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Estimating forest carbon fluxes in a disturbed southeastern landscape: Integration of remote sensing, forest inventory, and biogeochemical modeling

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[1] Quantifying carbon fluxes between the atmosphere and land surface requires detailed knowledge of the disturbance regime as well as the photosynthetic response of vegetation to climate. In this study, we use a combination of satellite remote sensing, forest inventory data, and biogeochemical modeling to assess forest carbon fluxes from central Virginia, a landscape pervasively disturbed by harvest. Using historical Landsat imagery, we have reconstructed the disturbance history and age structure of forest stands at a resolution of 90 m, from 1973–1999. Forest inventory data provide breakdowns of forest type and age structure for older stands. These data, together with climate and vegetation greenness from advanced very high resolution radiometer (AVHRR), are used as inputs to a version of the Carnegie-Stanford-Ames (CASA) biogeochemical model, which simulates the uptake, allocation, and respiration of carbon and associated effects of disturbance. Modeling results indicate that forests in the study region have an average net ecosystem productivity (NEP) of ~80 gC m^{-2} yr^{-1}, reflecting the young age structure of rapid-rotation forests. Variability in annual forest carbon fluxes due to variations in clearing rate and climate are also examined. We find that observed variations in clearing rate may account for NEP variability of ~30 gC m^{-2} yr^{-1}, while observed variations in climate may account for NEP variability of 80–130 gC m^{-2} yr^{-1}. Increased temperatures tend to drive both increased photosynthesis and increased heterotrophic respiration, buffering the system from larger swings in NEP. However, this response depends strongly on stand age.

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1. Introduction

[2] The consensus view is that about one quarter of the world's fossil fuel carbon emissions are being absorbed by land vegetation, through some uncertain combination of fertilization, climate enhancement of growth, and recovery from disturbance [e.g., *Bousquet et al.*, 2000; *Battle et al.*, 2000; *Casperson et al.*, 2000; *Pacala et al.*, 2001; *Houghton et al.*, 1999; *Nemani et al.*, 2002]. This conclusion reflects a long-term discrepancy between the observed increase of atmospheric carbon dioxide and known sources and sinks from fossil fuel emissions, tropical deforestation, and ocean solubility. However, this long-term perspective camouflages significant year-to-year variability. The annual rate of increase in atmospheric carbon dioxide has not been constant, but has varied from 1 to 5 Pg/yr since 1980 [*Houghton*, 2000] and is mainly driven by variability in the land sink [e.g., *Battle et al.*, 2000].

[3] Common process-based ("bottom-up") approaches used to identify the nature of terrestrial carbon sources and sinks include direct, local measurements using eddy flux methodologies [e.g., *Barford et al.*, 2001], analysis of forest inventory records [e.g., *Turner et al.*, 1995], and integration of historical land use records within biogeochemical models [e.g., *McGuire et al.*, 2001]. Each approach has limitations. While flux tower observations have been pivotal in linking physiologic processes to ecosystem carbon fluxes, the land area sampled by flux networks is too limited for regional and continental assessments [*Saleska et al.*, 2003; *Thornton et al.*, 2002]. These data may be used instead to calibrate biogeochemical models capable of simulating ecosystem fluxes forced by changing environmental conditions. Similarly, forest inventories can provide information on forest age and biomass, which can also be used to parameterize biogeochemical models. However, these inventories are often at decadal time steps and at spatial resolutions usually determined by political jurisdictions (such as counties in the case of the USFS Forest Inventory and Analysis or FIA Program).

[4] A variety of biogeochemical models have been published, generally using some combination of climate data, vegetation parameters, and remote sensing to estimate photosynthetic productivity of ecosystems. One common

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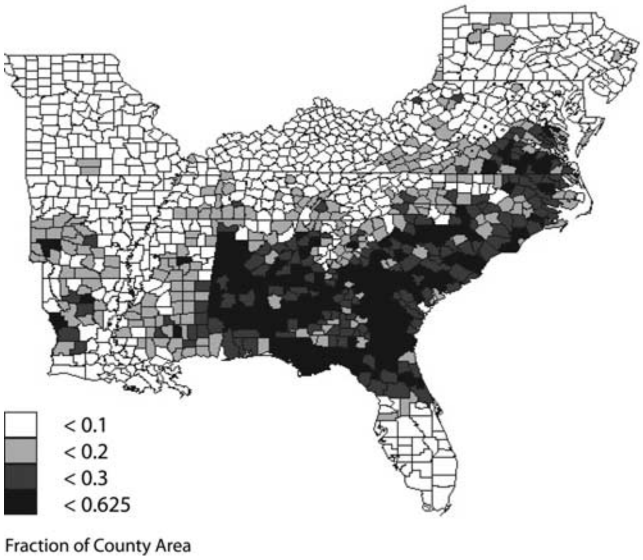

Figure 1. Map of southern and mid-Atlantic regions of United States, showing the percentage of each county occupied by young (<20 years old) timberland. The zone of rapid rotation pine forestry appears as a "belt" of young stands following the coastal and Piedmont physiographic zones of the region. Data are from U.S. Forest Service Forest Inventory and Analysis database.

difficulty has been the lack of information on regional disturbance patterns within forests. Disturbance events themselves (e.g. fire, insect defoliation, harvesting) tend to release large amounts of carbon to the atmosphere. Conversely, during recovery forests add biomass, sequestering carbon from the atmosphere. As a result, stand age, which depends directly on the disturbance history, is a strong determinant of net ecosystem productivity in forests. While some modeling studies have begun to incorporate disturbance [e.g., *Hurtt et al.*, 2002; *McGuire et al.*, 2001; *van der Werf et al.*, 2004], most rely on coarse-resolution data sets that only resolve the largest events. Fully quantifying the effects of human-induced disturbances, including logging, harvest, land-cover change, and urbanization, requires regional data on disturbance history collected at high resolution. The 33-year Landsat record, used in this study, offers one useful source for this information [*Cohen et al.*, 2002].

[5] In this study we combine biogeochemical modeling, remote sensing, forest inventory, and eddy flux data to study forest net ecosystem productivity in central Virginia. The study region is representative of the southeastern United States, where rapid-rotation harvests of planted pine have led to a condition of "perpetual disturbance," and the long-term replacement of natural pine and mixed-deciduous forest with young planted pine could have significant regional effects on carbon sources and sinks. Although the study area is relatively small, it offers a prototype for approaches that might be carried out on a continental scale. Our objectives are to (1) demonstrate a viable approach for incorporating both disturbance history and interannual climate variability within biogeochemical models in order to calculate realistic carbon fluxes; and (2) evaluate the relative contributions of disturbance and climate to interannual variability of carbon fluxes from the region.

6. Conclusions

[54] In this study we explored the integration of biogeochemical modeling, satellite-derived disturbance and photosynthetic measures, and forest inventory data to predict region patterns in NEP and NEP variability. Our key findings include the following. (1) Central Virginia forests acted as a biologic carbon sink during the study year of 1999, with an average biologic NEP of $\sim$80 gC m^{-2} yr^{-1}, reflecting the balance between high emissions from recent clear-cuts and high uptake by young regrowth. (2) These forests exhibit $\sim$80–130 gC m^{-2} yr^{-1} of peak-to-peak NEP variability due to climate and fPAR drivers, and about $\sim$30 gC m^{-2} yr^{-1} due to variability in disturbance rates. (3) NPP and Rh tend to covary in response to climate variations, thus acting as a "buffer" that prevents large swings in NEP. (4) Variability in NEP depends strongly on stand age.

[55] Current initiatives such as the North American Carbon Program require large-area, process-based assessments of carbon fluxes on monthly to annual timescales [*Wofsy and Harriss*, 2002]. Flux towers are invaluable for understanding the dynamics of specific sites, but their findings cannot easily be extrapolated across large areas [*Korner*, 2003]. Although regional in scope, this study has relied on biogeochemical modeling to make this extrapolation to scales of $\sim$150 km. Calibrating models to flux and inventory records, and then driving these models with spatially explicit records of vegetation type, climate, and disturbance, constitutes a viable approach for making spatially explicit, continental assessments of carbon fluxes.

[56] However, given the importance of forest age structure for determining both NEP and its variability, the paucity of knowledge on the age structure of the world's forests (including those of the United States) remains a roadblock for carbon studies. New technologies (such as spaceborne lidar) as well as improved forest inventories explicitly designed for carbon studies, could improve this situation. Optical data records, such as those from Landsat, can also be useful for characterizing recent forest dynamics across the globe since the 1970s.