Modeling Impacts of Environmental Change on Ecosystem Services across the Conterminous United States

P. Caldwell, G. Sun, S. McNulty, E. Cohen, J. Moore Myers

Abstract

Climate model projections suggest that there will be considerable increases in temperature and variability in precipitation across the conterminous United States during the next 100 years. These changes in climate coupled with changes in land use and increases in human population will likely have a significant effect on water resources, carbon fluxes, biodiversity, and the services they provide. As society reacts to changing environmental conditions, the adaptation and mitigation strategies for one ecosystem service could come at the expense of another. It is critical that planning tools be developed to evaluate these tradeoffs between ecosystem services so that sound management decisions may be made in the face of climate, economic, and demographic change. This paper presents the Water Supply Stress Index–Carbon & Biodiversity model (WaSSI-CB) and demonstrates its potential for predicting changes in water supply and demand, carbon dynamics, and potential biodiversity under multiple stresses. The core of WaSSI-CB is a water balance model (WaSSI) that is sensitive to land cover and climate and operates on a monthly time step at the 8-digit hydrologic unit code (HUC) watershed scale across the conterminous United States. Annual U.S. Geological Survey water demand estimates are adjusted for population, disaggregated to the monthly scale, and compared to groundwater and surface water supply to assess water supply stress. Gross ecosystem productivity, ecosystem respiration, and net ecosystem carbon exchange are estimated using actual evapotranspiration. Similarly, potential biodiversity of reptiles, birds, amphibians, mammals, vertebrates, and tree distribution and abundance are estimated as a function of evapotranspiration. We show how the model may be used to predict the effects of climate, population, and land cover change on water resources and carbon fluxes in the next 50 years using downscaled monthly future scenarios, population projections, and hypothetical changes in land cover. Finally, the paper explores tradeoffs among management strategies for these ecosystem services.

Caldwell and Sun are research hydrologists, McNulty is a research ecologist, and Cohen and Moore Myers are resource information specialists, all with the U.S. Department of Agriculture Forest Service, Eastern Forest Environmental Threat Assessment Center, Raleigh, NC 27606. Email: pcaldwell02@fs.fed.us.

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Introduction

Increasing water use in the United States has led to widespread hydrologic manipulation and consumptive off-stream water use, practices that alter river flows (Vörösmarty et al. 2004), threaten the sustainability of the resource (Alcamo et al. 2003), and degrade ecosystem function (Carlisle et al. 2010). Future changes in climate will place additional pressure on freshwater supplies (Bates et al. 2008). The effect of these stressors will be highly variable over both time and space, making it difficult to assess effects on water resources into the future.

Like water supply, carbon sequestration and biodiversity are valuable ecosystem services that are vulnerable to the effects of climate change and human activities (Nemani et al. 2003, Beer et al. 2010). Carbon sequestration, or net ecosystem exchange (NEE), is the difference between ecosystem respiration (Re) from autotrophs and heterotrophs and gross ecosystem productivity (GEP), or photosynthetic assimilation of carbon by foliage. When NEE for an ecosystem is negative, the ecosystem is a net carbon sink. When NEE is positive, the ecosystem is a net source of carbon. Ecosystem water use, or evapotranspiration (ET), is tightly coupled with ecosystem productivity (Law et al. 2002, Sun et al. 2011 a) and biodiversity (Currie and Paquin 1987, Currie 1991). As a result, NEE and biodiversity can be predicted based on ET, and the factors that affect ET (e.g. climate change, land use change) will also have an effect on NEE and biodiversity. Managing an ecosystem to enhance NEE or biodiversity will result in reduced residual water supply for human use because NEE and biodiversity increase with increasing ET.

Management tools are needed that can evaluate the tradeoffs between these ecosystem services at multiple spatial and temporal scales in the United States. Unfortunately, there are few integrated models of water supply and demand, carbon dynamics, and biodiversity with which to evaluate the effect of climate, land cover, and population change or the tradeoffs between management strategies for these ecosystem services. The U.S. Department of Agriculture Forest Service has developed the Water Supply Stress Index–Carbon & Biodiversity model (WaSSI-CB) that is intended to fill this need. The model can be used to project the effects of global change on water supply stress, carbon sequestration, and potential biodiversity across the conterminous United States at the 8-digit hydrologic unit code (HUC) watershed scale (Sun et al. 2008, Sun et al. 2011 a). In this paper, we apply the WaSSI-CB model to project the effects of population, land cover, and climate change on water supply, carbon sequestration, and potential biodiversity, and we explore tradeoffs among management strategies for these ecosystem services.

Methods

The core of WaSSI-CB is a monthly water balance model (WaSSI) that is sensitive to land cover and climate, computing the water balance for each of eight land cover classes independently in the approximately 2,100 8-digit HUC watershed scale across the conterminous United States. Evapotranspiration (ET), infiltration, soil storage, snow accumulation and melt, surface runoff, and baseflow processes are accounted for within each basin based on spatially explicit 2001 MODIS land cover (Figure 1), and discharge (Q) is conservatively routed through the stream network from upstream to downstream watersheds. ET is estimated with an empirical equation based on multisite eddy covariance ET measurements using MODIS derived monthly leaf area index (LAI), potential ET (PET_{hamon}), and precipitation (PPT) as independent variables (Sun et al. 2011 a, b). Estimation of infiltration, soil storage, and runoff are accomplished through the integration of algorithms from the Sacramento Soil Moisture Accounting Model and STATSGO-based soil parameters (Koren et al. 2003).

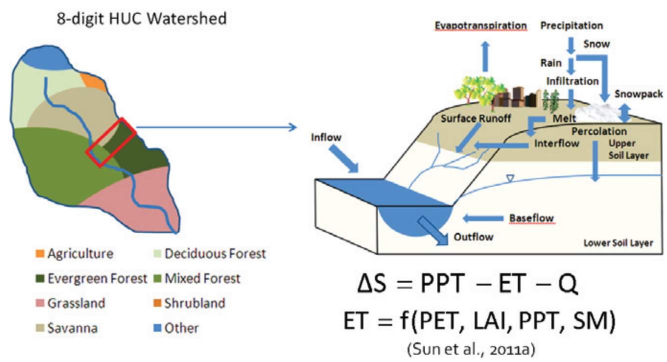

Figure 1. Schematic of the hydrologic processes simulated by the WaSSI-CB model.

Ecosystem GEP, Re, and NEE are estimated using actual evapotranspiration (AET) and water use efficiency parameters (Table 1) that were derived from measured site-level water and carbon fluxes for a variety of land cover types monitored by the FLUXNET (Sun et al. 2011 a).

Similarly, potential biodiversity of reptiles, birds, amphibians, mammals, vertebrates, and tree species richness are estimated as a function of PET and AET (Table 2; Currie and Paquin 1987, Currie et al. 1991).

While WaSSI-CB was designed to make projections regarding the potential diversity of multiple groups of biota, this paper focuses on tree species richness. The effects of development, habitat fragmentation, and forest management were neglected to simplify this hypothetical study, and HUC watersheds where total forest cover (sum of deciduous, evergreen, mixed forest, and savanna) was less than 10 percent of the total watershed area were excluded.

Table 1. Model parameters for estimating GEP as a function of AET, GEP = a*AET [g $C/m^2/mo$] and Re as a function of GEP, Re = m + n*GEP [g $C/m^2/mo$], after Sun et al. (2011 a).

Land cover class	a	m	n
Crop	3.13	40.6	0.43
Deciduous	3.2	30.8	0.45
Evergreen	2.46	9.9	0.69
Mixed forest	2.74	24.4	0.62
Grassland	2.12	18.9	0.64
Shrubland	1.35	9.7	0.56
Savanna	1.26	25.2	0.53
Water/urban/barren	1.53	9.7	0.56

Table 2. Model parameters for estimating potential biodiversity as a function of annual PET or AET, after Currie and Paquin (1987) and Currie et al. (1991).

Group	Model
Birds	1.40+0.00159*PET (PET<525 mm)
	2.26–0.0000256*PET (PET≥525 mm)
Mammals	1.12[1.0–exp(–0.00348*PET)]+0.653
Amphibians	0 (PET<200 mm)
	3.07[1.0–exp(–0.00315*PET)]
Reptiles	0 (PET<400 mm)
	5.21[1.0–exp(–0.00249*PET)]–3.347
Vertebrates	1.49[1.0–exp(–0.00186*PET)]+0.746
Trees	185.8/[1.0+exp(3.09–0.00432*AET)]

County-level 2005 annual U.S. Geological Survey (USGS) water demand and groundwater withdrawal estimates by sector (Kenny et al. 2009) were rescaled to the 8-digit HUC watershed scale, adjusted for population, and disaggregated to the monthly scale using regional regression relationships. Return flows by sector were computed using return flow percentages from the 1995 USGS report (Solley et al. 1998). The total water supply in each HUC watershed is the sum of surface water supply at the watershed outlet predicted by WaSSI-CB, total groundwater withdrawals, and the total return flow. Total water demand is the sum of the water use by all sectors in each watershed. The water supply stress index (WaSSI) is computed as the ratio of water demand to water supply (Sun et al. 2008). The WaSSI-CB model currently does not account for water storage in reservoirs or anthropogenic water diversion projects such as interbasin transfers and assumes that all surface water is available for human use.

Intergovernmental Panel on Climate Change (IPCC) AR4 scenarios A1B and B2 were assessed using downscaled CSIRO-Mk2.0, CSIRO-Mk3.5, HADCM3, and MIROC3.2 global circulation models for future scenarios according to the 2010 U.S. Forest Service Resources Planning Act Assessment to account for changes in population (Zarnoch et al. 2010) and climate (Coulson et al. 2007). WaSSI-CB results for all future climate scenarios were averaged to represent the mean (ensemble) response to climate change among these scenarios. Water use for the domestic sector was assumed to vary with watershed population projections according to an empirical per capita water use function. Water use for all other sectors was held constant at the 2005 level. Groundwater withdrawal rates from all sectors were also held constant at the 2005 level.

Results

Water Supply Stress

Total surface water supply for the conterminous United States was predicted to decrease as a result of climate change over the next 60 years from approximately 2.0 trillion m^3/yr in 2000 to 1.6 trillion m^3/yr in 2060 (Figure 2), due in large part to the effects of increasing temperature on ET, but also to decreasing PPT in some parts of the country.

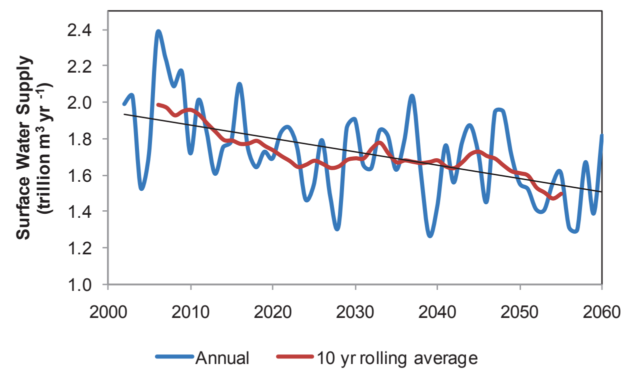

Figure 2. Predicted total U.S. surface water supply through 2060.

Changes in surface water supply will vary considerably across space (Figure 3), with the largest decreases in parts of the Great Plains region and the largest increases in the Southwest. These extreme changes in surface water supply may be misleading because surface water supplies are naturally low in these arid and semiarid environments. As a result, small absolute changes in supply can lead to large percentage changes. Much of the Great Plains region depends on declining groundwater supplies, so despite the lack of dependence on surface water, the Great Plains will likely continue to experience decreases in total water supply in the early part of the 21st century. The large percentage increases in surface water supply in parts of the Southwest are not significant in terms of absolute water supply, so these increases will have minimal effect on water supply in this region.

The WaSSI-CB model predicted that the total water demand in the United States will increase by 6 percent from 2001 to 2060 due to increasing population, with the largest increases in expanding metropolitan areas. The combined effect of decreasing water supply and increasing water demand resulted in increases in the water supply stress index (WaSSI) in most HUC watersheds. A long-term WaSSI value of 0.4 is commonly used as a threshold to identify watersheds experiencing some level of water supply stress (e.g., Alcamo 2000). Using this threshold, the Southwest and southern Great Plains regions were projected to experience water stress in 2051–2060 (Figure 4). Metropolitan areas of the east (e.g., Charlotte, NC; Atlanta, GA; South FL) were also projected to experience water stress.

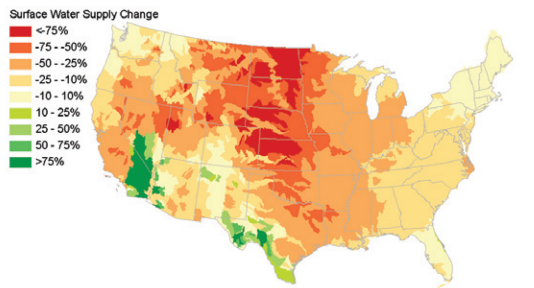

Figure 3. Change in mean annual surface water supply: 2051–2060 vs. 2001–2010.

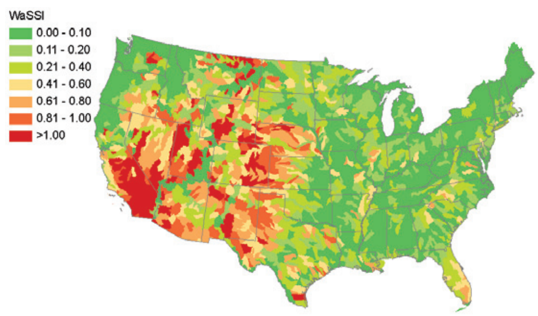

Figure 4. Mean annual Water Supply Stress Index (WaSSI) for 2051–2060.

Carbon Sequestration

Annual WaSSI-CB modeled NEE varied from a carbon source of 145g C/m^2/yr to a strong carbon sink of −1117 g C/m^2/yr (Figure 5). Carbon sequestration was highest in the Southeast, where abundant water and energy were available to drive ET and ecosystem productivity, and lowest in the West (excluding the Pacific Coast), where water was a major limitation. The total net annual carbon sequestration in the United States was 2.68 Pg C/yr during 2001–2010.

Carbon sequestration potential was largely projected to increase (NEE was more negative) across New England, the Upper Midwest, and Pacific Northwest and decrease across most of the Great Plains and Southwest regions (Figure 6) as a result of climate change. Areas that were carbon sources (NEE was positive) either in 2001–2010 or 2051–2060 are shown in gray. Ecosystem NEE is driven by AET, thus carbon sequestration potential will increase in areas with increasing AET and decrease in areas with decreasing AET. Regions where AET is historically energy-limited (i.e., high latitudes) were projected to have the largest increases in NEE as a result of increases in temperature. Regions where AET is historically water-limited (e.g., the Great Plains and Southwest) were projected to experience decreases in NEE due primarily to increases in temperature, but also to decreases in PPT in some areas. The predicted total net annual carbon sequestration in the United States was 2.81 Pg C/yr during 2051–2060, an increase of 4.9 percent from 2001–2010.

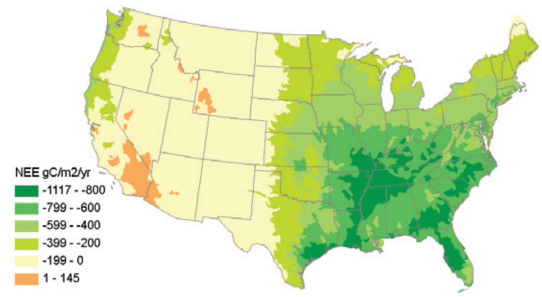

Figure 5. 2001–2010 mean annual net ecosystem carbon exchange (g C/m^2/yr).

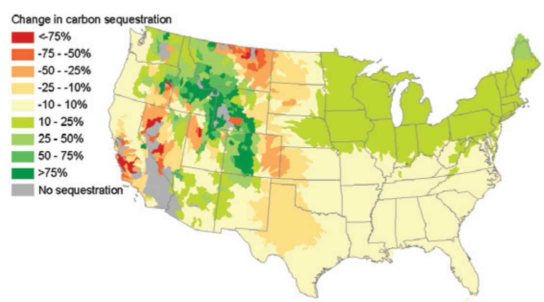

Figure 6. Change in mean annual carbon sequestration: 2051–2060 vs. 2001–2010.

Potential Tree Species Richness

Predicted potential tree species richness, or the number of tree species per unit area, assumes equilibrium conditions. The highest potential tree species richness was predicted for the Southeast, followed by the northern Pacific coast (Figure 7). These trends followed the spatial pattern of predicted AET across the United States. The Southeast, with abundant water and energy, had the highest AET rates and tree species richness. AET and tree species richness were water-limited in the Southwest and energy-limited in the Northeast, upper Midwest, and Pacific Northwest.

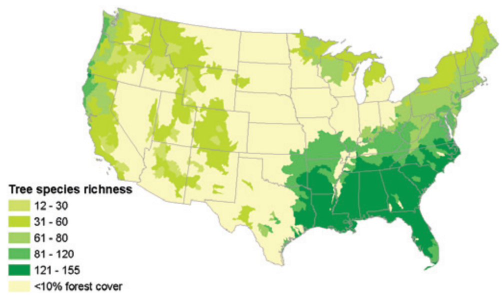

Figure 7. Historic tree species richness.

Tradeoffs Between Water and Carbon

Water yield and carbon sequestration are important societal services forested ecosystems provide. Unfortunately, managing forest resources to maximize one ecosystem service comes with a penalty in the other. To illustrate the tradeoffs between water and carbon, we developed a hypothetical scenario in which 20 percent of all forest land cover in the conterminous United States was converted to shrubland. This scenario may be a potential management option if increasing water supply were a top priority.

Water supply under this scenario had modest increases (up to 15 percent) in HUC watersheds dominated by forest land cover, particularly where the watersheds are in a "headwater" landscape position receiving minimal flow from upstream watersheds (Figure 8). This is partly because many of the "headwater" watersheds are dominated by forest cover, but also because the effects of this management strategy diminish in downstream watersheds as surface water supply was affected by nonforest land covers.

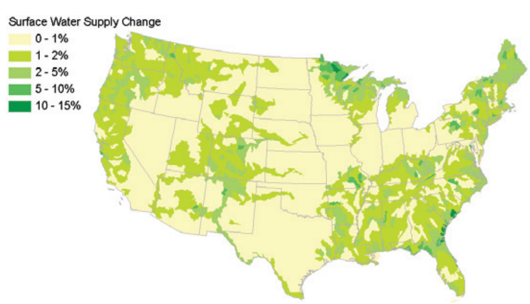

Figure 8. Change in 2001–2010 mean annual surface water supply due to a 20 percent forest conversion to shrubland.

While reducing forest cover by 20 percent increased water supply in some watersheds, this management option led to decreases in carbon sequestration potential over much of the East, Rocky Mountains, and Pacific Northwest (Figure 9) primarily because forest was the dominant land cover in these watersheds. The total net annual carbon sequestration in the United States under this scenario was 2.57 Pg C/yr during 2051–2060, a decrease of 4.1 percent from the 2001–2010 baseline case.

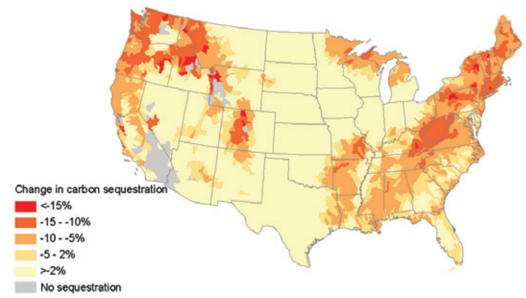

Figure 9. Change in 2001–2010 mean annual carbon sequestration due to a 20 percent forest conversion to shrubland.

On a regional basis, decreases in carbon sequestration (1–9 percent) as a result of this management action were greater than increases in surface water supply (0.4–1.6 percent) (Figure 10). The greatest effect occurred in regions with substantial forest cover and high AET (Northeast, Southeast, Northwest), and the least effect occurred in regions with minimal forest cover and (or) low AET (Midwest, Great Plains, and Southwest).

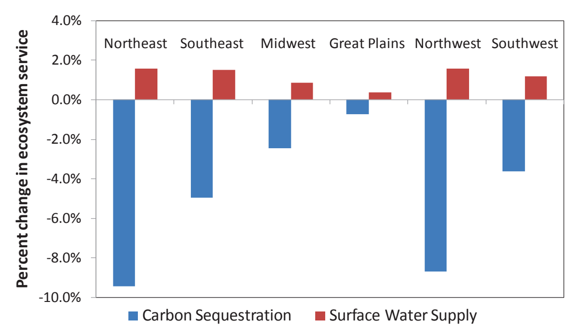

Figure 10. Change regional in 2001–2010 total annual surface water supply and total annual carbon sequestration due to a 20 percent forest conversion to shrubland.

Conclusions

In this paper, we showed how the WaSSI-CB model may be used to predict biodiversity and the effects of climate, population, and land cover change on water resources and carbon fluxes in the next 50 years, and we explored tradeoffs between water and carbon for a hypothetical management scenario where 20 percent of forest cover was converted to shrubland. Model projections indicated that surface water supply will decrease in much of the conterminous United States by 2060, and with water demand likely to increase as a result of population growth, water supply stress was projected to increase. Carbon sequestration potential was largely projected to increase across New England, the Upper Midwest, and Pacific Northwest, and decrease across most of the Great Plains and Southwest regions. Converting 20 percent of forest cover to shrubland led to modest increases in surface water supply and larger decreases in carbon sequestration as one might expect, but the change in water supply and carbon sequestration was highly sensitive to location and dominant land cover type.

The WaSSI-CB model is a work in progress, and several areas are currently under development: (1) reservoir storage; (2) interbasin transfer; (3) limitations on water withdrawal due to aquatic ecosystem needs; and (4) the effect of both climate change and land use change on water quality.

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