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MODELING EFFECTS OF LAND USE ON CARBON STORAGE IN THE FORESTS OF THE PACIFIC NORTHWEST, USA: A TEST OF METHODS*

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ABSTRACT

We are conducting a study to determine the flux of carbon (C) from forest land due to logging over the past twenty years in the Pacific Northwest, USA. Within the context of that study we are testing our methods over a 1.2 Mha area in the central Oregon Cascade Range. The methods include remote sensing of forest age, detection of changes in forest age, simulation of mean monthly temperature and precipitation, simulation of carbon storage in forest stands, and spatial extrapolation to create C storage maps. This paper describes our experiences to date.

1.0 INTRODUCTION

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 (C) in the terrestrial ecosystem change in response to a variety of land use practices?" Here, we describe a study in which technology is being developed to help narrow this uncertainty for a major terrestrial C pool, the temperate forests of the Pacific Northwest (PNW) region of the United States. Our focus is on the portion of the PNW region that consists of western Washington and Oregon, including the eastern slopes of the Cascade Mountains.

In our study we are further developing a forest-stand-level C storage model that responds to logging, a dominant land use in the region. The model is called Disturbed Forest Carbon (DFC). By linking DFC within a GIS to satellite imagery and climate simulation models, we extrapolate the model to a regional scale. Our methods permit the estimation of C currently stored in the forests of the PNW. The archive of LANDSAT Multispectral Scanner (MSS) and Thematic Mapper (TM) images provides a twenty year historical perspective of land use changes in the region. With these data we are

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assessing the recent historical impacts of regional land use on forest C stores, and thus net CO_2 flux to the atmosphere.

An earlier paper (Cohen et al., 1992) described the overall conceptual framework for this research. In another paper we discuss the challenges for remote sensing within this project (Cohen et al., 1993). Here, we will focus on an initial test of our methods, concentrating on an area of approximately 1.2 Mha in the central Oregon Cascade Range. No results are given here; they are forthcoming.

2.0 METHODS

Our methods for mapping forest C and determining C flux require several different steps: including 1) mapping of forest age; 2) mapping changes in forest age through time; 3) mapping, via simulation modeling and the meteorological record, mean monthly temperature and precipitation; 4) simulation of C storage using the ONSITE module of DFC; 5) spatial extrapolation to create C storage maps; 6) using the OFFSITE module of DFC to track harvested C through the forest products sector.

2.1 MAPPING FOREST AGE

Our approach for mapping forest age involves a combination of unsupervised classification and regression analysis. The classification provides a 95% accuracy (derived from a combination of ground and airphoto sampling) on the following classes: 1) water, 2) high alpine snow and ice, 3) open, nonvegetated land (<30% vegetation cover), 4) partially vegetated land (30-85% cover), 5) fully vegetated mixed deciduous/coniferous forest (>85% cover), and 6) coniferous forest (>85% cover). For now we make the assumption that class 3 is five years of age, class 4 is ten years of age, and class 5 is twenty years of age. These estimates are based on empirical observations. Within the conifer forest class (class 6), the stand age regression model developed by Cohen and Spies (1992) was applied. The regression model was derived from the relationships between the TM Tasselled Cap wetness index and ground survey data from a variety of forest stands. The model has a coefficient of determination of 0.81. Ground field checking revealed that accuracy for the map of age classes derived from this model is 75% for three classes: <80 years old, 80-200 years old, and >200 years old. For the combined land cover and age class map the overall accuracy is 83%.

Some of the error in the age model results from the fact that we selected only typical examples of forest conditions for model development. Thus, some atypical stands visited for accuracy assessment were outliers. These outliers were generally younger forest stands that appear older in the imagery because of an increased rate of structural development due to site conditions. We are currently evaluating means by which to obtain better estimates for age of these atypical stands.

2.2 CHANGE DETECTION

Change detection, when done in a spatially explicit manner involves spatial overlay of two or more images from different dates. Three types of change detection algorithms are commonly used: 1) difference, 2) ratio, and 3) principal component analysis (PCA). The difference and ratio algorithms require simply subtracting one image from another, or dividing one image by the other, respectively. These two algorithms are generally limited to comparison of two images, and should give similar results, except for how the resultant image is scaled. The PCA algorithm can be applied to any number of images, with each PC axis generally representing change between two distinct time periods. Other algorithms have been applied, but to date, only in isolated situations.

We have just begun to experiment with change detection using two TM images, and have some preliminary results to report. Our efforts to date involve the use of the Tasseled Cap wetness images from 1988 and 1991 scenes for the study area. To identify areas logged between the two dates, the 1991 wetness image was subtracted from the 1988 image. Different degrees of change were represented by different digital values in the change image, with harvested areas having the lowest values. After determining the threshold value representing change due to logging, we then smoothed the image to eliminate small groups of pixels that were falsely identified as logged due to a small amount of spatial misregistration between the two wetness images. This then became a "harvest" mask used with the derived C storage map, described later.

2.3 CLIMATE SIMULATION

Mean monthly precipitation and temperature are required to run the OFFSITE module of DFC. We had planned to use output from the PRISM model (Daly et al., 1993) to produce these data layers. Currently, PRISM provides only precipitation, with a grid cell size of roughly 6 km by 9 km for our study area. We have evaluated this layer and it appears to provide reliable information. We are now evaluating other models to obtain the desired spatially explicit temperature information. Until we obtain that data layer we are using a measure of forest productivity (Isaac, 1949) to simulate C storage in a forest stand. The measure of productivity used is site index, which has six classes within the study area. One of these classes is non-forest.

2.4 CARBON STORAGE STIMULATIONS

Using the ONSITE module of DFC we simulated forest stand C stores in living vegetation, woody detritus, and the forest floor over succession for five forest productivity classes within the study area (Isaac, 1949). The result was a set of five lookup tables (LUTs), one for each productivity class. For each of the five classes, the year that maximum bole production was reached and the maximum rate of bole production was adjusted to match the bole yields presented by McArdle and Meyer's (1930) Table 2. As

McArdle and Meyer presented their data in cubic feet per acre, we first transformed these values to Mg C per hectare by converting to cubic meters per hectare by multiplying by 0.069, assuming a bole density of 0.45 Mg per cubic meter and that a bole was 90 % wood and 10 % bark (bark was not included in McArdle and Meyer's volumes), and a carbon content of 50 %. Calibration to these transformed data indicated that bole production rates reached a maximum at 45 years and that the rate of peak production closely matched the values presented by McArdle and Meyer's Table 10 for all but the lowest production class. From the highest to the lowest productivity class the maximum rates of bole production used were 5.0, 4.4, 3.6, 2.4, and 1.8 Mg C per ha per year, respectively.

Production of other woody parts of trees was assumed to parallel bole production but at lower rates based upon their ratio to bole mass. We assumed that the branch/bole ratio was 0.08 and that the coarse root/bole ratio was 0.21 based upon Grier and Logan (1977). Mortality rates of all woody tree parts was assumed to be 0.6 % per year.

Production of foliage and fine roots was estimated from turnover rate and maximum biomass. Maximum biomass of these two components was estimated to occur at 45 years, and the turnover rates for foliage and fine roots were kept constant at 20 % per year and 50 % per year, respectively. We assumed that both foliage and fine root maximum biomass increased linearly with site productivity.

Variation in coarse woody debris, fine woody debris, dead roots, and forest floor C stores was assumed to be primarily controlled by rates of detrital production. This means that higher site quality forests will produce more detritus and therefore store more detritus. This pattern matches the overall regional pattern of detrital stores (Grier and Logan, 1977; Boone et al., 1988). Rates of decomposition for coarse woody debris, fine woody debris, dead roots, and forest floor were assumed constant across the range of productivity classes and set at 0.02, 0.03, 0.04, and 0.15 per year, respectively. While temperature, moisture, and litter quality all influence the decay rates of these detrital components, the way these variables change with site productivity is complex. In our next iteration we plan to examine how these variables are spatially distributed within each site productivity class to more accurately estimate decay rates.

Detrital inputs and losses also occurred when forests were harvested. For this analysis we assumed that the harvest and site preparation parameters were constant regardless of when and where a stand was harvested. This is, however, a gross simplification as harvest utilization standards have dramatically changed with time (Harmon et al., 1990). When a forest is harvested we assumed that 85 % of the boles (including bark) was removed from the site. We also assumed that during site preparation that 75 % of the fine woody debris and forest floor and 25 % of the coarse woody debris would be converted to CO_2 by fire.

Soil C was estimated using the Oregon STATSGO soil geographic data base (Soil Conservation Service, 1991). The data base consists of 217 spatially explicit map units for the state of Oregon, of which 18 are totally or partially contained in the study area. Each map unit is sub-divided into as many as 21 components, and each component is described by minimum and maximum values of several soil characteristics. The minimum and maximum values of the following characteristics were averaged and used to calculate mineral soil carbon content (Mg per ha) to a depth of 20 cm: organic matter (OM) concentration (% of <2 mm by weight, converted to % carbon by multiplying by 0.58), bulk density (g of <2 mm per cm^3 of <2 mm), and rock content (% of total weight, converted to % of total volume by assuming rock density of 2 g per cm^3). Mineral soil carbon content could not be determined to a depth greater than 20 cm because organic matter data were generally limited to the surface mineral soil horizon. The adequacy of this approach to estimate soil C over large regions is being tested by comparing results with measurements made at 400 locations in western Oregon.

2.5 SPATIAL EXTRAPOLATION

The details of our spatial extrapolation methods are given in Cohen et al. (1992). However, as mentioned earlier, because we did not have the desired temperature data layer we used a map of forest productivity classes for the study area (Isaac, 1949) as a proxy for the climate data layers. Thus, for each 25 m cell size of our study area (based on geocoded TM data), we determined the productivity class from a digitized version of the this map, and forest age from the age map of 1988. The productivity map indicated which C LUT to go to, and the cell's age indicated where in the LUT to find the C storage values for the different storage pools.

2.6 HARVESTED CARBON

The OFFSITE module of DFC uses a Markovian chain to predict amounts of various forest products in the PNW, and ultimately the amount of CO_2 produced by the decomposition or combustion of the products. Transition probabilities from the harvested tree boles to the various products through manufacturing processes, reuse, recycling, and finally to CO_2 were obtained from a variety of sources. Some data came from publications on efficiency of forest products manufacture, some from US Forest Service statistical summaries of production, and when a published source was unavailable, from expert opinion. The rates of decomposition were grouped into five categories from immediate (e.g., combustion) to indefinite (burial in landfills) and half-lives were assigned to each category for computation.

Once all of the probabilities have been set and the Markov matrix developed, any input of wood volume can be used to calculate how much CO_2 is being produced yearly and cumulatively by forest product manufacturing. Probabilities change with time, as a result of changing efficiencies in manufacturing. This is accommodated by changing the values in the matrix.

Using the harvest mask, which was overlaid onto the bole carbon storage map, we can determine the amount of carbon harvested and thus sent through the forest carbon sector. This amount is fed into the OFFSITE module's Markov matrix. Preliminary estimates are that 50 % of the bole is transferred into long-term forest products. We also assume that carbon in long-term forest products will be lost to the atmosphere at a rate of 2 % per year (Harmon et al., 1990).

3.0 CONCLUSIONS

In this study we have tested many of our proposed methods (Cohen et al., 1992), and have been successful at creating the needed maps of forest C stores. Some problems were identified and ways around them determined. Our next step is to redo the analysis on this test site, using a refined and more complete set of techniques, and to produce actual results that can be assessed for their accuracy and meaning.

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