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Land Cover Land Use Change
Year 3 Progress Report
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Modeling Strategies for Adaptation to Coupled Climate and Land Use Change in the United States

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Project overview

The overall science goal of this project is to leverage work that has generated both climate and land use forecasts that are consistent with the IPCC Special Report on Emission Scenarios (SRES) and, with rapid progress on the IPCC 5th Assessment Report, forecasts that are consistent with Representative Concentration Pathways. Importantly, this work will help prepare for next generation regionally focused IPCC scenarios that better incorporate the influences and feedbacks of land use change. Our specific objectives are to spatially predict future land use change, initially in the eastern United States, and to incorporate those predictions under different SRES scenarios and RCPs into an established state-of-the-art modeling system that assimilates data from a variety of sources and drives a set of coupled ecosystem and hydrology models. We are simulating the influence of potential mitigation and adaptation actions by predicting land use change scenarios that incorporate a range of best management practices (BMPs) associated with land cover and land use change. Our overriding hypothesis is that any of a number of land use BMPs will mitigate additional climate warming by increasing carbon sequestration via changes in primary productivity and reducing radiative forcings associated with energy cycle feedbacks to climate. While the forcings are not a primary focus of the project, the implications of trade-offs in productivity versus radiative forcings are implicit to the mitigation and adaptation scenarios upon which we will focus.

The research falls under three major categories: (1) Spatial predictive modeling of land use change; (2) Terrestrial Observation and Prediction System (TOPS) simulations under climate change scenarios; (3) TOPS Predictions under Land Use Change Scenarios. Under the latter two topics we will produce simulations of (a) carbon exchange and productivity, (b) hydrological and energy fluxes, and (c) effects of stormwater best management practices (BMPs) on (b).

Spatial Predictive Modeling of Future Land Use Change

We completed two sub-tasks as part of the spatial predictive modeling of land use change coupled with TOPS model runs. First, we developed a method to convert total impervious area (TIA) to directly-connected impervious area (DCIA) across gradients of land use intensity. Second, we generated a set of scenarios to represent DCIA reductions corresponding to different suites of stormwater BMPs under different levels of BMP adoption rates.

<u>Convert total to directly-connected impervious area</u>

Impervious area is a key linkage between land use and ecological function in TOPS. The effect of IA on hydrological fluxes is exacerbated by conveyance of run-off through storm-water systems such that directly-connected IA (DCIA) can be a better predictor of hydrological alteration than TIA (Wang et al. 2001; Brabec et al. 2002). Consequently, DCIA is often the focus of stormwater BMPs which are designed to delay and reduce runoff from DCIA by routing it through pervious surfaces or retaining it on site in basins (Walsh et al. 2009).

We used the “Sutherland equations” (Table 1; Sutherland 1995; EPA 2011) to estimate DCIA as a function of residential density for five landscape types: totally connected, highly connected, average connected, moderately disconnected, and extremely disconnected (Table 1). Sutherland developed these equations based on a two studies in the Portland, Oregon area (Laenen 1980, 1983). We computed DCIA using IA estimates at 90-100 m resolution, and then computed the average DCIA at 1 km^2 for input to TOPS.

Type	**Description**	**Equation**	**Land use surrogate**
Totally-connected	All urban area is storm-sewered, directly connected	DCIA=IA	Residential density > 10 units per acre
Highly-connected	High density residential with rooftops connected	$DCIA=0.4 * IA^{1.2}$	Residential density 2-10 units per acre
Average connected	Curb & gutter exist, typically commercial/industrial/institutional and medium density residential	$DCIA=0.1 * IA^{1.5}$	Commercial/industrial, residential 0.4-2 units per acre
Moderately disconnected	At least 50% of urban areas are not storm-sewered and residential rooftops are not directly connected	$DCIA=0.04 * IA^{1.7}$	Residential 0.05-0.4 units per acre
Extremely disconnected	Less than ~5% urban areas are storm sewered	$DCIA=0.01 * IA^{2.0}$	All other

Table 1. Description of five residential landscape types, their characteristic residential housing densities, and the equations used to estimate directly connected impervious area from total impervious area.

<u>Effects of best management practices on stormwater runoff</u>

As part of the their stormwater permitting program in New Hampshire and Massachusetts, the Environmental Protection Agency developed a technical support document for small MS4 (municipal separate stormwater systems) permits in New Hampshire and Massachusetts (EPA

2011). This technical document sets forth a methodology for estimating stormwater runoff reduction from BMPs applied to DCIA. Estimates of BMP runoff reduction rates were obtained from reviews of empirical BMP performance studies that measured runoff reduction amounts for multiple types of BMPs under varying soil infiltration rates and, in the case of infiltration basins and trenches, varying depths of runoff treated (Battiata 2010, EPA 2011). The estimated percent runoff reduction was subtracted from 1 to create a "disconnection multiplier" which, when multiplied by DCIA, serves as a rough estimate of the amount of impervious surface reduction that would yield a given level of runoff reduction. We adapted this methodology to generate national BMP scenarios assuming nine combinations of BMP application rates and BMP disconnection multipliers to represent a range of DCIA reduction scenarios (Table 2).

Estimated effectiveness	Adoption rate		
	10%	25%	75%
13%	1.3%	3.25%	9.75%
50%	5%	12.5%	37.5%
95%	9.5%	23.75%	71.25%

Table 2. Modeled reduction in DCIA as a function of the product of BMP effectiveness and adoption rate.

TOPS Predictions under Climate Change Scenarios

In the first year we utilized daily 250m resolution meteorological surfaces generated for the study region from January 2000 through December 2003 using the Surface Observation and Gridding System (SOGS; Jolly et al. 2005), a component of TOPS. SOGS automatically retrieves and stores observations from meteorological station networks and applies a library of interpolation algorithms to produce spatially continuous meteorological surfaces including surface air temperature (maximum, minimum, and average), precipitation, vapor pressure deficit, and shortwave radiation. For the grids for the Chesapeake region, we applied the SOGS gridding algorithms to produce the required meteorological inputs for TOPS for the land use change scenarios. In the second year, we applied TOPS to generate 1km resolution surfaces for the eastern U.S. for baseline runs for the period from 2001-2010. In addition, we generated future climate scenarios for the eastern U.S. based on downscaled WCRP CMIP3 scenarios (Maurer et al., 2007). In our initial experiments for the eastern U.S., we used three models (GFDL CM2.0, GISS-ER, CCSM3.0) and three scenarios for each model (A1B, A2, B1), for a total of nine climate scenarios (Figure 1). Since these scenarios only provide forecasts for temperature and precipitation, we also derived estimates of vapor pressure deficit and solar radiation following the methods described by Thornton et al. (1997) and Thornton and Running (1999). Since TOPS typically runs at a daily timestep, we also made a number of modifications to TOPS to facilitate use of the downscaled AR4 climate scenarios, which utilize a monthly time step.

In the third year of the project, we also obtained all available, completed climate scenarios from the Fifth Coupled Model Intercomparison Project (CMIP5), as well as the PRISM U.S. 800m monthly historical gridded climate surfaces. We initiated an effort to downscale all available CMIP5 climate scenarios (19 models to date) from the 2.6, 4.5, 6.0, and 8.5 representative concentration pathways (RCP) for the period from 1950-2099 (Figure 2). The downscaling utilized a statistical downscaling approach (bias-corrected spatial disaggregation) and was conducted using the NASA Earth Exchange. We are currently calculating the ensemble averages for the temperature and precipitation fields for each of the RCPs, and producing the derived meteorological fields required for the ecosystem model runs, including vapor pressure deficit and shortwave radiation.

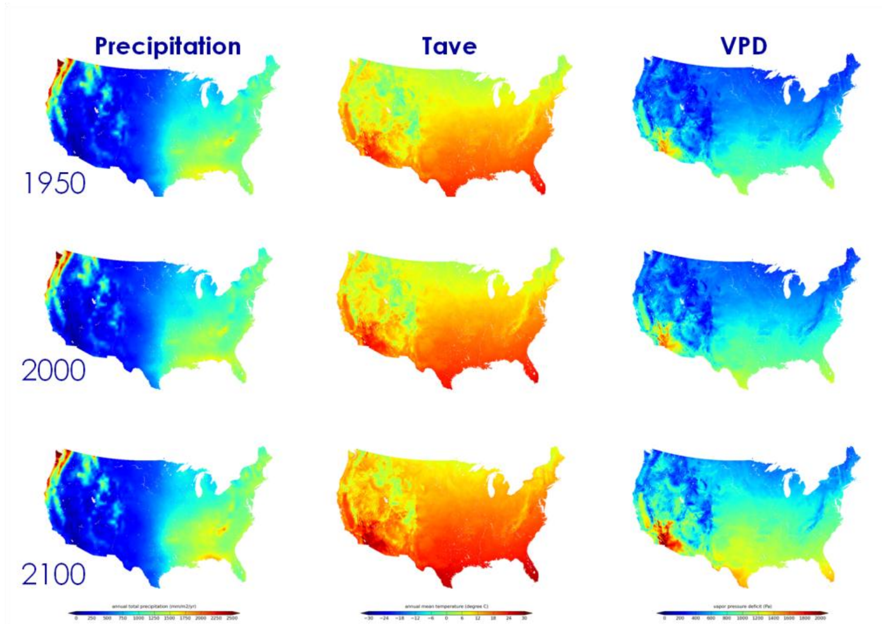

Figure 1. Downscaled 1km CMIP3/AR4 climate scenarios, from the GFDL CM2.0 model, A1B scenario

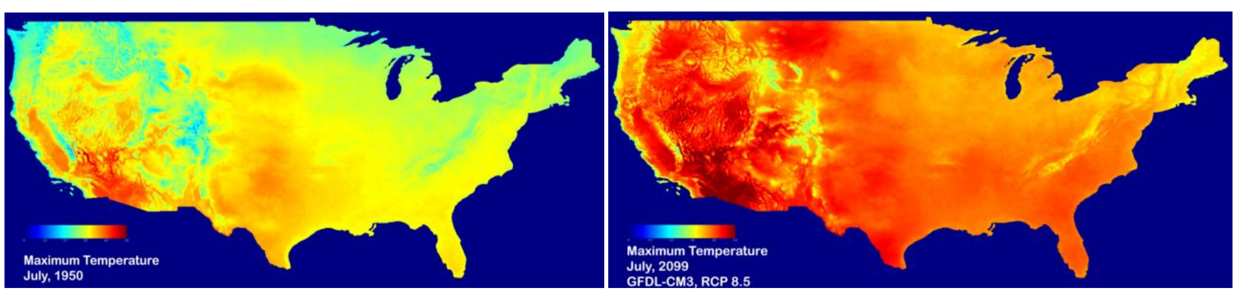

Figure 2. Downscaled 800m CMIP5/AR5 climate scenarios, from the GFDL CM3.0 model, RCP 8.5 scenario

TOPS Predictions under Land Use Change Scenarios

In the first year of the project, we conducted a modeling experiment to evaluate the potential impact of land use change and increasing urbanization on watershed outflow and gross primary production (GPP), and to demonstrate the potential utility of TOPS for evaluating the combined impacts of climate and land use change at the regional scale. We conducted these simulations in the Chesapeake and Delaware watersheds, where we have done much previous work at more local scales. TOPS simulations to evaluate the impact of land use change on runoff and GPP were conducted using the BIOME-BGC model, which has been integrated with TOPS as a component model. In this modeling experiment, TOPS was used to estimate various water (evaporation, transpiration, stream flows, and soil water), carbon (net photosynthesis, plant growth) and nutrient flux (uptake and mineralization) processes. TOPS requires as inputs spatially continuous data layers to describe the land cover, soil texture and depth, daily meteorology, and elevation across the land surface. We used satellite-derived estimates of leaf area index (LAI) to parameterize equations for photosynthesis and plant growth. Results from the initial modeling experiment indicated the ability of TOPS to quantify the potential for significant impacts to occur as a result of land use change and increased impervious surface area. In the second year of this project, we expanded the geographic domain to include the entire eastern U.S. using the land use and climate scenarios described above. Using TOPS, we conducted simulations to evaluate the independent and combined impacts of climate and land use change on runoff and ecosystem productivity. For each of the climate scenarios, we conducted runs to evaluate the effects of climate change alone, as well as model runs that utilized the corresponding SERGoM scenario (A1, A2, or B1) to evaluate the combined effects of climate and land use change (Figure 3). Initial results from these runs were presented at the LCLUC program meeting in 2011, and sample results are included below.

In the third year of the project, all data and model code was transferred to the NASA Advanced Supercomputing (NAS) facility, and the coupled climate and land use modeling experiments were continuing on NAS resources. In November, 2011, however, a complete disk failure at NAS resulted in the loss of 136TB of data, including the results from all model runs completed to date. Following this data loss, the decision was made to continue the analysis using the latest CMIP5 climate scenarios, rather than repeat the analysis using the older CMIP3/AR4 climate scenarios. This resulted in a delay in the project while the CMIP5 downscaling was prepared and carried out on NEX, and the CMIP5 RCPs were crosswalked to the SERGoM SRES scenarios. The CMIP5 downscaling is now complete, and we are resuming the coupled climate and land use change modeling experiments. Initial results will be available soon. Plans for 2012 include: 1) completion of the coupled climate and land use change scenarios for the eastern U.S., including use of the SERGoM BMP scenarios; 2) comparison of observed vs predicted monthly outflows for key watersheds in the U.S.; 3) compilation of results by watershed and land use type; and 4) preparation of results for publication.

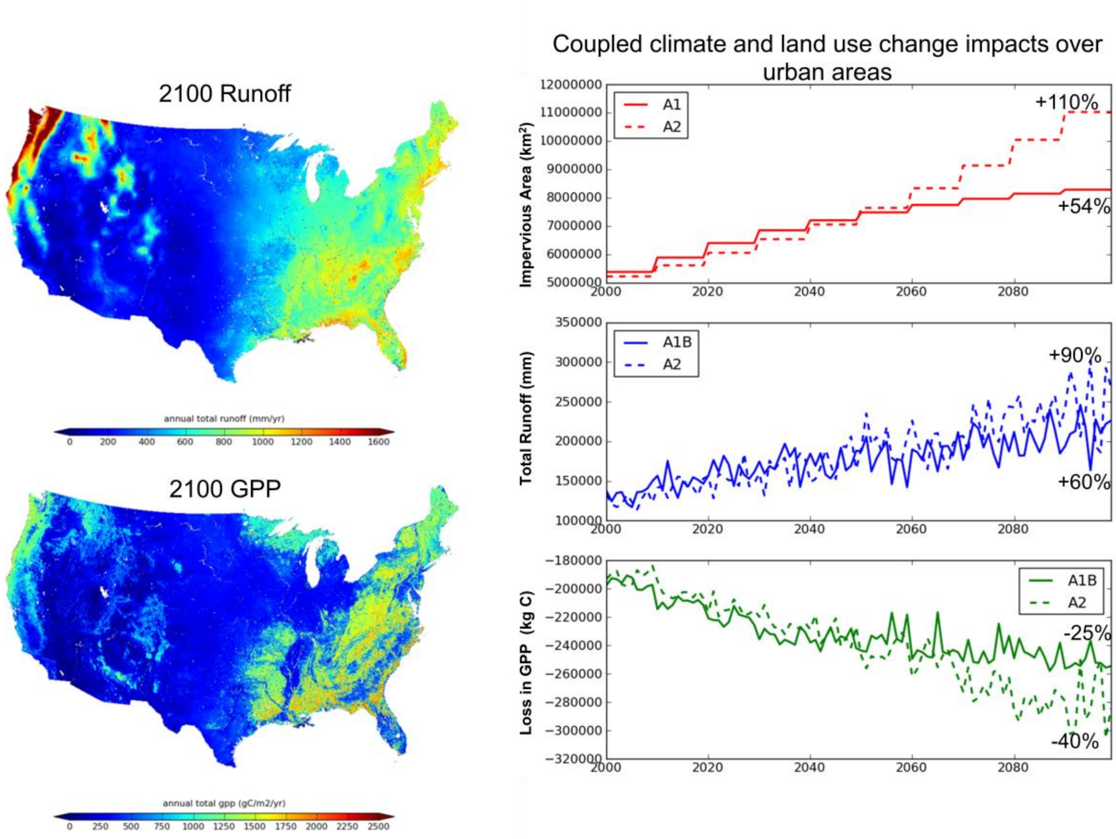

Figure 3. Sample results from the coupled climate and land use change model runs, showing predicted patterns in annual runoff and GPP for the U.S. at 1km resolution (left), along with the predicted changes in impervious surface area, runoff, and gross primary productivity for urban areas from 2000 to 2100 under the SRES A1B and A2 climate scenarios (right).

Project Related Publications to Date

Bierwagen, B.G., D.M. Theobald, C.R. Pyke, A. Choate, P. Groth, and P. Morefield. 2010. National housing and impervious surface scenarios for integrated climate impact assessments. *Proceedings of the National Academy of Sciences USA* 107(49):20887-20892.

Goetz, S. J., Fiske, G. & Jantz, C. A. (in press). On the relationship between stream biotic diversity and urbanization, past and future, in New England USA. Geospatial Techniques as applied to urban water issues (ed. by L. Patrick). Springer Press.

Goetz, S. J., Bond-Lamberty, B., Law, B., Hicke, J., Houghton, R. A., O'Halloran, T., McNulty, S., Meddens, A. J. H., Pfeifer, E. M., Mildrexler, D. & Kasischke, E. (in press). Observations and assessment of forest carbon recovery following disturbance in North America. *Journal of Geophysical Research Biogeosciences*.

Goetz, S. J., Sun, M. & Jantz, C. A. (2011) Changes in the hydrology of the Upper Delaware watershed with increasing urbanization. *Watershed Science Bulletin*, Fall 2011, 18-26.

Jantz, C. A., S. J. Goetz, D. Donato, and P. Claggett. 2010. Designing and implementing a regional urban modeling system using the SLEUTH cellular urban model. *Computers, Environment and Urban Systems* 34:1-16.

Theobald, D. M., S. J. Goetz, J. Norman, and P. Jantz. 2009. Watersheds at risk to increased impervious surface cover in the coterminous United States. *Journal of Hydrologic Engineering* 14:362-368.

Wang, W., J. Dungan, H. Hashimoto, A. Michaelis, C. Milesi, K. Ichii, and R. Nemani, 2011: Diagnosing and assessing uncertainties of terrestrial ecosystem models in a multi-model ensemble experiment: 1. primary production, *Global Change Biology* 17(3):1350-1366.

Wang, W., J. Dungan, H. Hashimoto, A. Michaelis, C. Milesi, K. Ichii, and R. Nemani, 2011: Diagnosing and assessing uncertainties of terrestiral ecosystem models in a multi-model ensemble experiment: 2. carbon balance, *Global Change Biology* 17(3):1367-1378.

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Project Related Presentations to Date

April 2012. S.J. Goetz, F. Melton, D. Theobald. Modeling Strategies for Adaptation(in the context of climate change & LCLUC projects). Annual LCLUC meeting. Rockville MD

February 2011. S.J. Goetz, B. Bond-Lamberty, B. Law, J. Hicke, R. A. Houghton, S. McNulty, A. J. H. Meddens, E. M. Pfeifer, C. Huang, D. Mildrexler, M. Sun, T. O'Halloran, E. Kasischke *Observations and assessment of forest recovery following disturbance in North America.* North American Carbon Program annual meeting (poster). New Orleans, LA

December 2010. F.S. Melton; S.J. Goetz; W. Wang; C. Milesi; D.M. Theobald; R.R. Nemani. *Modeling Coupled Climate and Urban Land Use Change in the Eastern United States*. American Geophysical Union annual meeting. San Francisco CA 2010.

December 2010. S.J. Goetz, R.Dubayah. *Introduction to the Application of Remote Sensing in Terrestrial Carbon Monitoring, Modeling and Management*. American Geophysical Union annual meeting. San Francisco CA 2010.

June 2009. S. Goetz, F. Melton, W. Wang, D. Theobald, C. Milesi. World Bank 5th Urban Research Symposium on Cities and Climate Change: Responding to an Urgent Agenda. Our contribution, entitled *Modeling Strategies for Adaptation to Coupled Climate and Land Use Change in the United States*, was selected as one of just a few to be included in the proceedings. Marseilles France.

October 2009. F. Melton, W. Wang, S. Goetz, C. Milesi, R. Nemani, H. Hashimoto, A. Michaelis, P. Votava. California Air Resources Board Forest Inventory Symposium. Invited presentation to the California Air Resources Board, *Assessing Impacts of Climate and Land Use Change on Carbon Fluxes with the NASA Terrestrial Observation and Prediction System*. Sacramento, CA.

Project Components and Schedule

SCHEDULE	**Year 1**		**Year 2**		**Year 3**	
Task	**Q1-Q2**	**Q3-Q4**	**Q1-Q2**	**Q3-Q4**	**Q1-Q2**	**Q3-Q4**
Land Use Change						
Model parameterization	■	■				
Scenario development		■	■	■		
Impervious conversions			■	■		
BMP development				■	■	■
TOPS						
Compilation of TOPS core data layers for region	■					
Selection of CMIP3 scenarios & validation of TOPS implementation using hindcasts & observed GPP & streamflow		■	■			
Regional climate scenarios and impacts w/ ensemble forecasts			■	■	■	
Incorporate land use scenarios and BMP parameterization			■	■	■	
Combined climate / land use change scenarios; ensemble forecasts for wshed simulations					■	■
Regional simulations					■	■
Analysis of forecast results						■

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Thornton, P.E., and S.W. Running, 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. *Agricultural and Forest Meteorology*, 93: 211-228.

Walsh, C.J., T.D. Fletcher, and A.R. Ladson. 2009. Retention capacity: a metric to link stream ecology and storm-water management. *Journal of Hydrologic Engineering* 45(1): 399-406.

Wang, L., J. Lyons, P. Kanehl, and B. Bannerman. 2001. Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Management* 28: 255-266.