Modeling Strategies for Adaptation to Coupled Climate and Land Use Change in the United States

Scott Goetz*
Woods Hole Research Center, Woods Hole MA 02540
sgoetz@whrc.org

Forrest Melton, Weile Wang, Cristina Milesi
Foundation of California State University, Monterey Bay / NASA Ames Research Center
fmelton@arc.nasa.gov

David Theobald
Colorado State University, Natural Resources Ecology Laboratory, Fort Collins CO
davet@nrel.colostate.edu

Summary: We used mapped and modeled land cover change in large watersheds of the eastern United States to explore the impacts of urbanization of hydrologic dynamics (runoff) and vegetation carbon uptake (gross productivity). We used the Terrestrial Observation and Predictions System (TOPS), a state of the art modeling framework for assimilating satellite data observations with ecosystem and hydrology models. We incorporated the future land use predictions into TOPS to establish a framework for simulating the influence of potential adaptation actions associated with land use. Our overriding hypothesis is that any of a number of land use practices can mitigate additional climate heating by increasing carbon sequestration via changes in primary productivity and hydrologic dynamics associated with energy cycle feedbacks to climate.

Key Words: Adaptation, climate change, ecosystem, hydrology, land use change, mitigation, modeling, satellite observations.

* Corresponding author

I. INTRODUCTION

Over the coming century, changes in climate and land use and land cover (LULC) have the potential to create major changes in land surface temperature, watershed runoff, and ecosystem productivity throughout much of the world, including the United States. The climate change scenarios in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) forecast warming of 3.5-12° C for the eastern U.S. by 2100. Work conducted to date by project team members and other research teams forecasts a nearly 50% increase in urban land cover classes and associated impervious surface cover over the next few decades across substantial portions of the U.S., particularly in the southwestern and eastern U.S. In combination, climate change and land use change are likely to create a series of cascading impacts on ecosystems, including changes in productivity, disturbance and hydrological properties.

There are a number of potential best management practices (BMPs) for land use planning and design that could be implemented to mitigate impacts resulting from changes in climate and LULC. These BMPs include urban reforestation, restoration of abandoned lands and riparian corridors, green roofing for commercial buildings, low impact development (LID) techniques for residential housing, and replacement of asphalt and concrete with permeable surfaces. All of these BMPs have the net effect of reducing impervious surface area (ISA), modifying albedo, mitigating the urban heat island effect, and increasing productivity and carbon sequestration in biomass within more urbanized and exurban developed areas. What is currently lacking, however, are broad-extent, regional simulations that demonstrate the potential cumulative benefits of coordinated state- and region-wide implementation of BMPs, particularly given the planned regional focus on the next generation (AR5) IPCC scenario development. Here we report the results of an initial modeling experiment to evaluate the impacts of projected land use change on ecosystem conditions across a 216,800 km^2 area encompassing the Chesapeake Bay and Delaware River watersheds (see Figure 1), and discuss this in the context of BMPs.

II. METHODS

The modeling analysis was conducted using the Terrestrial Observation and Prediction System (TOPS), a modeling framework that automatically integrates and preprocesses Earth Observation Satellite data fields so that land surface models can be run in near real-time or used to generate short and long-term forecasts (Nemani et al., 2007, 2008). Simulations to evaluate the impact of land use change on runoff and gross primary productivity (GPP) were conducted using BIOME-BGC (Thornton et al., 1997, 2005), which has been integrated with TOPS as a component model. In this modeling experiment, BIOME-BGC 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. BIOME-BGC requires as inputs spatially continuous data layers to describe the land cover, soil texture and depth, daily meteorology, and elevation across the land surface. BIOME-BGC can also use satellite-derived estimates of leaf area index (LAI) to parameterize equations for photosynthesis and plant growth.

1. Land Cover

Land cover data for the baseline runs (2000-2003) were derived from the National Land Cover Database (Homer et al., 2004). The 2001 NLCD 30m data set for the Chesapeake watershed was resampled to a spatial resolution of 250m using a majority vote algorithm. Land cover data for the future scenario used ISA forecasts from SERGoM for the year 2030 (Theobald et al. 2009), and used an ISA threshold of 10% to derive an urban mask for 2030 that was superimposed over the NLCD 2001 data. Figure 1 provides a comparison of the extent of urban land cover circa 2000 versus the increase in urban land cover projected to occur by 2030 (SERGoM).

BIOME-BGC uses biome classifications derived from the International Geosphere-Biosphere Programme (IGBP) land cover classification scheme (Loveland and Belward 1997), which required us to crosswalk the NLCD 2001 land cover classes to the corresponding IGBP classes. Our current implementation of BIOME-BGC does not include a biome parameterization for urban environments. Future work will address this limitation, but for this initial experiment we simulated urban environments using the 'Barren' land cover class, and made corresponding adjustments to the soil texture and rock depth layers, as described below. To simulate the effect of impervious surface area (ISA) in urban environments on runoff and productivity, we changed the land cover class from urban to barren for pixels with ISA > 10% in the 2000 and 2030 land cover data layers prior to crosswalking the NLCD land cover to the corresponding IGBP class.

2. Soils and Topography

Data on soil texture and soil depth was derived from the U.S. STATSGO2 database (http://soils.usda.gov/survey/geography/statsgo/). TOPS includes complete U.S. soil texture and rock depth grids at a spatial resolution of 1km, and data for this analysis were resampled to a spatial resolution of 250m to match the resolution of the other data layers. In addition, as an initial approximation of ISA in urban environments, soil texture layers were set to 98% clay and rock depth was adjusted to 0.10m for pixels corresponding to urban land cover classes or ISA > 10%. Elevation data were resampled from the U.S. 30m national elevation data set (NED) (http://ned.usgs.gov/) to a resolution of 250m by taking the average elevation of all pixels within each 250m pixel.

3. Meteorology

Daily 250m resolution meteorological surfaces were generated for the region from January 2000 through December 2003 using the Surface Observation and Gridding System (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 gridding algorithms based on DAYMET that follow Thornton et al. (1997) to produce the required meteorological inputs for BIOME-BGC. This initial modeling experiment only evaluated impacts of project land use change. As such, the daily climate data for 2000-2003 was used for both the baseline (2000) and future (2030) scenarios. Future work will apply climate downscaling techniques to examine the combined impacts of climate and land use change.

4. Leaf Area Index

TOPS is capable of using simulated seasonal growth patterns, climatologies derived from historic satellite observations, or direct satellite observations of the land surface to estimate leaf area index and parameterize vegetation conditions within the model on a daily timestep to track the observed seasonal patterns in vegetation growth. For this experiment, we used applied the MODIS MOD15A2 (Myneni et al., 2000) fallback algorithms for calculating leaf area index (LAI) from the MODIS MOD13Q1 250m NDVI data from March 2000 to December 31, 2003. Daily LAI estimates were interpolated from the 8-day MODIS composites using a spline function. As with the climate data, the timeseries of LAI estimates from 2000-2003 were used for both the baseline (2000) and future (2030) scenarios.

5. Streamflow Data

Daily streamflow data from 2000-2003 at the UGSS Streamflow Gauge at Trenton NJ (ID# 01463500, Latitude 40°13'18", Longitude 74°46'41, Drainage Area 6,780 square miles) were retrieved from the USGS National Water Information System (http://waterdata.usgs.gov/nwis) for use in evaluating estimates of watershed outflow from TOPS for the region.

III. RESULTS

Daily total watershed outflow for the region was calculated and compared against observed watershed outflow at the USGS streamflow gauge at Trenton, New Jersey (Figures 2a & 2b). Since BIOME-BGC does not include capabilities for spatially explicit hydrologic routing, a running 11-day average was used to calculate outflow for comparison to the observed streamflow. The running average was used to correct for the time required for water to be transported throughout the watershed. Also, because the drainage area covered by the Trenton gauge is about 9% of the total area of the model experiment, a corresponding weighting factor is applied to the model simulated runoff. In spite of the above stated model limitations in hydrological routing, Figure 2 indicates that the simulated runoff is consistent with the observations in both daily variability and accumulated magnitude. Indeed, the difference of the accumulated outflow is less than 4% during the four-year period.

Projected runoff patterns for 2030 follow the same general pattern as the 2000 baseline scenario, but with increases in runoff volume per storm event of as much as 15%. Figure 3 provides a comparison of projected average daily runoff for the baseline and future land cover scenarios, and Figure 4 summarizes the difference in average daily outflow from the two simulations. The expansion of ISA in the 2030 scenario clearly leads to an significant increase in instantaneous runoff on rainy days, as indicated by the positive spikes in Figure 4. On the other hand, the expansion of ISA also decreases the soil-water holding capacity and, as a result, runoff after the storms in the 2030 scenario decreases more rapidly than in the 2000 scenario, as indicated by the negative spikes in Figure 4. This increase in hydrologic "flashiness" is characteristic of increasing impervious cover within watersheds. Based on this initial modeling experiment, the predicted change in cumulative annual runoff from the watershed was approximately 1%, with a cumulative average increase in runoff of 1.5 billion m^3–H_2O/yr above the baseline total outflow volume of 150 billion m^3–H_2O/yr (Figure 5a & 5b). Consistent with expectations, this increase in runoff volume is geographically concentrated around regions forecasted to have substantial increases in ISA (Figure 6).

Daily average estimated GPP for the baseline and future scenarios are summarized in Figure 7a. Not surprisingly, the intra-annual patterns in productivity track one another closely as a result of using the 2000-2003 climate data for both the baseline and future modeling scenarios. Because the region is dominated by deciduous temperate forest, changes in GPP were most significant during the summer months (Figure 7b). Projected decreases in GPP in this modeling experiment were estimated at 14 million kg-C per year (Figure 8b, or approximately 5% of the total annual estimated GPP of 290 million kg-C for the region (Figure 8a). These changes were again concentrated in areas forecasted to undergo substantial urbanization by 2030 (Figure 9).

IV. DISCUSSION

Despite the relatively simplified parameterization of urban land cover and the lack of explicit hydrologic routing in BIOME-BGC, estimated watershed outflow from TOPS replicated observed streamflow volumes with reasonably good accuracy. Use of an 11-day moving average to calculate runoff volumes from TOPS dampened the magnitude of the peaks in runoff, but improved the overall match of predicted versus observed streamflow for 2000-2003. More rigorous parameterization of urban biomes within BIOME-BGC will likely further improve agreement between estimated and observed runoff. Since the primary goal of this effort was to quantify the cumulative magnitude of changes in GPP and watershed outflow, obtaining a perfect match between predicted and observed runoff was not considered essential.

While a number of studies have examined the effects of increasing ISA on water quality (see Goetz et al. 2008 for a recent synthetic analysis and Schueler et al. 2009 for a recent review), there have been relatively few studies that have examined the relationship between increasing ISA and surface runoff, and only one previous study on this topic could be located for the northeastern U.S. Carlson (2004) applied the SLEUTH model to forecast increases in ISA to 2025 in the Spring Creek watershed in Pennsylvania, and reported an increase in surface runoff and peak flow of a few percent (with the magnitude of the change varying slightly according to the method used to calculate the impact of ISA on runoff). This result is consistent with the predicted 1% increase in cumulative runoff and up to 15% increase in peak flow from our modeling experiment. A comparative study of different watersheds, conducted in the vicinity of Atlanta GA by

Rose & Peters (2001), also reported that observed peak flows were 30-100% greater in highly urbanized versus less urbanized watersheds. While the study did not report an overall increase in runoff or change in the runoff coefficients (runoff as a fractional percentage of precipitation), they did report that the recession period for the urbanized watershed was 1-2 days less for the other streams evaluated, which is consistent with the results of our study.

Predicted changes in GPP in this modeling experiment are likely to be somewhat overestimated because use of a 'Barren' biome class to represent urban environments, while suitable for representing ISA within urban environments, fails to capture productivity associated with urban landscaping and small parks. The estimate of a 5% decrease of the baseline total GPP in 2000, however, provides an upper bound for potential loss of productivity as a result of increasing urbanization in the Chesapeake and Delaware watersheds through 2030.

Future work will follow the approach used by Milesi et al. (2005) to develop a modified savannah biome parameterization to represent urban environments, and will include multiple parameterizations of urban environments to further evaluate the potential for various best management practices to mitigate impacts on GPP (e.g., urban reforestation, green roofing, smart growth, etc). Use of additional biome parameterizations for urban environments should increase the accuracy of forecasted impacts to GPP and watershed outflow. In addition, while this initial experiment focused on the potential impacts of land use change on watershed outflow and productivity, future work will also apply the downscaled climate scenarios described previously to evaluate the combined impact of climate and land use change on the region.

V. CONCLUSION

We conducted a modeling experiment to evaluate the potential impact of land use change and increasing urbanization on watershed outflow and gross primary productivity, and to demonstrate the potential utility of TOPS for evaluating the combined impacts of climate and land use change at regional to national scales. Results from this modeling experiment indicate the potential for significant impacts to occur as a result of land use change and increased impervious surface area, with increases in total average watershed runoff of approximately 1%, and potential losses of GPP of as much as 5% through 2030, with increasing impacts expected beyond 2030. Future work will examine the additional potential impacts resulting from the combination of land use and climate change, and the extent to which different best management practices could mitigate these impacts.

VI. BIBLIOGRAPHY

Carlson, T.N., (2004). Analysis and Prediction of Surface Runoff in an Urbanizing Watershed Using Satellite Imagery. Jou*rnal of the American Water Resources Association* 40(4):1087-1098.

Goetz, S.J., & Fiske, G. (2008). Linking the diversity of stream biota to landscapes in the mid-Atlantic USA. *Remote Sensing of Environment*, *112*, 4075-4085

Homer, C. Huang, C. Yang, L. Wylie, B. Coan, M. (2004). Development of a 2001 National Landcover Database for the United States. *Photogrammetric Engineering and Remote Sensing* 70(7):829-840.

Jolly MW, Graham JM, Michalelis A, Nemani RR, Running SW (2005). A flexible, integrated system for generating meterological surfaces derived from point sources across multiple geographical scales. *Environmental Modeling Software* 20:873-882.

Loveland, TR, and AS Belward (1997). The IGBP-DIS global 1km land cover data set, DISCover: first results. *International Journal of Remote Sensing* 18(15):3289-3295.

Milesi, C., Running, S.W., Elvidge, C.D., Dietz, J.B., Tuttle, B.T., & Nemani, R.R. (2005). Mapping and modeling the biogeochemical cycling of turf grasses in the United States. *Environmental Management, 36*, 426-438.

Myneni, R., Knyazikhin, Y., Glassy, J, Votava, P., and N Shabanov (2003). User's Guide FPAR, LAI (ESDT: MOD15A2) 8-day Composite NASA MODIS Land Algorithm. Available on-line [http://cybele.bu.edu/modismisr/products/modis/userguide.pdf, last accessed 4/14/09].

Nemani, R., Votava, P., Michaelis, A., White, M., Melton, F., Coughlan J., et al. (2007). *Remote sensing methodologies for ecosystem management*. In: Food & Water Security Ed : U. Aswathanarayana, Taylor & Francis Book Series, pg 1-19.

Rose, S, and N Peters (20001). Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* 15(8):1441-1457.

Schueler, T.R., Fraley-McNeal, L., & Cappiella, K. (2009). Is Impervious Cover Still Important? Review of Recent Research. *Journal of Hydrologic Engineering, 14*, 309-315.

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

Thornton, P. E., Running, S. W., & Hunt, E. R. (2005). *Biome-BGC: Terrestrial Ecosystem Process Model, Version 4.1.1*. Model product. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/805.

Thornton P. E., Running, S. W., & White, M. A. (1997). Generating surfaces of daily meteorological variables over large regions of complex terrain. *Journal of Hydrology* 190:241-251.

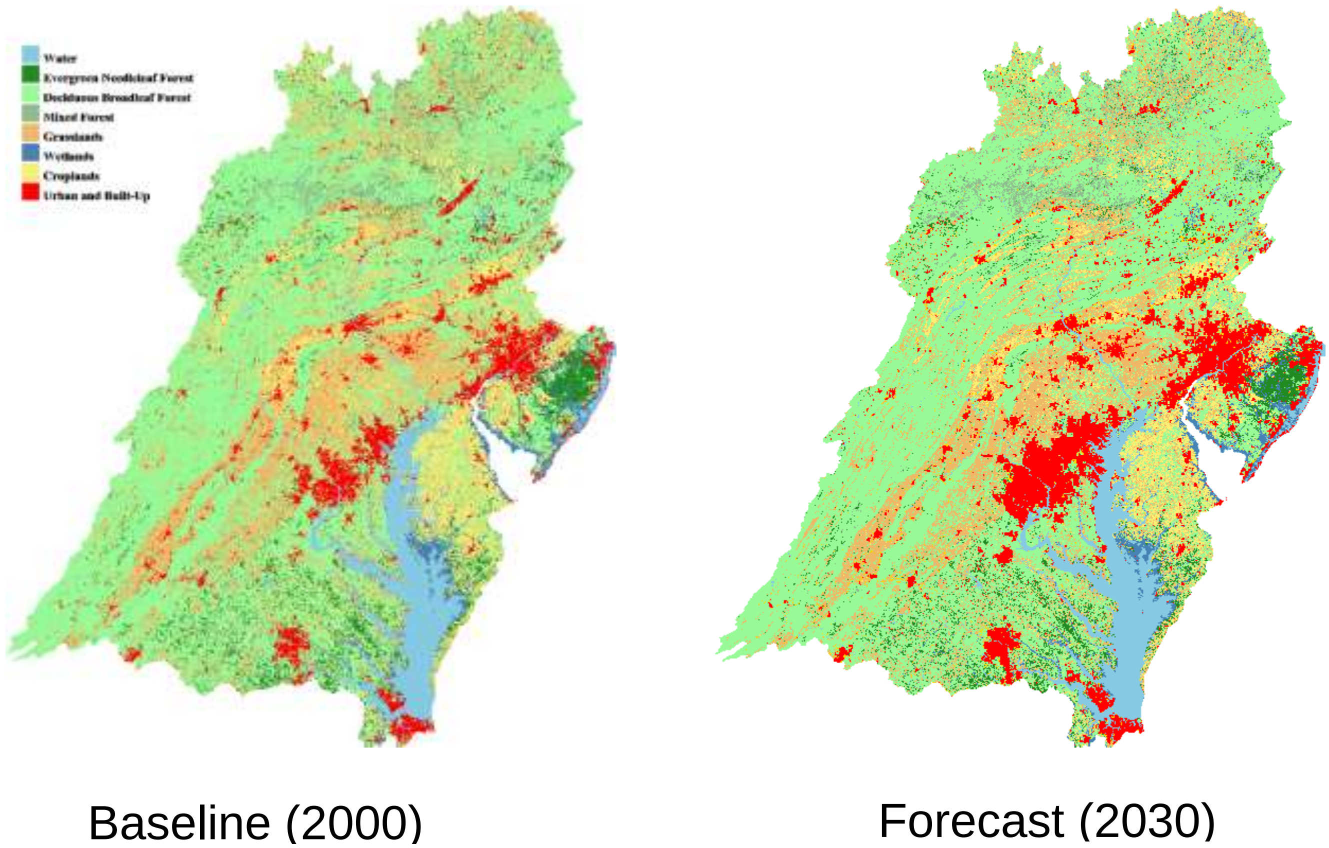
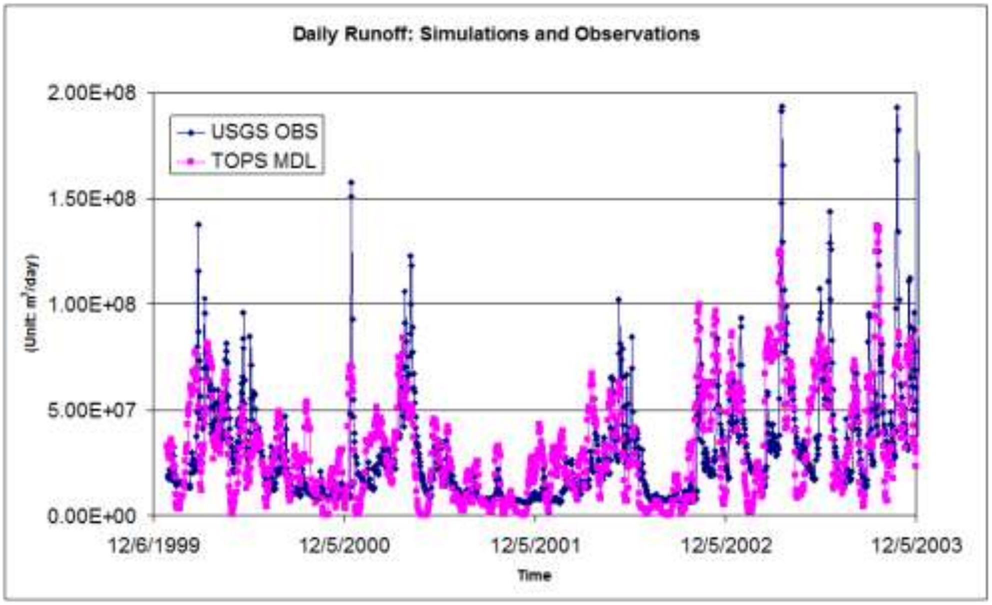


Figure 1: Increase in urban land cover (shown in red) from 2000 to 2030. The 2000 map is derived from the NLCD 2001 data (Homer et al. 2004), and the 2030 map is derived from SERGoM estimates using a threshold for impervious surface area of 10% to define urban areas (Theobald et al. 2009).

(a)


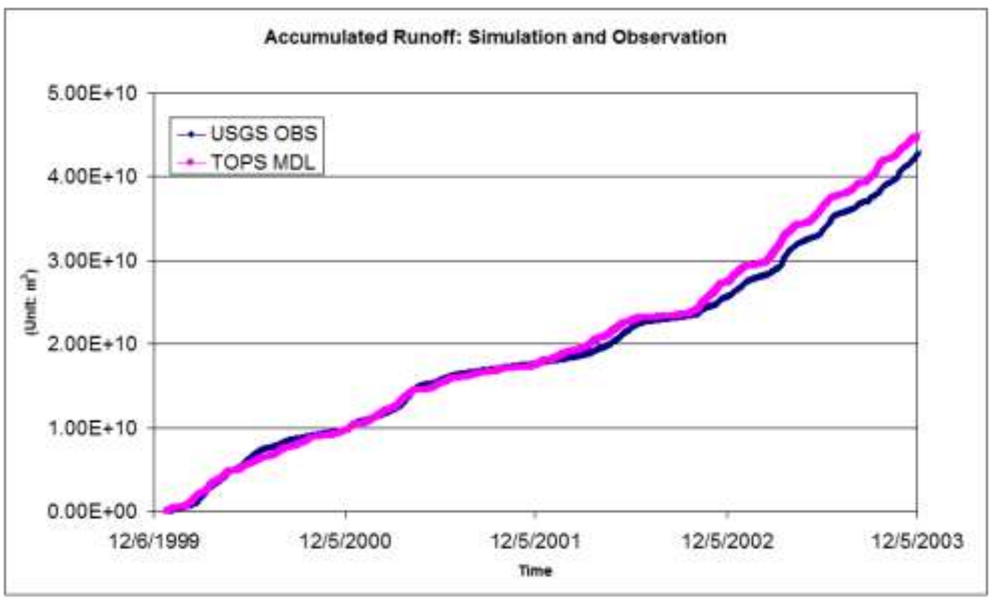
(b)


Figure 2: Comparison of predicted daily (a) and cumulative (b) runoff from TOPS against observed runoff from the USGS stream gauge at Trenton for 2000-2003.

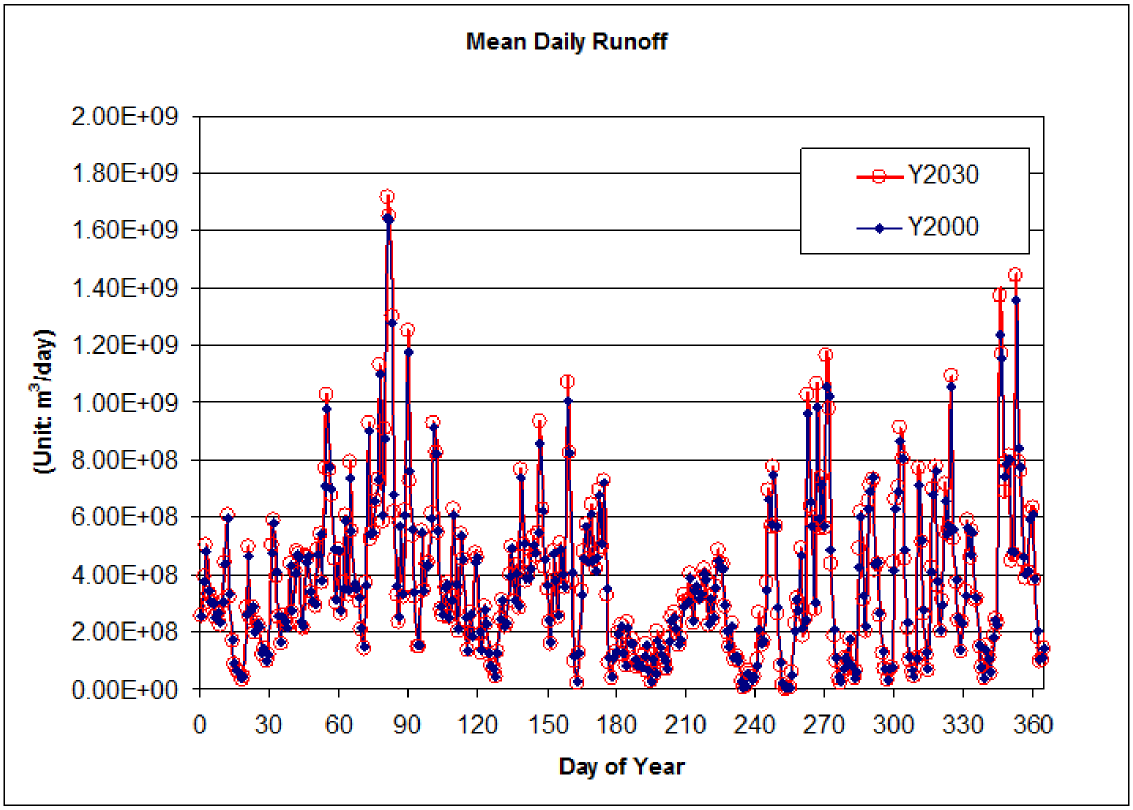


Figure 3: Average daily runoff (in cubic meters per day) over a four year period calculated using daily meteorological surfaces from 2000-2003 and the baseline land cover from 2000 (blue line) and forecasted land cover from 2030 (red line).

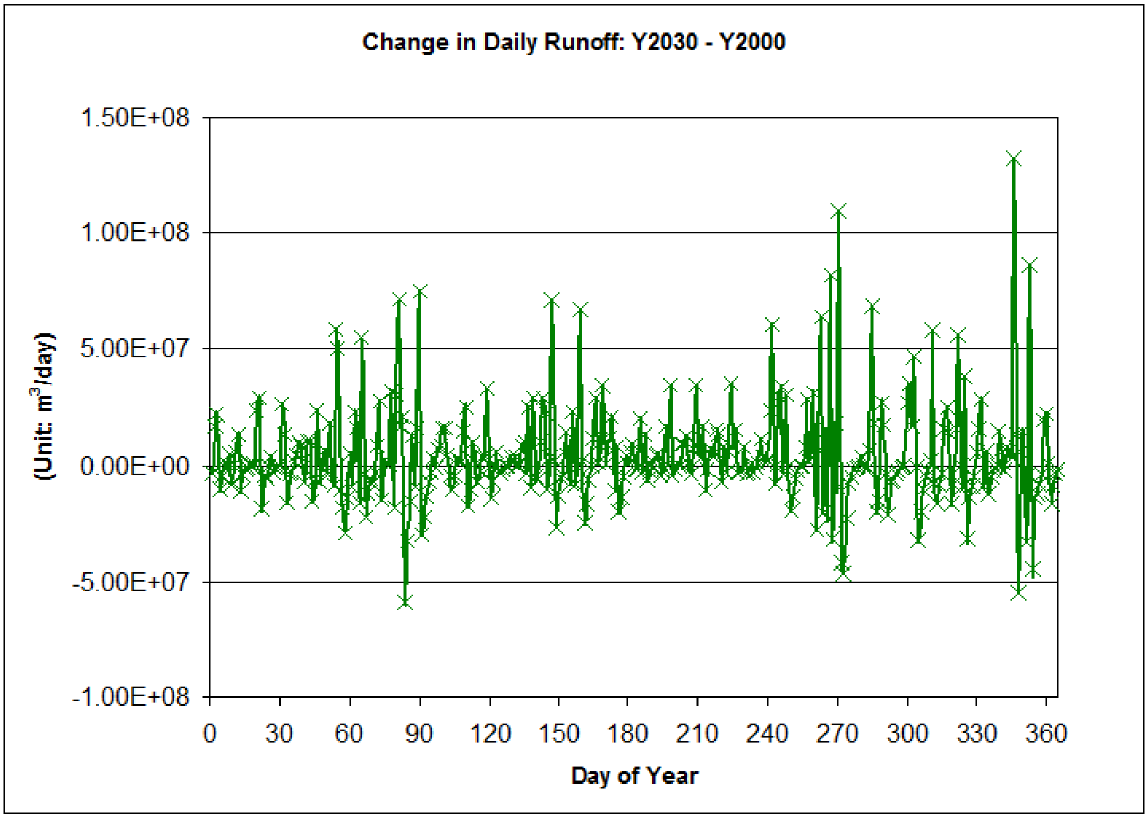
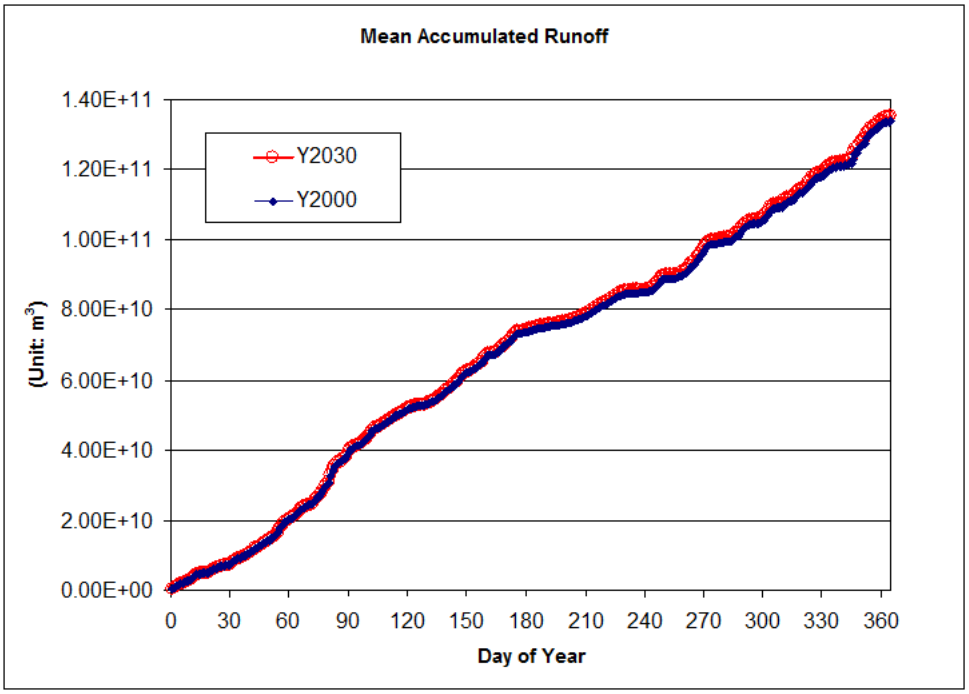


Figure 4: Predicted change in average daily runoff over the four year simulation period expressed as the difference between the forecast (2030) and baseline (2000) scenarios.

(a) 

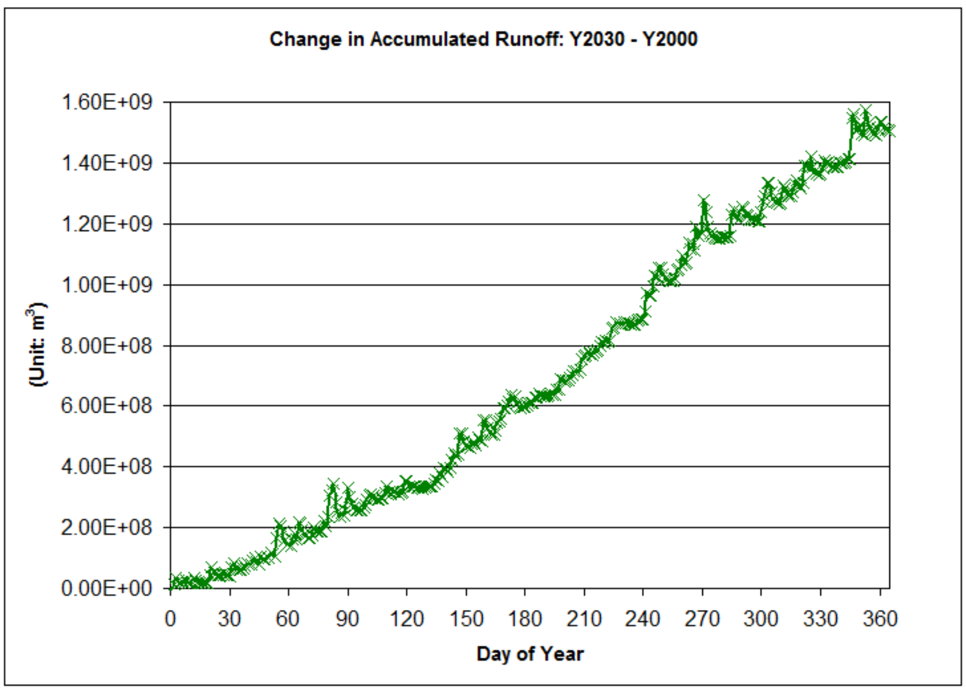
(b) 

Figure 5: Forecasted average cumulative runoff over the four year simulation periods. Total cumulative runoff for both the baseline (2000) and forecast (2030) scenarios is shown in (a), and the difference between the baseline and forecast scenarios is shown in (b).

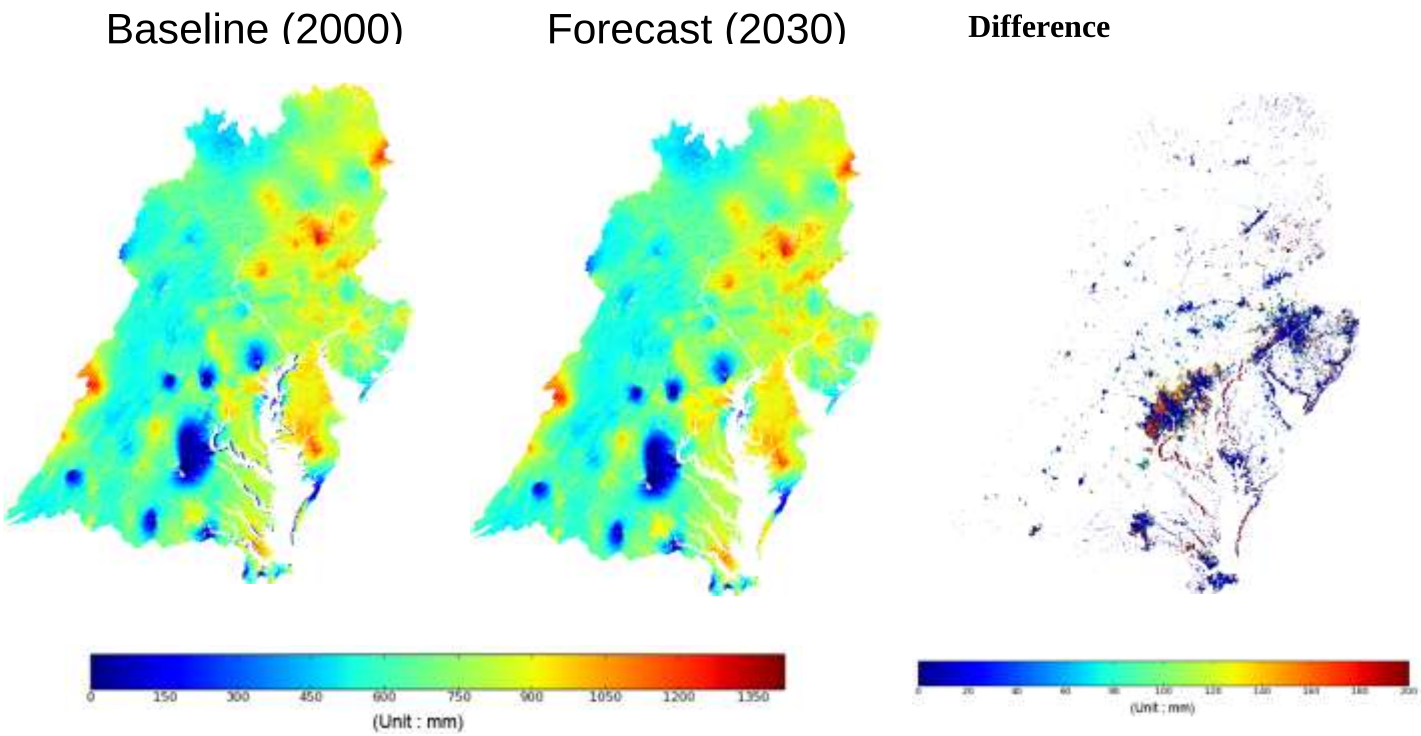
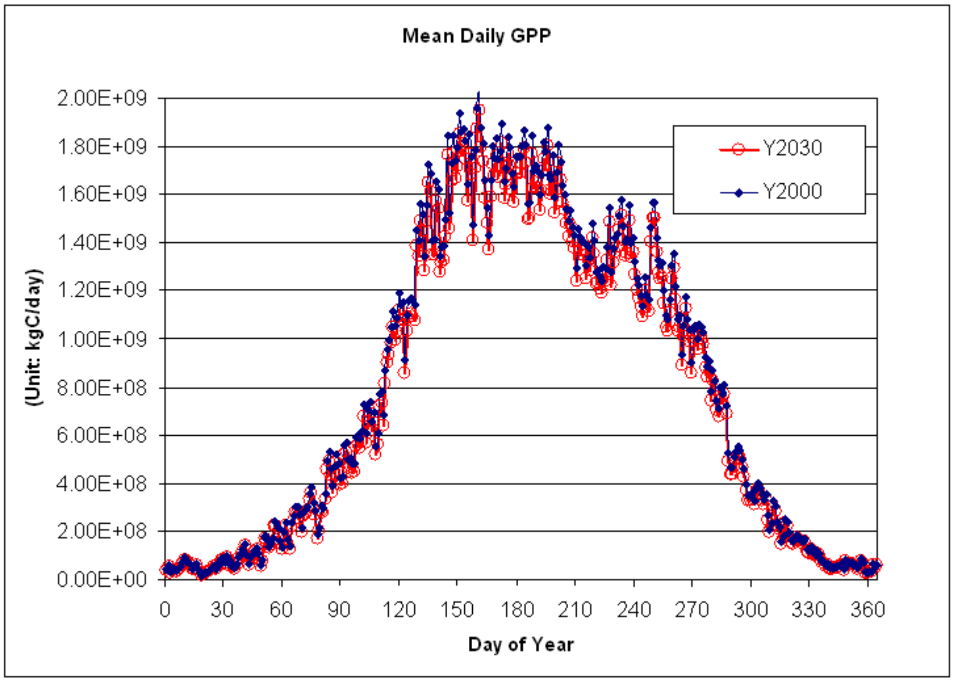
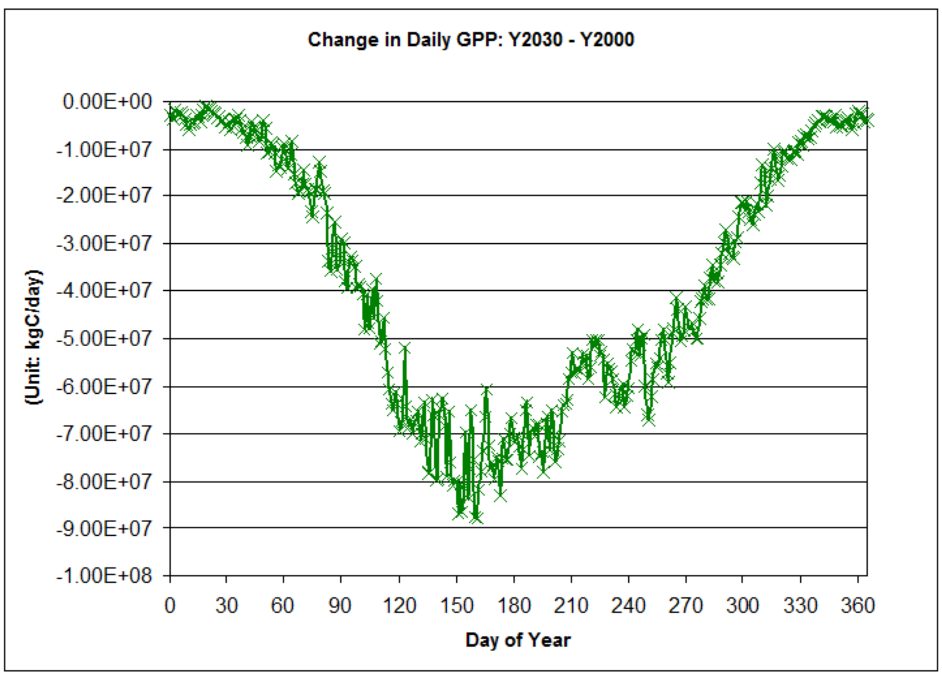


Figure 6: The average annual total runoff for the baseline (2000) and forecast (2030) scenarios, and the projected increase in average annual runoff, expressed in depth of water in mm.

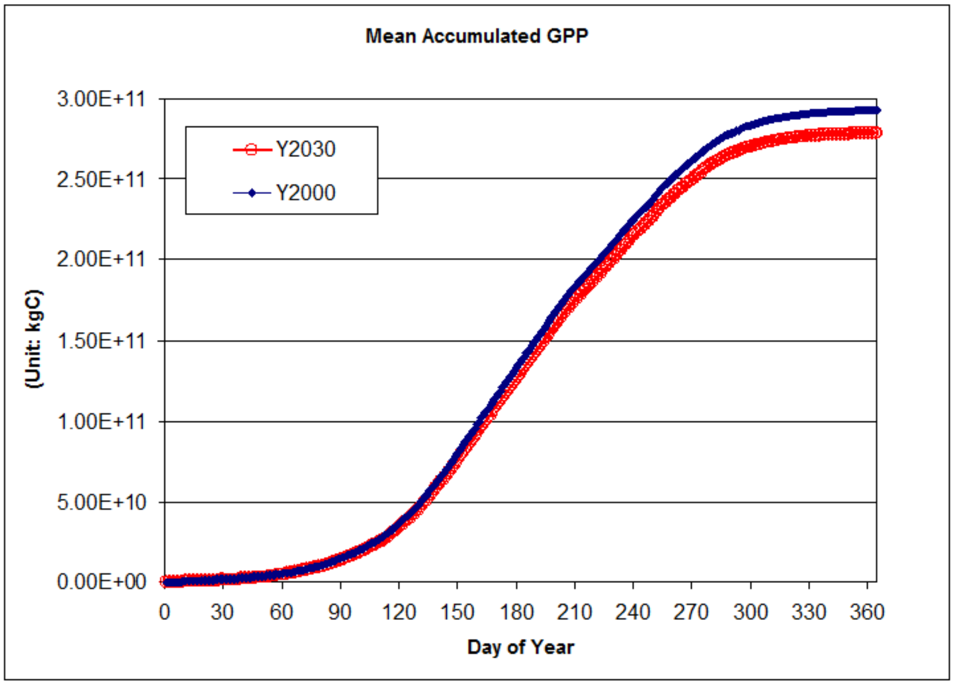


(a)

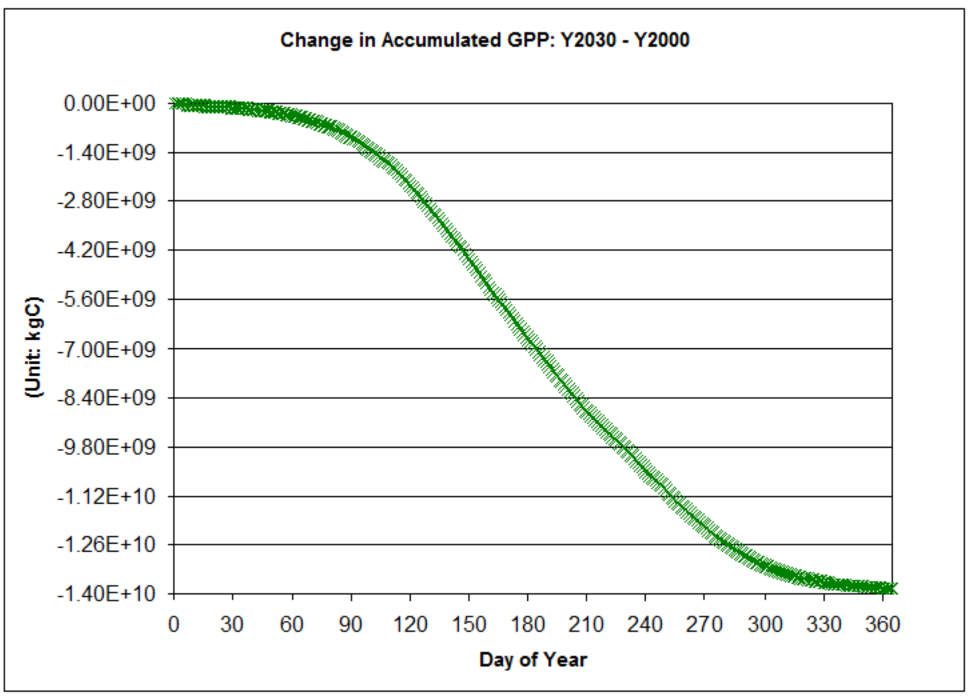


(b)

Figure 7: Forecasted average daily GPP over the four year simulation periods. Average total daily GPP for the study region for both the baseline (2000) and forecast (2030) scenarios is shown in (a), and the difference between the baseline and forecast scenarios is shown in (b). Units are expressed in kg of carbon per day.



(a)



(b)

Figure 8: Forecasted average cumulative GPP over the four year simulation periods. Average cumulative GPP for the study region for both the baseline (2000) and forecast (2030) scenarios is shown in (a), and the difference between the baseline and forecast scenarios is shown in (b). Units are expressed in kg of carbon.

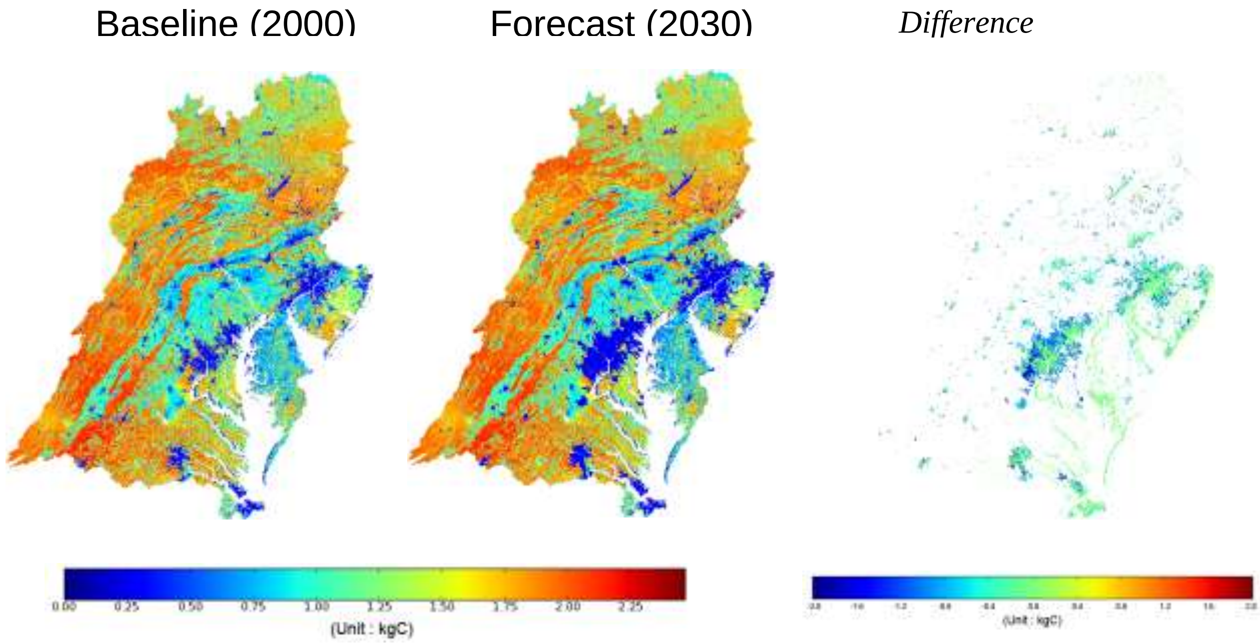


Figure 9: The average annual total GPP for the baseline (2000) and forecast (2030) scenarios, and the projected decrease in average annual GPP, expressed in kg of carbon.