Carbon dynamics in heterogeneous landscapes: fusing remote sensing and spatial ecological models.

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ABSTRACT

Mitigation of global atmospheric CO_2 concentration is possible in north-temperate forests, but large measurement uncertainties currently prohibit directed land management. The uncertainties are associated with finely scaled, but ubiquitous, spatial-ecological processes and their integrated effects on carbon sequestration over large areas. Caused by landcover changes—but persisting long after the initial transition—these "edge effects" increase adjacent productivity by alleviating resource limitations of interior forests, to which current models are implicitly biased. To incorporate edge dynamics into modern carbon-accounting techniques, I will fuse spatio-temporal ecological models with remotely sensed landcover inventories: first remotely sensing relevant parameters of forest cover and heterogeneity, then using the mapped estimates to test a phenological edge effect, and finally simulating forest dynamics in heterogeneous, urbanizing landscapes. This project will shrink uncertainty surrounding temperate-forest productivity and ultimately bring ecological models driven by remotely sensed data closer to scales at which land management decisions are made.

INTRODUCTION

Land management to mitigate rising atmospheric CO_2 concentrations has attracted much interest, especially in forested landscapes [1]. However, for mitigation to occur, carbon-accounting models must be calibrated to the regional scales at which management acts. Currently, leading regional estimates are "scaled up" from sub-hectare mensuration plots by reference to classified landcover maps [2]. But due to the intentional location of plots in homogeneous forest stands, these summations are insensitive to spatial heterogeneity and may therefore impart errors when applied to heterogeneous, mixed-use landscapes [3].

Regional productivity is also estimated through atmospheric measurements of CO_2 concentrations [2]. In contrast to landcover inventories, these measurements are implicitly sensitive to spatial processes, but are applicable at scales far coarser than those of land management decisions. Atmospheric measurements estimate north-temperate forest productivity to be approximately 1 Gt C/yr greater than do landcover inventories [4], a difference attributed in part to the two methods' different treatments of spatial pattern [4,5].

Spatial landcover patterns drive forest carbon sequestration through known ecological processes. Deforestation impacts C pools directly, but may also leave lasting legacies of altered forest productivity [6]. Known as "edge effects", nonforest cover may increase neighboring forest productivity due to temperature-lengthened growing seasons [7] and to greater light availability at forest edges [8, 9, 10] but may also reduce net sequestration through thermally accelerated respiration.

Deforestation drives carbon flux, both directly through biomass removals and indirectly through edge effects. Both of these are important in temperate forests, where past agricultural clearing and current urbanization have made edges a dominant feature of modern forest landscapes. Over 43% of continental-U.S. forestland is within 90 meters of an edge [11], and swidden forest-clearing patterns similar to those of past American agricultural expansion are currently progressing in areas worldwide [12]. Given the prevalence of edges on modern landscapes, even a slight per-area effect could result in large impacts on regional and global C budgets.

Objectives

I will investigate edge effects on forest productivity in the mixed pine-hardwood forests of the North Carolina Piedmont, by fusing spatio-temporal ecological models with remotely sensed inventories of forest cover. I hypothesize that, although the net effect of urbanization is a loss of carbon, forest edges are more productive per unit area than intact forests, and so increase regional sequestration above current model estimates. Research will proceed in three steps: (1) remote sensing of forest parameters, (2) detecting a phenological edge effect at regional scales, and (3) re-scaling ZELIG, a spatially explicit forest gap model [13], to regional extents by meta-modeling it on remotely sensed parameters. In this proposal, I focus on the first and second steps, providing greater detail on remote sensing methodology and less on the subsequent modeling efforts. The models and rescaling via meta-modeling have been described in detail elsewhere [14, 15, 16].

Study site

North Carolina's Triangle region, located on the Piedmont Plateau and named for its polycentric urbanization pattern defined by the apical cities of Raleigh, Durham, and Chapel Hill, experienced a 38 % human population increase between 1990 and 2000 [17]. The area's pre-industrial land use was predominantly shifting agriculture, with abandoned fields succeeding through pine to hardwood forests [18], but this pattern has been superceded in many locations by recent urban development [16]. Succession in these forests is visible as a shift from persistent- to deciduous-leaved vegetation [18, 19], and compared to interior forest, edges are characterized by greater, more variable temperatures and increased annual growth rates of several tree species [10].

The dynamics of Piedmont forests are well known, and so provide an excellent opportunity for model calibration and validation. Also, their representation of forest↔agriculture→urban dynamics makes these suburbanizing, forest-aggradation landscapes ideal case studies of the linkages between landuse, landcover, and carbon dynamics occurring globally.

METHODS

I will accomplish the proposed research in three stages: (1) remote sensing of forest parameters, (2) detecting a known fine-scale edge effect in regional-scale imagery, and (3) modeling regional landcover dynamics. The project will thus move from detection and measurement of edges, to rescaling one particular edge effect, to simulation of forest dynamics as affected by edge. The first stage is a prerequisite to both later stages, and so is already well under way. The second stage will use time-series of MODIS Enhanced Vegetation Index (EVI) to test a hypothetical lengthening of the growing season at edges. In the third stage, I will use ZELIG and a simple urbanization model [16] to simulate forest carbon response to the dynamic edge environment.

1. Estimation of forest parameters: *(October, 2004 – December, 2005)*

This project requires a large, multivariate dataset (Table 1). The majority of these data will be remotely sensed, and the remainder will be gathered from the Duke Forest archives or measured by myself in the field. Remote-sensing techniques are described for each objective in the sections below.

Table 1. Project data requirements and sources.

Parameter	Source	Spatial coverage	Temporal coverage
forest composition	Landsat	regional	1986 – 2001
forest edge	Landsat	regional	1973 – 2001
forest height	lidar, SAR, stereography	sub-regional	2001 – 2003
phenology	MODIS	regional	daily after 2/24/2000
Terrain	lidar	regional	2001
DBH/ basal area	Duke Forest	variable	ca. 1930 – present
tree-species composition	Duke Forest	variable	ca. 1930 - present

1a. Development of composition and edge rasters: (January, 2005 – August, 2005).

Maps of forest composition and edge are necessary to extrapolate fine-scale simulation results regionally. I developed an algorithm to estimate deciduous- and persistent-leaved vegetation cover from seasonal pairs of Normalized Difference Vegetation Index (NDVI) images and applied it to an atmospherically corrected Landsat pair from 2001. I also calculated an edge index, dpNDVI, for each Landsat pixel in the Triangle as the maximum difference of percent-scaled NDVI between opposite cardinal and diagonal pairs of cells within a 9-pixel focal window. Not all edges are discrete at measurable scales, and the NPP response to slight edges is unknown. It is therefore necessary to retain as much information as possible in the metric, so that this variation is not excluded prior to estimation of its effect. To validate the edge map, I sampled the Duke Forest to likewise measure edges in tree basal area (dBA) spanning the dpNDVI gradient. BA- and NDVI-edge were significantly, but weakly correlated, but dpNDVI was decidedly preferable to dBA for detecting edges on mega- to giga-pixel landscapes. This is due to logistical constraints of field measurement in large landscapes, but also because of the remarkable sensitivity of dpNDVI to known edges, such as those associated with the adjacency of roads and forest (Fig. 1). I am approaching the successful completion of this stage of the project, and the generated data products—forest-composition from Landsat pairs for 1986, ‘91, ‘97, and 2001 and edge from 1984, ’86, ’89, ’91, 97, and 2001—will be used both as calibration for forest simulations and as data inputs to regional meta-models.

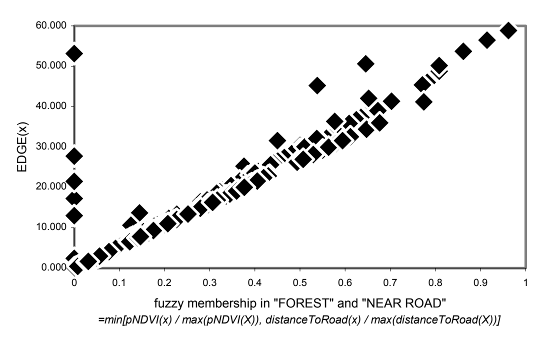

Figure 1. Correlation of NDVI-edginess and fuzzy membership in “roadside forest” ($n = 343$, $r = 0.953$, $p < 0.01$.).

1b. Regional biomass measurement: (October, 2004 – December, 2005)

Vincent and Saatchi (1999) recommended P-band synthetic aperture radar (SAR) backscatter measurements calibrated to lidar altimetry and interpreted with multispectral data as the most effective and economical means of estimating carbon stocks at regional scales. Collaborating with Paul Siqueria at NASA Jet Propulsion Labs (JPL) and doctoral candidate Mike Wolosin at Duke University, I have compiled a dataset capable of testing their recommendations. The dataset consists of five components: (1) X- and P-band returns and backscatter rasters collected by the GeoSAR instrument over a 343-km^2 area of the Triangle in October, 2001; (2) a forest-height raster estimated by subtracting the P- from the X-band return of the GeoSAR data; (3) point-measurements of tree height selected from the North Carolina Floodplain Mapping Program’s airborne lidar dataset; (4) a canopy-depth raster interpolated from points estimated stereographically from aerial videography; and (5) persistent- and deciduous-leaved vegetation rasters estimated from a winter/summer pair of 1999 Landsat images.

The primary aim of our collaboration is to cross-validate the three forest-height datasets using the forest-composition data as stratification. But once validated, the forest-heights may be used to initialize and calibrate forest models, and the P-band backscatter measurements may be used as a proxy for aboveground forest biomass. Thus, fusion of radar and multispectral data will fuel forest-ecosystem simulations through ZELIG and will be applicable at regional scales, and the P-band backscatter measurements will help translate the simulated states of forest patches into carbon estimates. Much research is still needed on how best to measure biomass with the accuracy, precision, and efficiency required for regional application, and I do not promise a final solution here. However, my analyses of this unique dataset will test the current state of the science and thereby push us closer to an operational regional biomass-estimation system.

2. Edge effects on GPP: *(January, 2006 – December, 2007)*

A location's annual gross primary production (GPP) is its daily GPP, summed over the days of the growing season. As such, it is governed directly by the number of days between the vernal and autumnal growing-season limits. The autumnal limit is driven by a variety of factors interacting with the vegetation community, but the vernal limit is determined largely by species composition and temperature [7, 20]. South-facing edges in Piedmont forests are, on average, annually 2° C warmer than interior forest [10], and increased solar radiation on south-facing edges is even sufficient to shift the composition of boreal forest stands to more productive tree species [9]. In that increased radiation accelerates green-up, and the length of the growing season limits GPP, the increased energy load of forest edges may cause a positive residual effect of forest clearing on GPP.

The edge effect is unlikely to integrate over short time-spans to balance biomass losses by forest clearing, but it may persist over the duration of the edge itself, integrating over time to equal a significant, but currently unknown increase in suburban forest GPP. To investigate the magnitude of this effect, I will statistically estimate the effect of dpNDVI on a phenological series of MODIS-derived Enhanced Vegetation Index (EVI) rasters.

Piedmont vernation, or "green-up", regularly happens entirely within the month of March, and so 16-day EVI-composites (MOD 13) may not be able to resolve differences in green-up date. It will therefore be necessary to compute EVI directly from daily MODIS surface reflectances (MOD 9) during March. The MOD 9 image-series is available from February 24, 2000 to the present, so each pixel will have five years of data from which to build an expectation of the edge effect. The dpNDVI raster, calculated originally from Landsat data (30-m resolution) will be re-scaled to 250-m (MODIS) resolution by summation within the extent of each MODIS pixel, and forest-community types will be derived from a pair of persistent- and deciduous-leaved vegetation rasters, aggregated to 250-m resolution by averaging the fractional cover of included Landsat pixels. The edge effect will be calculated over the range of dpNDVI, in units of EVI-days, as the average deviation from the expected greenup-date of each community type. Increased temperatures associated with urban pavement likewise accelerate green-up [7], and so to eliminate indirect, spurious correlation with this "urban heat island" effect, MODIS 8-day composites of land-surface temperature (MOD 11) will be resampled to daily resolution by linear interpolation and included in the regression. Both of these partial regression coefficients will then be multiplied by the temperature- or dpNDVI-value of each pixel in the landscape and summed, providing area-weighted estimations of the regional edge and heat-island effects on GPP.

3. Model-based integration: *(January, 2007 – December, 2008)*

To integrate the various data types and extrapolate fine-scale processes regionally, I will use two models, a forest gap simulator and a landcover-change classification tree. First, I will use ZELIG version FACET [15, 21] to integrate field- and remotely sensed data and to extrapolate demographic processes to the regional scales of Landsat and MODIS products. Second, a classification tree of landcover change [18] will provide landcover and edge scenarios to the regional, FACET-based simulations of carbon dynamics.

Gap models simulate forest demography and structure at spatial resolutions near that of remotely sensed parameters, and can therefore be used to rescale processes by transferring relationships from the scales of field data—through those of image-derived parameters—to the regional scales of land management and policy [14]. Whereas most gap models simulate patch dynamics in spatial isolation, ZELIG patches influence their neighbors through local processes such as shading, and so ZELIG is uniquely capable of simulating forest-ecosystem dynamics in heterogeneous landscapes [22]. Coupling sub-models of demographic processes (i.e., tree establishment, growth, and mortality), soil water balance, and C:N dynamics, ZELIG simulates complex ecosystem feedbacks in response to spatial forest heterogeneity.

Using ZELIG's FACET version, I will simulate forest patches of various characteristics (e.g., edge-value, aspect, stand age, soil type, topographic position, forest composition) and integrate forest processes to stand biomass dynamics. I will then extrapolate these processes to coarser spatial scales by regressing stand behaviors on meso-scale parameters and simulating a regional raster of MODIS pixels. The calibrated FACET model will be exercised in Monte Carlo fashion to explore the parameter space of stand characteristics and generate a higher-level summary of how edge effects, stand condition, and environmental constraints affect forest process and biomass dynamics.

To provide boundary conditions for FACET simulations, I will generate landscapes of forest cover with a classification tree (CART [24]) of landcover change calibrated to the Triangle's dynamics over the past ten years [18]. Extrapolating current trends, the CART model will forecast urbanization at the spatio-temporal scale of land management decision-making, and these forecasted scenarios will be used as boundary conditions to the forest models. This CART model has been used to analyze spatial relationships in suburban deforestation [16] and predicts forest conversion with nearly 85% accuracy—sufficient for the landcover change scenarios to be considered here.

Finally, I will use the forest and landcover change models to estimate biomass losses to forest urbanization and gains to forest succession, ultimately arriving at a regional biomass dynamic and carbon balance. This last computation is nearly identical to current carbon accounting methods, but due to the spatial sensitivity of the underlying models, will calculate budgets inherently reflecting spatial processes.

Significance and potential for Earth Science applications

A projected outcome from NASA's Earth System Science program is a 50% improvement in the confidence of estimates of atmospheric CO_2 concentration by 2014. In order to manage landscapes for carbon sequestration, land managers and policy makers need these robust estimates of carbon flux for the landscapes under their supervision. However, current regional carbon accounting methods are too uncertain to support regional management. Explicit inclusion of known edge effects may narrow the uncertainty in regional model estimates and allow entry of local landholders into carbon markets. The operational, regional carbon accounting system that this study works toward would require remotely sensed measurements of forest parameters and ecological models to translate these parameters into extant and projected productivity. Ultimately, quantification of landscape carbon flux will allow migration of climate change from an economic externality to an integral component of the human system, and this study, targeted directly at one of its major sources of uncertainty, is a means to that end.

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