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Modelling carbon storage in highly fragmented and human-dominated landscapes: Linking land-cover patterns and ecosystem models

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ABSTRACT

To extend coupled human–environment systems research and include the ecological effects of land-use and land-cover change and policy scenarios, we present an analysis of the effects of forest patch size and shape and landscape pattern on carbon storage estimated by BIOME-BGC. We evaluate the effects of including within-patch and landscape-scale heterogeneity in air temperature on carbon estimates using two modelling experiments. In the first, we combine fieldwork, spatial analysis, and BIOME-BGC at a 15-m resolution to estimate carbon storage in the highly fragmented and human-dominated landscape of Southeastern Michigan, USA. In the second, we perform the same analysis on 12 hypothetical landscapes that differ only in their degree of fragmentation. For each experiment we conduct four air-temperature treatments, three guided by field-based data and one empirically informed by local National Weather Service station data. The three field data sets were measured (1) exterior to a forest patch, (2) from the patch edge inward to 60 m on east-, south-, and west-facing aspects, separately, and (3) interior to that forest patch. Our field-data analysis revealed a decrease in maximum air temperature from the forest patch edge to a depth of 80 m. Within-patch air-temperature values were significantly different ($\alpha = 0.01$) among transects (c.v. = 13.28) and for all measurement locations (c.v. = 30.58). Results from the first experiment showed that the interior treatment underestimated carbon storage by ~8000 Mg C and the exterior treatment overestimated carbon storage by 30,000 Mg C within Dundee Township, Southeastern Michigan, when compared to a treatment that included within-patch heterogeneity. In the second experiment we found a logarithmic increase in carbon storage with increasing fragmentation ($r^2 = 0.91$). While a number of other processes (e.g. altered disturbance frequency or severity) remain to be included in future experiments, this combined field and modelling study clearly demonstrated that the inclusion of within-patch and landscape heterogeneity, and landscape fragmentation, each have a strong effect on forest carbon cycling and storage as simulated by a widely used ecosystem process model.

1. Introduction

Processes of land-use and land-cover change (LUCC) are characterized by local complexities and feedbacks that produce global consequences (Foley et al., 2005), including effects on climate (Houghton et al., 1999; Schimel et al., 2000; Barford et al., 2001). The alteration of the earth's surface changes the albedo (Pielke et al., 2002); sensible and latent heat flux; evaporation (Betts et al., 1996); biodiversity (Poschlod et al., 2005); biophysical characteristics that contribute to nutrient and hydrological cycling (Hubacek and Vazquez, 2002); and carbon (C) storage (Dixon et al., 1994). Each of these biophysical functions significantly influence global climate (Riebsame et al., 1994). Globally, land-use change in the 1980s and 1990s contributed 1.4[1] and 1.6 Pg C yr^{-1} to the atmosphere (1 Pg = 10^{15} g = 1 Gt) and represented approximately 30% of anthropogenic efflux of carbon to the atmosphere (Dixon et al., 1994). Conversely, mid-to-high latitude forest expansion driven by reduced agricultural land use in the 1990s (Gower, 2003) contributed to a net carbon sink by land-use within these regions (Fan et al., 1998; Caspersen et al., 2000).

Because LUCC is complex and driven by human activities, understanding its' effects on ecosystem processes involves studying a coupled human–environment system. To date, a number of projects have determined the dominant mechanisms influencing these coupled systems and in some cases mapped (with measured error)

[1] Land-use change flux based on Chapter 7 of the 2007 Intergovernmental Panel on Climate Change (IPCC) report, which noted the land-use change induced carbon efflux to the atmosphere to be 1.4 (0.4–2.3) Pg C yr^{-1} for the 1980s and 1.6 (0.5–2.7) Pg C yr^{-1} for the 1990s. Values in parentheses represent range of uncertainty.

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observed spatial patterns of LUCC (e.g. Deadman et al., 2004; Huigen, 2004). However, most LUCC projects fall short by failing to incorporate measurements of key ecological functions (e.g. biogeochemical cycling) and how those functions affect and are affected by human systems. It is necessary to represent both of these types of interactions if we wish to assess the influence of local LUCC on global climate change. This problem is recognized by a number of government agencies and affiliations (e.g. Turner et al., 1995; Lambin et al., 1999; Gimblett, 2002; Parker et al., 2002; Lobo, 2004; Gutman et al., 2004; GLP, 2005).

Paralleling LUCC initiatives are ecological studies that use models to explore the effects of succession, disturbance, competition, biophysical changes, and geography on ecosystem structure, function, and biodiversity (Parton et al., 1987; Jeltsch et al., 1996; He et al., 1999a,b; Gustafson et al., 2000; Shugart, 2000; Urban and Keitt, 2001; Howe and Baker, 2003). Ecosystem process models that focus on biogeochemical cycling have found utility in global climate change research because they are typically applied at resolutions $\geq$1 km^2 and can quantify evapotranspiration, water use efficiency, carbon (C) and other nutrient pools and fluxes. In contrast to the coarse-scale resolution ($\geq$1 km^2) typically employed by ecosystem process models, some models such as BIOME-BGC or 3-PG have been successfully applied at a resolution of 30 m (Coops and Waring, 2001). While successfully applied at relatively fine resolutions, few if any such models incorporate the effects of ecosystem patch edge, shape (e.g. irregular forest patch perimeters), size, or edge-to-area ratios on ecosystem function. Therefore, applying a model such as BIOME-BGC to simulate forest C in two landscapes with equal forest area, but different spatial pattern, would produce equal amounts of total forest carbon.

However, microclimate and biophysical characteristics are altered along a transition zone between the adjacent ecosystem (e.g. prairie) and the forest interior (Matlack, 1993) on the scale of tens to hundreds of meters. On exposed forest patch edges, light and wind may penetrate beneath closed canopies causing gradient changes in temperature, moisture, and the vapour pressure deficit deep into the forest (Chen et al., 1995). The depth of penetration and alteration of climate characteristics is a function of forest type, structural characteristics (e.g. stem density), aspect, and side-canopy presence (Matlack, 1993). For eastern deciduous forests these effects have been observed to penetrate into patches in the range 15–50 m, while edge-effect penetration has been observed to be greater than 240 m in Douglas fir forests (Chen et al., 1995).

In addition to edge effects, landscape heterogeneities in the form of patch shape, patch size, landform, and proximal land use and land cover may influence local climate. For example, the perimeter/area ratio of a patch along with patch size can describe the degree of core area of a forest patch that is buffered by local climate (Collinge, 1996). The physical characteristics of the landscape (i.e. landform) such as slope and aspect influence the degree of incident solar radiation; elevation influences adiabatic processes; and proximity to water features can influence humidity levels, each of which can affect local climate (Rosenberg et al., 1983). Similarly, different types of land uses and land covers have also been shown to influence local climate (Landsberg, 1970). For example, urban heat islands have extended influence on temperature values beyond city limits (Arnfield, 2003) and agricultural lands can affect heat fluxes and influence thunderstorm frequency (Raddatz, 2007).

As a step towards integrating LUCC and ecosystem models focused on biogeochemical cycling, we addressed issues of edge and landscape heterogeneity, whereby the landscape is composed of forest patches of variable shapes and sizes within a matrix of other types of land cover. Our research addresses two specific questions through analysis of ecological field data, its subsequent incorporation into BIOME-BGC, and application to the heterogeneous landscape of Southeastern Michigan. The primary question is: How does a more realistic treatment of forest patch size and shape in a fragmented and human-dominated landscape, through microclimate edge effects, alter calculations of the forest carbon balance using the ecosystem process model BIOME-BGC? In order to address this question we additionally explore: What are the spatial and temporal differences in air temperature in forest patch edges and interior in a particular human-dominated landscape, and how far into a typical forest patch do these microclimatic differences penetrate?

2. Materials and methods

2.1. Study area

Our study area was located within the heterogeneous, fragmented, and human-dominated landscape of Southeastern Michigan. Forest patches in this region primarily exist as secondary growth forest, remnants of abandoned agricultural land. Agriculture peaked as a land use in the area in the late 1880s to 1900 and has declined from 1910 to the present. Since then, heterogeneity of the landscape has been increasing due to LUCC at the urban–rural interface. While the region is representative of land-use histories and land-cover patterns of the Midwest and populated regions in the eastern temperate zone of North America, we chose a single township (i.e. Dundee Township, in Monroe County, Southeastern Michigan, USA) 12,577 ha in area, as our study area to conduct both field work and model application (Fig. 1).

In 2001, approximately 10% (1277.28 ha) of the study area was forested (Homer et al., 2007—NLCD data). The amount of forest in Dundee Township was below average for Southeastern Michigan where the mean during the same time period was 28% forest (standard deviation 13%) based on 140 townships sampled from the 10 adjoining counties (Genesee, Lapeer, Lenawee, Livingston, Macomb, Monroe, Oakland, St. Clair, Washtenaw, and Wayne). Dundee Township illustrates the extent to which the regional landscape has been modified, fragmented, and become dominated by anthropogenic land uses. The township is now composed of 262 forest patches in an agricultural and residential matrix with a mean forest patch size of 5.02 ha (standard deviation 10.45 ha). The total patch edge in Dundee Township is 398 km and the edge density (total edge/total landscape area) is 31.64 m ha^{-1}.

From within Dundee Township we chose a single forest patch, typical of the region, to conduct our field study. The forest patch provided ideal characteristics to study changes in daily minimum and maximum temperatures from the forest patch edge inward. Our field study patch consisted of a single, privately owned, eastern deciduous forest patch that was situated (1) 0.5 km from the nearest creek and 0.7 km from other tree cover, (2) on a slope less than 3°, and (3) within a uniform surrounding vegetation (i.e. corn and soy crops). The edges of the selected patch were linear, partially closed side-canopy, and perpendicular to the cardinal directions. The 220 m $\times$ 210 m (4.62 ha) forest patch was approximately 80 years in age with a canopy height of 24–30 m. The dimensions of the patch ensured that measurement points were not located where the influence of two adjacent edges could overlap. To the best of our knowledge the patch had not experienced any significant major disturbance in the past 80 years, although some wind throw is a normal part of the disturbance regime in this region (Frelich, 2002) and did occur along two of our three transects during our study period.

Our field study patch was located within the Maumee Lake Plain ecosystem type (Albert, 1995), which runs across much of the eastern boarder of Southeast Michigan. Forests in this ecosystem are characterized by beech-sugar maple or elm-ash species (Albert, 1995). The loamy sand on which the site is located was produced from glacial outwash sand and gravel, postglacial alluvium, and