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MODELING THE EFFECT OF LAND USE ON CARBON STORAGE IN THE FORESTS OF THE PACIFIC NORTHWEST

Warren B. Cohen[1], David O. Wallin[2], Mark E. Harmon[2], Philip Sollins[2], Christopher Daly[3], and William K. Ferrell[2]

[1]USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR 97331 USA
[2]Department of Forest Science, Oregon State University, Corvallis, OR 97331 USA
[3]Department of General Science, Oregon State University, Corvallis, OR 97331 USA

ABSTRACT

Global warming, as a result of increasing CO_2 and other greenhouse gases in the atmosphere, has been hypothesized for many years. The precise role of land use in this scenario, though widely recognized as important, remains largely unknown. One compelling question is "How will the balance of carbon in the terrestrial ecosystem change in response to a variety of land use practices?" We describe a study in which methodology is being developed to help narrow this uncertainty for a major terrestrial carbon pool, the temperate forests of the Pacific Northwest region of the United States. In this study we are further developing a carbon storage model that responds to forest harvesting, the dominant usage of land in the region. By linking the carbon model to satellite imagery and a climate simulation model, we are estimating the current amount of carbon stored in the forests of the Pacific Northwest. The archive of LANDSAT Multispectral Scanner (MSS) images permits a twenty year historical perspective of land use changes in the region. With these data we are assessing the recent historical impacts of regional land use on forest carbon stores.

INTRODUCTION

Ameliorating the effects of global climate change on natural and intensively managed ecosystems will require considerably more knowledge than we currently possess about the responses of ecosystems to changes in temperature, moisture, nutrient availability, and disturbance. A central question yet to be answered is the role of the terrestrial ecosystem in regulating atmospheric concentrations of greenhouse gases.[1,2,3] Answering this question largely depends on our ability to assess how the net storage of carbon in the terrestrial ecosystem will change. Two primary factors will alter carbon storage: 1) direct effects of changing climate and CO_2 concentrations on ecological processes, and 2) natural disturbances and land use. In this paper we focus on land use, a critical topic globally that has been identified as a priority issue in research initiatives at national and international levels.[4] Land use is particularly important to incorporate more directly into global climate change assessments because it is amenable to management and may drive or limit species migrations.[5,6,7]

In contrast to fossil fuel release,[8] the contribution of CO_2 from the terrestrial ecosystem, and the effect of changes in land use patterns on this contribution, have been extremely difficult to estimate at the global scale.[1,9] Current estimates of carbon released as a result of land use changes alone range from 0.4 to 2.6 Pg of carbon per year.[10,11] Likewise, estimates of whether the terrestrial ecosystem is a net source, sink, or in equilibrium vary among studies.[1,2,3] These large uncertainties stem in part from a lack of information at the regional scale concerning land use. This lack of information will persist unless the importance of regional scale natural disturbances and changes in land use are adequately addressed.

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In this paper we focus on the Pacific Northwest region of the United States (western Washington and Oregon, including the eastern slopes of the Cascade Mountains), where land use change over the last several decades has been extensive. Land use change includes type conversion (e.g., forest to urban or agriculture), but in the Pacific Northwest this has occurred on a relatively insignificant proportion of the landscape. The majority of land use change that has occurred is the conversion of natural forest to plantation or, inadvertently, to brush fields. Although on a global scale conversion of natural forest to plantation forest may have a relatively insignificant impact on carbon flux, in the Pacific Northwest the impact of this conversion appears to be significant. In preliminary work with our carbon storage model (Disturbed Forest Carbon, DFC) we estimated that as much as 2% of the carbon released from land use change globally in the past century may have originated in this region as a result of harvesting old-growth forests.[12] This is largely because forests of the region are more productive, and therefore have the potential to store more carbon, than any other forest ecosystem in the world.[13]

Objectives

Two specific objectives are addressed here: 1) to further develop our stand-level forest carbon model, DFC, so that it can be used to evaluate consequences of land use on the storage of carbon in a variety of forest systems, and is therefore applicable at a regional level; and 2) to use the LANDSAT Multispectral Scanner (MSS) data archive, in conjunction with DFC and a climate simulation model, to quantify changes in carbon stores in Pacific Northwest forests during the last two decades.

METHODOLOGY

Harmon et al.[12] developed DFC to assess the effect of logging old-growth coniferous forests on carbon exchange between the forest and the atmosphere. The model has two basic modules: ONSITE and OFFSITE, as illustrated in Figure 1. ONSITE tracks carbon stores in a forest stand in separate pools, as a function of time since major disturbance, or stand age. Major driving variables for ONSITE are mean monthly temperature and precipitation. We are improving ONSITE so that processes (e.g., tree growth, death, and decomposition) respond to other important variables and to changing regimes of these variables at a given site. Currently, ONSITE simulates changes in carbon stores with succession for a "typical" Pseudotsuga/Tsuga stand. We also are parameterizing ONSITE for other forest types in the region. The OFFSITE module simulates the disposition of trees after harvest, taking into account breakage, the various products made from tree boles, and their rates of decay and destruction. Within OFFSITE, harvested boles are converted to various forest products including plywood, lumber, paper, and waste products. Logs being processed into each of these forest products have a parameter to define ratio of product to waste. In an earlier version, we divided wood products into long- and short-term storage classes, with turnover times of <5 years and >50 years.[12] Waste products were added to the short-term pool assuming the major use was as paper or fuel.

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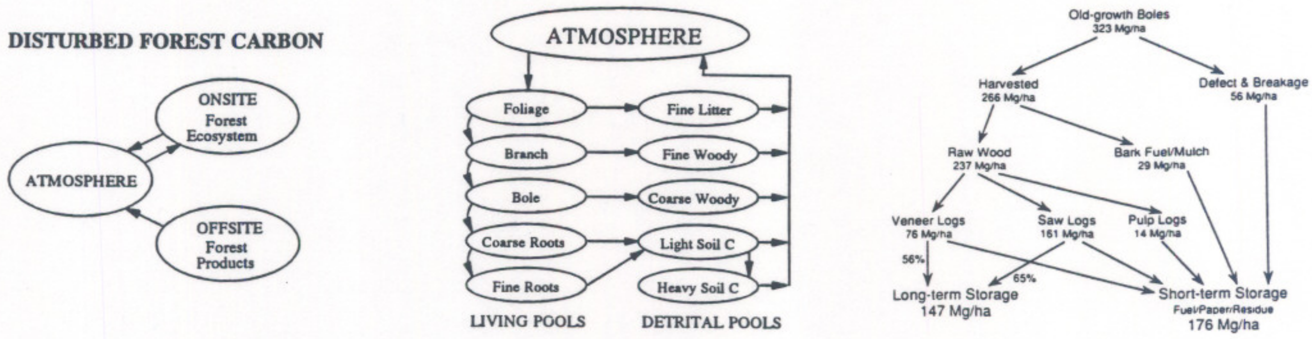

Figure 1. Left) Overall structure of the Disturbed Forest Carbon model (DFC). Center) Structure of the ONSITE module. Right) Structure of the OFFSITE module with hypothetical quantities of carbon shown.

The ways in which forest stands in the Pacific Northwest have been harvested and regenerated have greatly changed in the last 100 years. This has significantly altered the amount of carbon removed from the forest. There has been a switch from a period when wildfire and natural regeneration were the major stand replacement factors, to a period of ever-increasing harvesting and tree establishment (via planting) efficiencies. Thus, whereas most of the carbon 100 years ago remained on-site during stand replacement, now a large proportion of carbon is commonly removed and turned into forest products. Additionally, with different solar radiation and moisture regimes imposed by changing land use practices, wood decomposition rates have changed. To improve model estimates, we currently are incorporating into DFC new sources of data on utilization efficiencies and decomposition rates. An example of DFC output incorporating these new data is given in Figure 2.

Soil carbon varies markedly across the Pacific Northwest. Values range from lows of 30-40 Mg ha^{-1} on some high-elevation pumice soils[14] to over 250 Mg ha^{-1} at some forested sites along the Oregon Coast,[15] where the amount of carbon in the soil equals or even exceeds that in vegetation and litter. There is virtually no correlation between soil carbon levels and age or biomass of the forest. Other factors of soil formation, such as topography, climate, and parent material, appear to control soil carbon levels more than does vegetation. Depth of volcanic ash may be an especially important datum since ash-derived soils appear to have accumulated unusually large amounts of carbon. Earlier versions of DFC did not adequately incorporate these important soil formation factors to model soil carbon. We are now compiling available soil carbon data along with information on the controlling factors.

Extrapolation of DFC to a regional scale is a multi-step process. As Figure 3 illustrates, ONSITE is first run for a variety of temperature and precipitation combinations to create carbon storage look-up tables (LUT). Second, a stand age map is created from satellite imagery. Third, a climate simulation model (PRISM) is used to develop maps of temperature and precipitation regimes across the region from digital elevation model (DEM) and meteorological data. Finally, the first three steps are combined to create carbon stores maps. This final step is accomplished by combining the results of the first three steps, as follows. Temperature and precipitation for each forest stand (from the respective temperature and precipitation maps) dictates which carbon storage LUT to use, and stand age (from the age map) dictates where in the LUT to find the amount of carbon stored in each living and detrital pool of the ONSITE module for each stand. One carbon stores map will be constructed for each pool, and a total carbon stores map will be created by summing the individual pool maps. Use of the LANDSAT MSS data archive permits creation of carbon stores maps from 1972 to present. We are creating these maps at five year intervals (Figure 3).

Our approach to estimate stand age with satellite imagery is similar to that used in our earlier study.[16] There, we developed a regression model (r^2=0.81) using the wetness feature (referred to as the maturity index[16]) of the Thematic Mapper (TM) tasseled cap transformation[17] to predict stand age. The maturity index requires reflectance data from bands 5 and 7 of LANDSAT TM imagery, which MSS imagery does not have. However, subsequent work indicates that the normalized difference vegetation index (NDVI) also yields good results (Figure 4), and this index is easily calculated from MSS imagery. For use in this study, ground-level stand age data exist for well over 1000 sites around the region. All MSS imagery will be radiometrically normalized using procedures outlined by Hall et al.[18]

Data from nearly 300 meteorological stations around the region are being used in conjunction with DEM and a climate simulation model to obtain the required raster-based temperature and precipitation maps. For this we are using the PRISM model (Precipitation-elevation Regressions on Independent Slopes Model).[19] PRISM is uniquely suited to mountainous terrain, because it incorporates a conceptual framework that allows the spatial scale and pattern of orographic effects to be quantified and generalized.

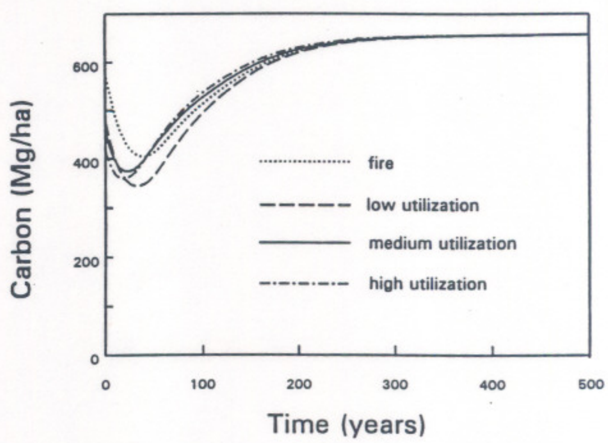

Figure 2. Example output from the DFC model. Shown are total carbon stores from a forest stand, over time, as a function of conditions under which stand replacement was initiated (e.g., wildfire and three degrees of wood removal from the site). The declines in carbon stores in the early stages of stand replacement are a result of biomass decomposition.

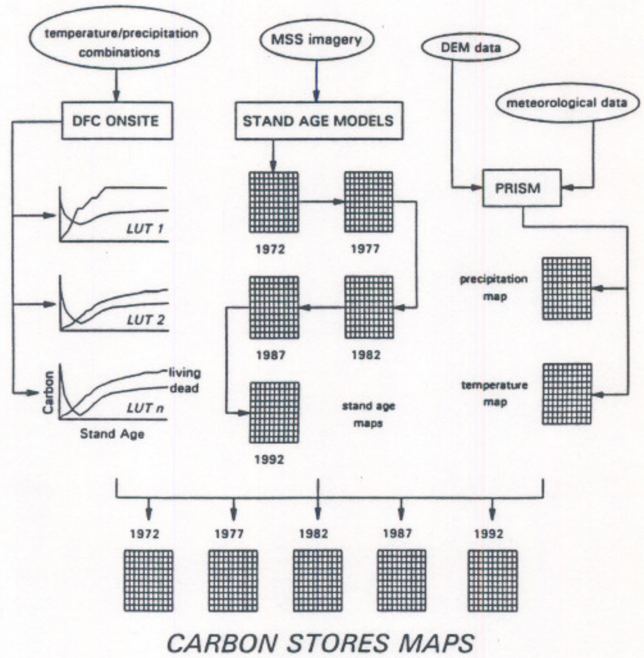

Figure 3. Conceptual framework for generating regional carbon stores maps.

To derive the total stores of carbon on-site in the region for a given year we sum the values in all cells of the appropriate carbon stores map, as shown in Figure 5. Subsequently, a temporal profile of on-site carbon stores for the entire region is created. When a given stand age map detects that a stand has been harvested, the merchantable portion of the above-ground carbon is exported from the landscape to the OFFSITE module. Merchantable carbon harvested (MCH) then is partitioned into various long-term and short-term storage pools within OFFSITE. OFFSITE is used to create the temporal profile of carbon stores off-site by combining decomposition off-site and inputs of MCH. The temporal profile of regional carbon exchange between the forest and the atmosphere (carbon flux) is then computed by combining carbon stores on-site with carbon stores off-site.

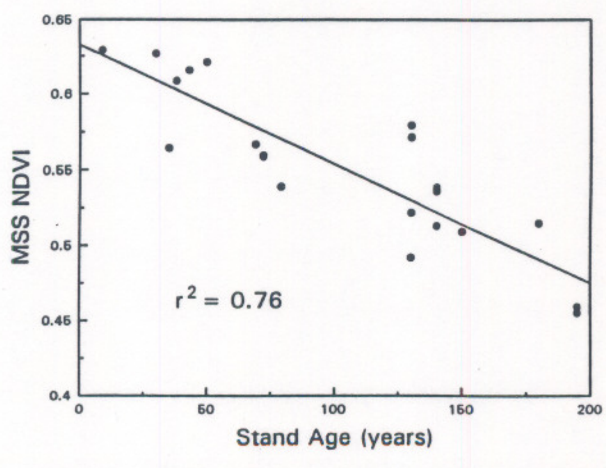

Figure 4. Results of an initial assessment of the relationship between the MSS NDVI and age of forest stands.

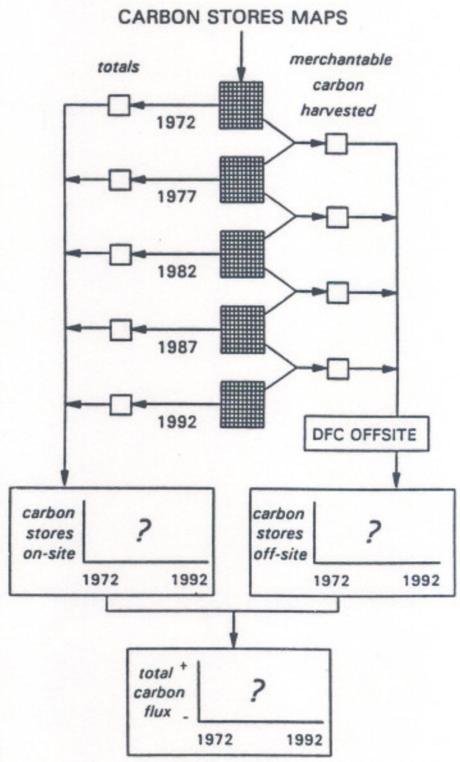

Figure 5. Conceptual framework for generating regional carbon flux profiles.

DATA RESOLUTION AND SCALING ISSUES

The project described here is based on the integration of three different, independently validated models: 1) carbon flux, 2) stand age, and 3) climate simulation. Although in concept this integration is straight forward, each model is parameterized using different input variables, and many model functions are nonlinear, or use transformed variables. Furthermore, the models were designed to function at different scales. Thus, we must consider questions concerning data resolution and interactions across multiple scales.

The DFC model is a set of non-linear functions of primary drivers such as temperature, precipitation, and stand age. Because of this, certain ranges of each of these drivers are more influential on carbon estimates. For example, as illustrated in Figure 2, the ONSITE module is asymptotic after a stand age of about 200 years. Thus, it is essential that most of the sensitivity of the satellite imagery to stand age be between zero and 200 years. As demonstrated by Cohen and Spies,[16] this is indeed the case with TM data. Fortunately, as shown in Figure 4, MSS imagery also has a high degree of sensitivity to the same range of stand ages. There is little to be gained from developing stand age models using satellite imagery that are sensitive to stand ages beyond 200 to 250 years old.

The PRISM model produces mean monthly temperature and precipitation maps as a linear function of DEM and meteorological station data. The resulting maps contain large numbers of different temperature and precipitation values across the region. The ONSITE module needs combinations of these temperature and precipitation values as input parameters. However, logistically, it is impractical to run DFC for all possible temperature and precipitation combinations. Additionally, as with stand age, this also is unnecessary. Thus, we must identify classes of input parameter combinations that are both most prevalent in the region, and most strategically placed from the standpoint of DFC sensitivity. To accomplish this, we perform a cluster analysis on the two-dimensional data set containing temperature and precipitation map values, and modify the results based on DFC sensitivity.

Currently, our methodology incorporates the assumption that spatial interactions do not exist between adjacent ground resolution cells. That is, carbon stores for each pixel in the region are determined independent of conditions on adjacent pixels. Although this approach provides a useful first approximation, we will conduct sensitivity analyses to determine the importance of spatial interactions on estimates of carbon stores. Perhaps the most important interactions are hydrologic. Although PRISM models temperature and precipitation for each pixel in the region, this does not necessarily tell us how much water is available to support plant growth, and thus, carbon accumulation in standing biomass. Water availability also is strongly influenced by soil texture and topography. For a slope with uniform soils and receiving uniform precipitation, soil moisture will be higher at the bottom of a slope than at the top. Hence, determining soil moisture conditions for any given pixel in a watershed will require information from adjacent pixels.

A final point for discussion concerns ground cell resolution size. The fundamental cell size for our stand age models is approximately 80m, the size of MSS pixels. Although DFC requires stand-level information, definition of stand boundaries would be difficult with larger pixels across the highly fragmented landscapes of the Pacific Northwest. Although PRISM can be run for any cell size desired, outputs at anything smaller than a few kilometers are likely to be meaningless. We use the smallest reasonable cell size for determining temperature and precipitation classes. Then, as DFC requires only mean values for each stand, we overlay our stand polygons over the temperature and precipitation maps and calculate mean values.

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