1-layer bucket model (Vorosmarty et al. 1989), employing the Shuttleworth & Wallace (1985) approach to determine evapotranspiration (ET). The stomatal conductance, used to calculate the transpiration, is based on the Ball et al. (1987) approach. Felzer et al. (2009, 2011) provide a complete description of the model. Inputs into the model (see Fig. 2 in the main text) include monthly climate (surface air temperature, precipitation, fractional cloud cover [used to derive photosynthetically active radiation, PAR], vapor pressure, diurnal temperature range); annual atmospheric CO_2; monthly surface ozone; and static datasets including mean wind speed, vegetation and land use, soil texture, and elevation (Felzer et al. 2004).

Since warming will result in higher respiration and decomposition rates, it is important to understand how we have modeled these temperature dependencies. Maintenance respiration is based on the LaRS temperature function (Hanson et al. 2004), while heterotrophic respiration is based on Lloyd & Taylor (1994). Both approaches involve a variable Q10 value that is consistent with a slower increase in respiration at higher temperatures. Maintenance respiration acclimates to increasing temperature by occurring at a reference rate for each grid cell based on its 'optimum temperature.' We do not employ this acclimation to the function for heterotrophic respiration, which occurs at a reference rate at a temperature that is fixed across grid cells.

We recently revised the model (TEM-Hydro2), including improved land use approaches and a reduced-form open nitrogen cycle (Felzer 2012). This study uses the version of TEM-Hydro from Felzer et al. (2011) but adds some of the improved treatment of crops and urban areas. Since there is no disturbance in these experiments, the relevant features are controlled by crop harvesting and management. Crop products go into the 1 yr product pool. Our crop parameterizations are based on maize. Seeds are removed during harvest when the growing degree-days (GDD) with a base temperature of 9°C surpasses a threshold of 1500°C-days (Neild & Newman 1990), and the remaining carbon and nitrogen are returned to the soil organic pools as stubble. Based on calibration to measured maize yields, carbon and nitrogen from the labile pool are allocated only to the seed pool during the month when GDD surpasses this threshold, and any extra labile carbon is returned to the seed pool at the end of the growing season. Harvesting occurs in October if the GDD threshold has not been surpassed. We apply 15 g N m^{-2} fertilizer to crops in May, consistent with mean values for Kentucky bluegrass (Osmond & Bruneau 2006) and for the Kellogg Biological Station (Sanchez et al. 2004). We do not allow for tillage or irrigation of crops. Urban areas are essentially treated as savannas, with 50% temperate deciduous forest and 50% tall grassland.

In a terrestrial ecosystem model (TEM), several parameters for the primary fluxes are calibrated based on data for carbon and nitrogen stocks and fluxes from well-studied sites. The calibrations determine the coefficients of the carbon and nitrogen fluxes (gross primary productivity [GPP], plant nitrogen uptake, net nitrogen mineralization, autotrophic respiration, heterotrophic respiration) and so scale the functional dependencies for the particular target biomes. These coefficients are then used to extrapolate to other grid cells of similar biomes. Calibration sites are shown in Table S1. For this study, new calibrations were done for tall grassland, tropical rainforest, xeromorphic forests, and Mediterranean shrubland. The half-saturation constant indicates how much CO_2 fertilization takes place, with values of 200 representative of C3 plants (high fertilization), values of 40 representative of C4 plants (limited fertilization), and values of 120 representative of a mixture of the two.

Downscaling and bias correction

Climate data from the coarse-resolution global climate models must first be downscaled and bias corrected before using them as input to TEM-Hydro for climate impact studies such as this one. We rely primarily on the downscaling and bias correction of Maurer et al. (2007), which is applied for each of the CMIP3 models for 3 scenarios to the conterminous US at 1/8° resolution. Bias correction is based on applying 21st century anomalies to a higher resolution dataset of climate means from the 20th century. Therefore, the 20th century data are the observed data, while the 21st century data are the downscaled and bias-corrected data for each model and scenario. We also independently compare the 20th century climate model output to the high-resolution 20th century observed data by interpolating it to the equivalent grid first, though we do not use these data for TEM-Hydro runs. The purpose of this comparison is to determine if the models are accurately capturing the 20th century trends as one measure of reliability of their future trends.

We developed monthly input datasets to force TEM-Hydro for the conterminous US at a spatial resolution of 1/8° longitude × 1/8° latitude (50589 grid cells) for the 20th century (1905–2000) (Daly et al. 1994) and three 21st century scenarios, A2, B1, and A1B, for 15 of the CMIP3 models, similar to the approach taken in Felzer et al. (2011) for the western US. This resolution was chosen based on the CMIP3 multi-model dataset, which includes bias-corrected and spatially downscaled climate projections derived from CMIP3 data and served at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/ (Maurer et al. 2007).

Historical climate datasets (1904–2000) are developed in this study from the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 1994) downscaled data at 1/24° resolution, or about 4.6 km. These data include monthly maximum and minimum temperature, dewpoint temperature, and precipitation, and are used to create TEM input datasets of mean temperature, diurnal temperature range, vapor pressure, and precipitation by aggregating up to the 1/8° resolution. Clouds are interpolated from the half-degree Climatic Research Unit version 2.0 (CRU2.0) dataset (Mitchell et al. 2004). Surface ozone is interpolated from the US AOT40 dataset developed by Felzer et al. (2004) based on US Environmental Protection Agency CASTNET and AQS ozone data. All interpolations are done using a nearest neighbor approach. The nearest neighbor interpolation assigns the value of the nearest grid in the low-resolution dataset to the grid in the high-resolution dataset.

Results of 20th century runs of the climate models are compared with historical climate data to determine model performance for the last century. These data are not run through the TEM-Hydro model, as there are large biases, which are corrected for the future but which would not be representative of the 20th century climate responsible for the observed ecosystem response. We regionalized these data from each model without any additional interpolation. The raw climate model data, which differ for each of the CMIP3 models, include surface temperature, precipitation, surface-specific humidity, and surface downwelling shortwave radiation. We convert surface-specific humidity to vapor pressure using the surface temperature. We convert surface downwelling shortwave radiation to clouds using computed top-of-the-atmosphere radiation and the TEM cloud function and to PAR using the TEM assumption that PAR is 45% of surface downwelling shortwave radiation.

Projections of 21st century climate conditions are developed for all 3 scenarios (Special Report on Emissions Scenarios B1, A1B, A2) (IPCC 2007) using results from 15 of the available CMIP3 models (Meehl et al. 2007) (see Table 1 in the main text). Surface temperature and precipitation were derived from the CMIP3 data at 1/8° resolution by Maurer et al. (2007), who apply a statistical method of downscaling and bias correction that has been used in climate impact studies of the northeastern US and California (Maurer et al. 2007, Hayhoe et al. 2008). Since projections of minimum and maximum temperatures were not required to be archived, IPCC can only provide these data for a small number of the models; as a result, we have had to hold the diurnal temperature range constant as the value derived from historical data covering the period 1904–2000. Clouds and vapor pressure are downscaled directly from the half-degree datasets developed for Felzer et al. (2009) and bias corrected using a delta/ratio approach based on the model anomalies from each model's 20th century simulation and the PRISM historical dataset. Future ozone levels are also downscaled at half-degree resolution and held constant at year 2000 AOT40 values.

The land use and land cover data are developed from the 1 km Global Land Cover Classification dataset (DeFries et al. 2000, Hansen et al. 2000), which is based on the NASA/NOAA Pathfinder advanced very high resolution radiometer land dataset. This dataset is a snapshot of land use and land cover from 1981 to 1994. We converted 13 land types to TEM vegetation categories (see Fig. 3 in the main text), using further detail from the TEM vegetation descriptions where needed (Felzer et al. 2011, Felzer 2012). These categories include natural vegetation, cropland, and urban areas. Ideally, land use and land cover would not be static and would include disturbance, but no disturbance datasets exist at this high spatial resolution, so we have chosen to use present land cover and land use, which is more broadly representative of the 20th century than potential vegetation. Our approach is similar to the approach taken in Felzer et al. (2011) for the western US.

Other static datasets include wind speed, soil texture, and elevation. These data are downscaled from 0.5 × 0.5° resolution to 1/8 × 1/8° resolution using a nearest neighbor approach. The wind speed is from CRU2.0. Soil texture and elevation are based on the standard TEM datasets (Felzer et al. 2004).

Experimental design

Our approach is to use the observed 20th century climate and downscaled/bias-corrected 21st century climates for the 15 climate models and 3 scenarios for individual TEM-Hydro experiments. In our experimental design (see Fig. 2 in the main text), the first step is to equilibrate the model to historical climate to generate initial values for each stock, based on our dynamic equilibration using 1905–1944 and a CO_2 value of 305 ppm, which is the mean over the equilibration time period. The model is run iteratively until carbon, nitrogen, and water stocks stabilize. Then, the equilibrium conditions are used as starting conditions for a transient historical run from 1905 to 2000 using the PRISM-based observational dataset as described above. Projections for 2000 × 2099 are then run from year 2000 starting conditions for all 44 emissions scenarios (15 A2 scenarios, 15 B1 scenarios, and 14 A1B scenarios, as described in Table 1 in the main text).

The linear trend from the 30 yr before and 100 yr after 2001 were calculated based on the basis of the *t*-test statistic (Eq. 1) to determine the 95% confidence interval.The purpose of this test is to determine if the trends are statistically significant with respect to the interannual variability. We focused our discussion on the 30 yr historical period because trends during this period of rapid change are more representative of the future than during previous times, and also do not include the relatively strong aerosol forcing of the mid-20th century. To remove the effects of short-term climate variation and focus on the longer term trend, we also analyze the statistics of the 5 yr running means for each of these periods. Using 5 yr running means also eliminates the need to consider autocorrelation between years. We consider linear trends, although it is likely that non-parametric trends better characterize the evolution of the system. These linear trends are better than simple decadal differences because they include information from each year and are not biased by decadal anomalies. Future model refinements should include formulations that account for such non-linearities. The *t*-statistic for a linear regression is calculated as follows:

$$t = \frac{m}{\sqrt{\frac{\Sigma\left(y_i - \hat{y}\right)^2}{n-2} \Big/ \Sigma\left(x_i - \bar{x}\right)^2}} \quad (1)$$

where m is the slope, n is the degrees of freedom, y_i and x_i are the individual y and x values for each year, $\hat{y}$ is the predicted value from the linear regression equation, and $\bar{x}$ is the mean x value (2050). For each region, we assess the magnitude of increase or decrease of a particular variable by the year 2099, if the trend is significant, based on the slope multiplied by the number of years. The results are processed for the each of the National Climate Assessment (NAST 2001) megaregions for the conterminous US by first computing the mean for each region and then using these as the basis for the trends and significance. We conducted a univariate analysis, per Smith et al. (2009), in which models are applied to each region individually rather than attempting to combine them into an overall statistical model. As a measure of model agreement, if over 70% of the models (i.e. 10) show a statistically significant increase, decrease, or no significant trend, then we consider that trend consistent across the CMIP3 model set. This pertains to a 'model convergence' reliability criterion of Giorgi & Mearns (2002).

Model checking is done by comparing TEM-Hydro carbon and water fluxes to those produced by FLUXNET-MTE for the period 1982–2000. FLUXNET-MTE (Jung et al. 2009, 2011) uses FLUXNET observations of carbon dioxide, water, and energy fluxes upscaled to the global scale using the machine-learning technique Model Tree Ensembles (MTEs). The MTE method is used to predict site-level GPP, terrestrial ecosystem respiration, net ecosystem exchange, latent and sensible heat based on remote sensing data, climate and meteorological data, and information on land use (Jung et al. 2011). Jung et al. (2011) applied the trained MTEs to generate global flux fields at a 0.5 × 0.5° spatial resolution, covering the globe except for Antarctica, with a monthly temporal resolution from 1982 to 2008. We upscale the TEM-Hydro 20th century means and trends for GPP, net ecosystem productivity (NEP), and ET to the half-degree resolution for comparison to FLUXNET-MTE.

Table S1. Calibration sites for TEM-Hydro. Temperate savanna consists of 50% temperate deciduous forest and 50% short grassland if west of 100° W but tall grassland if east of 100° W. Tropical savanna consists of 50% tropical rain forest and 50% short grassland

Biome	Site	Vegetation	CO_2 half saturation	Primary reference
Boreal forest	Bonanza Creek, AK, USA	Black spruce	200	Van Cleve et al. (1983), Felzer et al. (2011)
Temperate coniferous forest	Harvard Forest, MA, USA	Red pine	200	McClaugherty et al. (1982), Felzer et al. (2011)
Temperate deciduous forest	Harvard Forest, MA, USA	Red oak, red maple	200	McClaugherty et al. (1982), Felzer et al. (2011)
Short grassland	Pawnee, CO, USA	Blue grama (C4)	40	Clark (1977), Felzer et al. (2011)
Tall grassland	Konza, KS, USA	Big bluestem and Indiangrass	40	Owensby et al. (1999), Johnson & Matchett (2001), Williams et al. (2004)
Xeric shrubland	Curlew, UT, USA	Winterfat (C3) + shadscale saltbush (C4)	120	Caldwell et al. (1977), Felzer et al. (2011)
Xeromorphic forest, Mediterranean shrubland	Guanica, Puerto Rico, USA	Oysterwood (large range of species)	200 (forest), 120 (shrubland)	Murphy & Lugo (1986), Raich et al. (1991)
Tropical rainforest	Ducke, Brazil	Broadleaf evergreen species	200	Franken et al. (1979), Raich et al. (1991)
Crops	Kellogg Biological Station, MI, USA	Maize	40	Smith & Gross (2006)

Table S2. Future (A1B) climate and TEM-Hydro ecosystem trends. Trends are from 2001 to 2100, and are based on the slope of the regression over 100 yr, using 5 yr running means. Trends are in **bold** if 70% of the models show increases or decreases; *italics* indicate that the 'robust' changes represent neither increasing nor decreasing trends, because the majority of the trends are not significant. Non-bold indicates that models do not agree. Units are changes as percent differences, except for tair (°C m^2 per 30 y) and net ecosystem productivity (NEP) (g C m^2 per 30 yr)

A1B	PNW	West	G.P.	MW	SE	NE	US
tair_jja	**4.30**	**4.02**	**4.28**	**4.33**	**3.74**	**3.78**	**4.10**
tair_djf	**3.02**	**3.09**	**3.48**	**4.02**	**2.63**	**3.67**	**3.29**
prec_jja	-16.47	1.34	-9.20	-4.32	-4.56	3.91	-4.88
prec_djf	**14.28**	***3.92***	3.91	9.11	0.42	**15.67**	6.25
par_jja	1.28	-0.96	1.30	**1.78**	**2.21**	**1.97**	**1.03**
par_djf	**-5.26**	-1.53	-1.84	-4.21	0.88	-3.76	-1.83
clds_jja	-3.42	**4.72**	-4.01	**-4.42**	**-4.94**	**-4.05**	-2.74
clds_djf	**8.56**	27.10	12.91	**9.11**	1.71	**9.37**	11.97
vpr_jja	**19.54**	**23.17**	**15.80**	**17.03**	**14.94**	**21.83**	**17.39**
vpd_jja	**42.74**	**28.48**	**45.89**	**60.14**	**48.08**	**37.65**	**41.06**
NPP_ann	**31.66**	**19.37**	-1.44	**7.02**	**18.72**	**27.11**	**14.59**
Crop Yield	**68.70**	**51.35**	7.17	-7.71	1.47	-1.11	-1.16
NEP_ann	**21.07**	*4.70*	*3.72*	7.61	26.09	26.65	11.64
Soil C	**-6.21**	**-12.89**	**-19.22**	**-13.22**	-6.89	**-6.58**	**-11.34**
Runoff_jja	**-30.03**	**-37.58**	-20.31	-6.37	-20.22	-11.38	**-19.81**
Runoff_djf	**40.80**	18.48	-24.85	36.38	-11.57	**67.50**	**12.44**
Smoist_jja	**-5.65**	**-4.89**	**-8.23**	-4.03	**-6.48**	-0.53	**-5.71**
ET_jja	**11.65**	**7.88**	1.61	3.25	1.50	5.24	**3.53**
Snowpack_djf	**-40.53**	**-43.99**	**-24.17**	**-55.09**	**-104.15**	**-53.26**	**-43.30**
Snowmelt_mam	**-44.01**	**-41.80**	**-25.70**	**-60.26**	**-108.99**	**-54.66**	**-45.31**

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