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Simulation and sensitivity analysis of carbon storage and fluxes in the New Jersey Pinelands

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A major challenge in modeling the carbon dynamics of vegetation communities is the proper parameterization and calibration of eco-physiological variables that are critical determinants of the ecosystem process-based model behavior. In this study, we improved and calibrated a biochemical process-based WxBGC model by using in situ AmeriFlux eddy covariance tower observations. We simulated carbon dynamics of fire-dominated forests at tower sites and upscaled the tower site-based simulations to regional scale for the New Jersey Pinelands using LANDSAT-ETM land cover and DAYMET climate data. The Extended Fourier Amplitude Sensitivity Test approach was used to assess the higher-order sensitivity of model to critical eco-physiological parameters. The model predictions of CO_2 net ecosystem exchange (NEE) and gross ecosystem production (GEP) were in agreement with the eddy covariance measurements at the three tower sites in 2005. However, the model showed poor fit in 2006, grossly overestimating NEE and the ratio of ecosystem respiration to GEP because the model did not reflect the carbon loss caused by severe defoliation related to an outbreak of gypsy moths in that year. The model simulations indicated that wildfire reduced annual NEE in pine/scrub oak forest, while prescribed burning in oak/pine and pine/oak stands led to temporary increase in NEE for a period 1–2 years post burning. The uncertainty and sensitivity of the model carbon simulations were mainly attributable to the 2nd- and higher-order interactions between carbon allocation parameters, specific leaf area and fire mortality intensity.

1. Introduction

Terrestrial ecosystems can serve as either a net carbon sink or a net source, and play an important role in determining carbon storage and fluxes at regional and global levels (Aber and Driscoll, 1997; Law et al., 2001; Walther et al., 2002; Sitch et al., 2003; Wang et al., 2010). In the past decade, the rate of sequestration by North American forests has been estimated at 0.23 petagrams of carbon per year (Goward et al., 2008). This offsets about 13% of the fossil fuel emissions from the continent. However, the uncertainty about the estimate of forest carbon flux is as high as nearly 50% (Goward et al., 2008). Part of this uncertainty in quantifying carbon flux is due to carbon dynamics of landscape or regional forest ecosystems in response to natural and anthropogenic disturbances (Lane et al., 2010; Wang et al., 2010).

In recent years, great strides have been made through the integration of spatially-explicit ecosystem models, remote sensing derived land cover, eddy covariance measurements and environmental variables to quantify carbon cycling dynamics across multiple spatial and temporal scales (Keane et al., 2002; Rollins et al., 2006; Updegraff et al., 2010). As conventional forest inventory techniques and eddy covariance measurements are useful benchmarks to determine carbon sequestration for a specific vegetation types in certain landscape settings, ecosystem process models provide an important means of estimating the spatial and temporal details of changes in carbon storage and fluxes (White et al., 2000; Law et al., 2001; Thornton et al., 2002; Pan et al., 2006; Updegraff et al., 2010). Previous literature suggested that spatially explicit ecosystem models should not only capture the most critical interactions between environmental drivers and ecosystem processes, but also accurately convey the impact of natural and human disturbances on the processes of CO_2 uptake, storage and emission (White et al., 2000; Thornton et al., 2002; Lane et al., 2010; Updegraff et al., 2010). A critical evaluation of

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a model's ability to explain the within-site and between-site variability in forest inventory data or flux measurements is essential before broader scale applications of the model can be pursued (Law et al., 2001; Thornton et al., 2002; Pan et al., 2006). Thus, there is a growing need for coupled observational and modeling strategies to simulate and map response of carbon storage and cycling to natural and human disturbances for particular regions of concern.

A key determinant of a model's utility for specific landscapes or regions is the proper calibration of the model's driving variables with locally-applicable parameterization and sensitivity of the model's input parameters (Aber et al., 1997; White et al., 2000; Gertner, 2003; Matsushita et al., 2004; Miao et al., 2004, 2009; Makler-Pick et al., 2011). To examine the applicability of the Biome-BGC model across a range of conditions, for example, White et al. (2000) collected highly site- and species-specific eco-physiological parameters for major temperate biomes and assessed the factorial sensitivity of NPP (net primary productivity) for five critical parameters. For a given species or biomes, variances of many eco-physiological parameters are high enough to significantly influence prediction quality. For instance, the allocation ratio of new stem carbon to new leaf carbon of pitch pine (*Pinus rigida* Mill.) and white oak (*Quercus alba* L.) ranged from 1.28 to 1.99 and from 0.80 to 1.36, respectively (Olsvig, 1980; White et al., 2000). Specific leaf area of the evergreen needle leaf (ENF) biome varied from 2.8 $m^2\,kgC^{-1}$ for *Pinus resinosa* to 11.5 $m^2\,kgC^{-1}$ for *Pinus taeda* of the eastern US forests (Scherzer and Hom, 2008). Thus in approaching a finer scale application of a broadly parameterized ecosystem process model, careful attention must be paid to examining this uncertainty. Further, the specific form and coefficients of the biogeochemical model equations are generally based on empirical laboratory and/or field observations, and thus are not always applicable under all conditions. Accordingly, sensitivity analyses are prerequisites for model building and application in any setting, be they diagnostic or prognostic (White et al., 2000; Saltelli, 2002; Saltelli et al., 2000; Miao et al., 2004; Miao and Li, 2007, 2010; Saltelli and Annoni, 2010).

The objective of this study is (i) to improve and calibrate the WxBGC model tool, a coupled Biome-BGC and WxFIRE model, by using locally-derived eco-physiological parameters and historical fire records; (ii) to make higher-order sensitivity and uncertainty analysis of the model carbon simulations to eco-physiological parameters; and (iii) to simulate and map carbon storage and fluxes of the US New Jersey Pinelands region. In this study, the WxBGC model was modified and validated against AmeriFlux (Long-term flux measurement network of the Americas) eddy covariance measurements in representative uplands forests that spanned the gradient from oak/pine to pine/oak to even more heavily fire disturbed pine/scrub oak during the years of 2005 and 2006 (Clark et al., 2004, 2009). Sensitivity analysis was carried out through the Extended Fourier Amplitude Sensitivity Test (EFAST) approach to examine the main effects and higher-order interactions between the eco-physiological input parameters and their contribution to the uncertainty of carbon dynamic predictions. The validated WxBGC model was then applied across a longer time span to examine model behavior in relation to fire disturbance and across the broader New Jersey Pinelands region to predict and map carbon dynamics and distribution at the regional scale.

2. Materials and methods

2.1. Model description

The WxBGC model was developed by the USDA Forest Service National LANDFIRE project (Steinwand and Nelson, 2005; personal communication) to generate consistent and comprehensive spatially explicit biophysical layers containing vegetation, litter, soil carbon, water vapor, fire disturbances, etc. of Multi-Resolution Land Characterization (MRLC) zones, in support of the US national LANDFIRE prototype and vegetation mapping. The WxBGC model integrate the WxFIRE and Biome-BGC models and is able to implement parallel simulations for large-scale landscape ecosystems at a finer resolution on a Linux (Red Hat 8.0)-based multiple-node cluster. As a widely calibrated model, the Biome-BGC model seeks to mechanistically represent ecosystem cycles of carbon, water, and nutrients through an integrated consideration of biology and geochemistry (Running and Gower, 1991; White et al., 2000; Thornton et al., 2002). The WxFIRE model is used to map vegetation, fuels, fire regimes and fire condition classes in the LANDFIRE project, and computes climate-based biophysical variables at any landscape scale or resolution using daily weather data, topography and soil parameters, and a diverse set of integrated environmental functions (Keane et al., 2002). Detailed descriptions of the Biome-BGC and WxFIRE models can be found in Running and Gower (1991), Thornton et al. (2002) and Keane and Holsinger (2005), respectively.

In the current study, we modified the WxBGC model to simulate carbon storage and dynamics of the New Jersey Pinelands. The model improvements are summarized as follows:

(i) *Combination of random and spatially heterogeneous fire disturbances into the model.* Inherited from the Biome-BGC model, the original WxBGC model set disturbance intensity (i.e., the whole-plant mortality rate parameters) through plant eco-physiological parameter input files and considered disturbance as a continuous and spatially homogenous disturbance. In other words, disturbance occurs at every pixel every time step with a constant intensity. The assumption may be true for chronic harvest cutting, herbivory and insect defoliation within large areas, but may not be applicable to episodic and spatially heterogeneous disturbances such as wildfire and windfall. Based on our review of historical fire occurrence records of the New Jersey Pinelands for the years between 1924 and 2007, we improved the model to randomly generate fire events between March and April for spring prescribed burning by using uniform random distribution and stochastically initiate wildfire event dates using a Gaussian distribution. In this study, we set April 20 as the mean and 40 days as the standard deviation of Gaussian distribution for New Jersey pinelands wildfire disturbance events, respectively. Therefore, our modified WxBGC version includes stochastic rather than deterministic fire disturbance. We empirically classified fire intensity (i.e., fire mortality rate) into five levels: no fire, prescribed burning (we assumed prescribed fire burned 30% of dead stem, litter and coarse woody debris, and 5% of live carbon which represents burned shrub and grass), moderate non-replacement wildfire (35% of all carbon to be burned), heavy non-replacement wildfire (50% of all carbon to be burned) and replacement wildfire (>60% of all carbon to be burned) (Little, 1979; Boerner, 1981; Boerner et al., 1988). We set fire disturbance to directly reduce a proportion of the initial values of all plant and fine litter state variables immediately before the disturbance as did Thornton et al. (2002). The affected proportions of the leaf, fine root, live wood, and fine litter C and N pools are assumed to be lost to the atmosphere.

(ii) *Combination of remote sensing land cover data into the model.* In order to generate consistent and comprehensive biophysical layers of carbon and water dynamics of MRLC zones, the original WxBGC model hypothetically assumes a spatially homogeneous land cover (i.e., evergreen needle leaf or grass) for given landscape or region. We coupled remote sensing-derived land cover mosaics into the model to spatially explicitly simulate comprehensive biophysical layers of real heterogeneous ecosystem mosaics. Except for meteorological data, the improved version includes 11-layers of geo-reference spatial inputs such as elevation (m), aspect (°), slope (%), hillshade (dimensionless), soil depth (m), sand percent, silt percent, clay percent, land cover type, fire time and intensity (percent of tree fire mortality). We set other geographic or environmental variables (e.g., albedo, N-deposition, etc.) to Biome-BGC default values (White et al., 2000; Thornton et al., 2002).

(iii) *Improvements of output functions.* The original WxBGC model does not output monthly and annual predictions but the 18-yr average predictions of 42 variables. We restructured the output functions of the WxBGC model into timely and spatially explicit variable-oriented output functions, i.e., 42 monthly and annual biophysical variables including transpiration, actual evapotranspiration, leaf area index, net ecosystem exchange of CO_2, gross primary productivity (GPP), soil carbon, etc. The internal time step of the model is still daily. Theoretically, the model could output daily predictions, but output file sizes would be as high as over hundreds gigabytes for the New Jersey Pineland at finer resolution (say less than 100-m resolution), therefore the daily output function was inactivated.

It is worth noting that the original model classified DEM and DEM derivatives into several group levels and aggregated some similar neighbor pixels into one map unit to reduce total pixel numbers and computations due to the large spatial scale of MRLC zone 60. The improved version is straight up the original pixels of land cover and geo-referenced environmental variables.