MULTI-ANGULAR SATELLITE REMOTE SENSING AND FOREST INVENTORY DATA FOR CARBON STOCK AND SINK CAPACITY IN THE EASTERN UNITED STATES FOREST ECOSYSTEMS

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ABSTRACT:

Terrestrial vegetation plays a major role in regulating the global carbon cycle and in turn the climate of the Earth system. It is believed that the North America forest ecosystems are a net sink for anthropogenic carbon. However, significant uncertainties exist in quantifying this claim. Inaccurate and incomplete characterization of forest vegetation is among the main causes to these uncertainties. To characterize forest vegetation for global carbon cycle and climate change research at large spatial scales, satellite remote sensing, particularly coarse-resolution remote sensing is an appropriate means. While there have been many successful applications of AVHRR and MODIS data, improvements in accuracy are still urgently needed for reducing uncertainties in related carbon cycle modeling. Multi-angular remote sensing is a new field in remote sensing and has been recently accepted as necessary. It is different from conventional nadir-only remote sensing observations in that multi-angular spectral measurements are sensitive to vegetation canopy structures, thus having the potential to enhance the characterization of forest vegetation. In this paper, we present a case study using MISR to characterize not only land cover types but also forest growth stages in the eastern United States forest ecosystems. Combined with forest inventory data, the magnitude of current carbon stock and carbon sink capacity in the Shenandoah National Park forest has been estimated. It is demonstrated that by introducing forest age differentiation, significant improvements can be made in estimating the magnitude of carbon stocks and sinks in the forest ecosystems.

1. INTRODUCTION

Terrestrial vegetation plays a major role in regulating the global carbon cycle and in turn the climate of the Earth system. It has been demonstrated in the literature that the temperate forests in North America are a net sink for anthropogenic carbon (Sarmiento and Gruber, 2002). However, the magnitude of this sink is still significantly uncertain (Gurney et al., 2002). Among the major causes to these uncertainties are the quality and availability of data sets for characterizing the forest ecosystems on the land surface which are required by carbon cycle modeling.

Remote sensing from space may be the only feasible means to collect these data sets at regional to global scales (Foody and Curran, 1994). Coarse-resolution remote sensing has been playing an important role in this aspect, particularly the NOAA-AVHRR Pathfinder data and currently the EOS-MODIS data. For example, many researchers have presented their land surface characterization and classification results based on these sensor data, including the high temporal-frequency data products of NDVI, LAI, fPAR, NPP and land cover and land cover change products (e.g., Tucker et al., 1985; Townshend et al., 1987; DeFries et al., 1995; Loveland et al., 1995; Lim and Kafatos, 2002, etc.).

Multi-angular remote sensing is a new field in remote sensing and has been accepted as very useful in the past years. It is special in that multi-angular measurements can be sensitive to vegetation canopy structures (Foody and Curran, 1994; Chen, et al., 2003; Diner et al., 1999) thus having the potential to enhance the discrimination and characterization of forest vegetation (Lotsch et al., 2003). However, in this aspect, there have been very few studies done in directly applying multi-angular remote sensing.

In this paper, we present a case study using the most advanced multi-angular remote sensor namely MISR (Multi-angle Imaging SpectroRadiometer) to characterize temperate forest vegetation not only land cover types but also the forest growing stages in the eastern United States forest ecosystems. Combined with forest inventory data from USDA Forest Service (Cost, 1986), the magnitude of current carbon stock and sink capacity in the Shenandoah National Park forest are estimated and assessed as regards to the degree of improvement.

2. METHODS

2.1 Study Site and Data

The Shenandoah National Park is located in the northwest part of the State of Virginia, along the Appalachian Mountain in the eastern United States. Hardwood forests dominate the park and much of Shenandoah today is an "oak-hickory" forest based on information from the park service.

It is a typical temperate forest ecosystem in the eastern United States. Since the park was established, human perturbations have been limited to the minimum possible extent. Therefore, it is a perfect site to study the sink for anthropogenic carbon for unperturbed terrestrial ecosystems.

For this study, we collected a 1.1km resolution MISR granule, from NASA Langley Atmosphere Science Center DAAC on Sept. 6, 2002. After mosaicing and subsetting operations, we cut out a MISR scene covering all the counties surrounding this park. This MISR image has been terrain calibrated. It has nine angles namely DF, CF, BF, AF, AN, AA, BA, CA, DA in which F indicates forward viewing angle and A indicates afterward viewing angle, AN indicates nadir view while A, B, C, D indicate the four angles 26.1°, 45.6°, 60.0° and 70.5°. At each angle, MISR collects spectral measurements at four bands namely Blue, Green, Red and Near Infrared (NIR) (Figure 1).

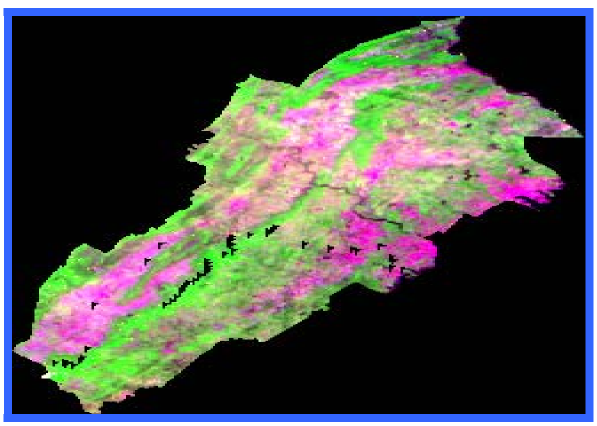


Figure 1. The original MISR image is displayed by a false color composite of Green, NIR and Red bands. On this image, forest vegetation is green. The green strip in the middle of this image is the Shenandoah National Park. The small black flags indicate our ground truth sites (MISR data collected from NASA Langley DAAC, 2003).

Because there are a large number of pixels blocked by the topography at large viewing angles, we excluded the two larger angles, both the forward views and afterward views. As a result, only five angles are used in this study, including measurements namely BF, AF, AN, AA and BA. For validation purposes, in the summer of 2003, we collected in-situ ground truth data for land cover land use types and forest growing stages within and around the Shenandoah National Park (Figure 1).

For estimation of carbon stock and carbon sink capacity in the live forest vegetation, we also collected woody biomass information from USDA Forest Service based on USDA Forest Service 1984 forest inventory North Carolina report where they defined the woody biomass as the green weight of aboveground wood and bark in live trees (Table 1).

Rang of forest age (yr)	**Average forest age (yr)**	**Carbon density (kg/m^2)**	**Change rate in carbon density ($kg/m^2/yr$)**
0-10	5	5.975	0.71
11-20	15	13.075	0.32
21-30	25	16.275	0.54
31-40	35	21.675	0.368
41-50	45	25.35	0.252
51-60	55	27.875	0.432
61-70	65	32.2	0.005
71-80	75	32.25	-0.105
81-90	85	31.2	0.048
90-	95	31.675	NA

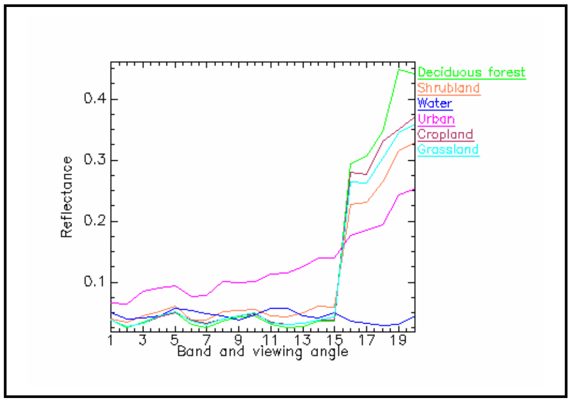
Table 1. Carbon density and rate of change in carbon density for above-ground woody biomass in deciduous forest (Adapted from USDA Forest service forest inventory North Carolina, 1986)

2.3 Isolating Forest Pixels by Land Cover Classification

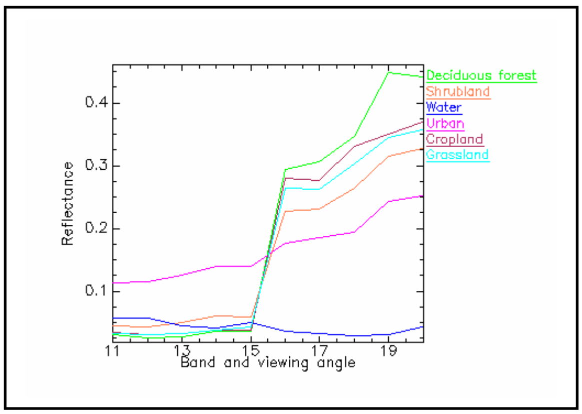
In order to estimate forest growing stages, we must isolate forest pixels from non-forest pixels on remotely sensed imagery, since the existence of other land cover land use types would make forest growing stages analysis difficult. We can do this by applying a classification procedure on the MISR image for the main land cover land use types in this region such as *Forest*, *Water, Urban, Shrubland, Grassland, Cropland* etc.

First, we combined the five-angle (BF, AF, AN, AA, BA) four-band (Blue, Green, Red and NIR) reflectance into one image, thus forming a 20-band multi-angular multispectral image in the band-angle order. The ground truth data were overlaid on top of this image, so that the multi-angular multispectral spectral samples for different land cover land use types were collected from the image and averaged for each land cover land use type (Figure 2a). It is observed that the minor variations in reflectance in the Blue and Green bands may not help in enhancing the discrimination among the land cover and land use types of interest.

Therefore, we determined to use the angular spectral measurements only at Red and NIR bands as shown in figure 2b.



(a)



(b)

Figure 2. Multi-angular multispectral samples for the main land cover land use types in this region: (a) showing all the angles and bands. The numbers on the x-axis indicates the band viewing angles (1-5 indicates BlueBF, BlueAF, BlueAN, BlueAA, BlueBA; 6-10 indicates GreenBF, GreenAF, GreenAN, GreenAA, GreenBA; 11-15 indicates RedBF, RedAF, RedAN, RedAA, RedBA; 16-20 indicates NIR-BF, NIR-AF, NIR-AN, NIR-AA, NIR-BA), (b) showing all the angles but only the Red and NIR bands, here on the x axis, 11-15 indicates RedBF, RedAF, RedAN, RedAA, RedBA while 16-20 indicates NIR-BF, NIR-AF, NIR-AN, NIR-AA, NIR-BA.

Using the spectra in figure 2b as known endmembers, we applied the supervised classification method, namely Spectral Angle Mapper (SAM) on this ten-band MISR image. In this classification procedure, we used the threshold 0.1 which was determined by interactively analyzing the rule file for *Deciduous Forest* referencing a high accuracy TM-based classification. After the classification, we converted these forest pixels into a region of interest (ROI). Using this ROI as a mask, we isolated the forest pixels from non-forest pixels on the original MISR image (Figure 3)

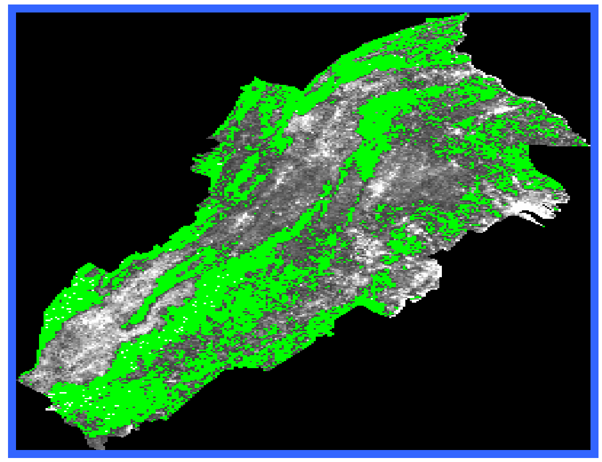


Figure 3. Illustration of forest pixels isolated from non-forest pixels on the original MISR image after land cover land use classification.

It is observed in figure 3 that, the Shenandoah National Park forest boundary is very clear, therefore we extracted the Shenandoah National Park forest pixels by masking all the pixels outside the park (Figure 4).

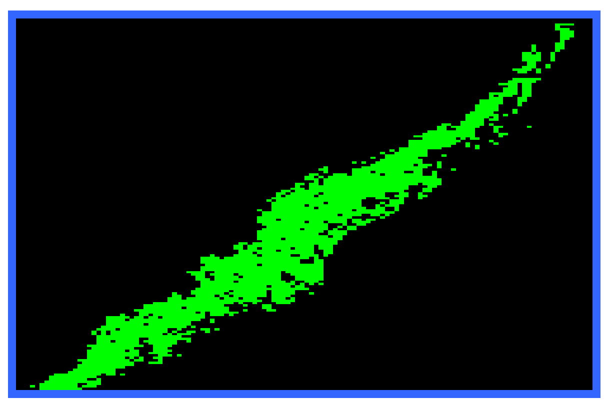
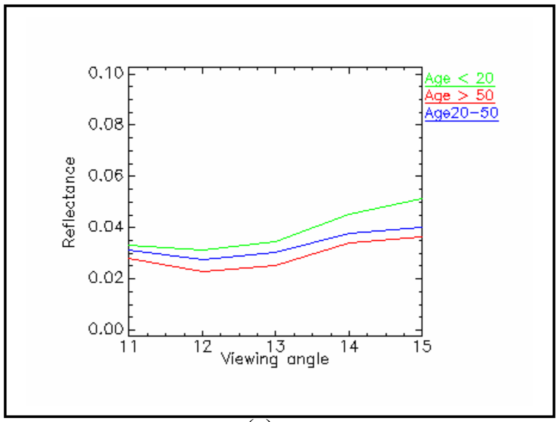


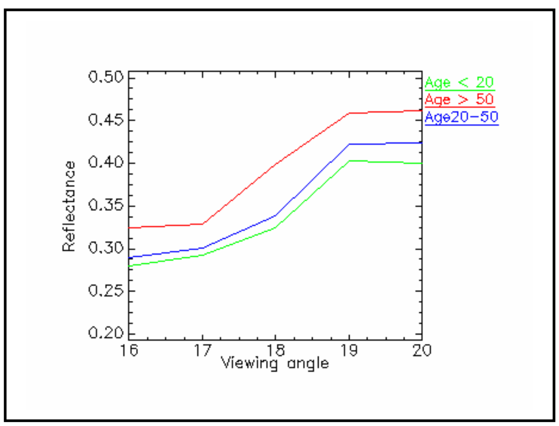
Figure 4. The forest pixels isolated for Shenandoah National Park.

2.4 Forest Age Estimation

Through the same procedure used above in the land cover land use classification, we collected multi-angular multispectral samples for different forest growing stages, based on ten-year age interval. The age groups include 10-20 years old, 20-30 years old, 30-40 years old, 40-50 years old and 50-60 years old. After a preliminary spectral analysis, we found that three age groups can be discriminated by MISR spectral data. They are the age group less than 20 years old, age group 20-50 years old, and age group over 50 years old. Their spectral samples were shown in figure 5.



(a)



(b)

Figure 5. Multi-angular multispectral samples for three forest growing stages: (a) showing their angular spectral variations at Red band. On the x-axis, 11-15 indicates viewing angles BF, AF, AN, AA, BA, (b) showing their angular spectral variations at NIR band. On the x-axis, 16-20 indicates viewing angles BF, AF, AN, AA, BA.

Using the same classification method as for the above land cover land use classification, we classified the forest pixels in the figure 4 and obtained the spatial distribution of forest age in the Shenandoah National Park (Figure 6).

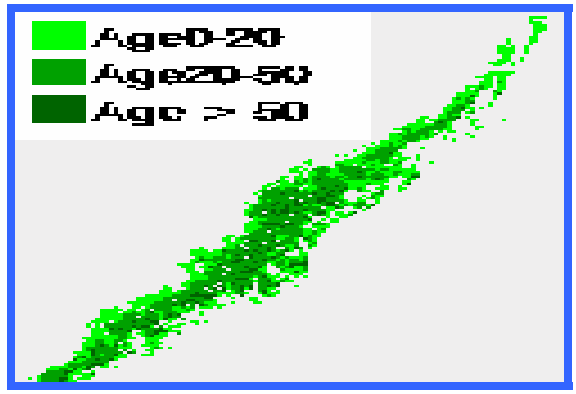


Figure 6. The spatial distribution of forest age in the Shenandoah National Park estimated from MISR analysis.

2.5 Forest Inventory Data Analysis

The forest inventory was carried out by USDA Forest Service in 1984 (Table 1). Based on table 1, it is observed that the forests' carbon density is always increasing during the first 60 years of their growth. After 60 years, it changes very little, implying that in this region for the deciduous forest vegetation, the photosynthesis and respiration processes are almost balanced after the first 60 years of growth. Within the 60 years period, the forest apparently is uptaking CO_2 from the atmosphere, since the carbon density is increasing with the ages. However, the increasing rates at different forest ages are quite different implying that forests in different growing stages have different capacities of uptaking CO_2. Therefore, age differentiation is very important to lower the uncertainties in estimating current carbon stock and carbon sink capacity in the temperate deciduous forests. Based on the three age groups we specified in section 2.4, we calculated the average carbon densities and average rates of change in carbon density, which are required in the following carbon stock and sink capacity analysis: when the age is less than 20 years, the average carbon density is 9.5kg/m^2, the biomass increasing rate is 0.51kg/m^2/yr; when the age is between 20 and 50 years, the average carbon density is 21.1kg/m^2 and the biomass increasing rate is 0.38kg/ m^2/yr; when the age is over 50 years, the average carbon density is 31.0kg/ m^2 and the biomass increasing rate is 0.09kg/ m^2/yr.

2.6 Estimation of Carbon Stock and Sink Capacity

If we know the carbon stock in the forest ecosystems, then we can infer annual changes in carbon stock thus we can determine whether the forest ecosystems are a source or a sink and the magnitude of these sources and sinks. If we know the sink capacity of forest ecosystems at different growing stages, then we can predict how much CO_2 would be absorbed by forest ecosystems in the future. This can help predicting future CO_2 concentration levels in the atmosphere and in turn their effects on land surface temperature.

We used the following equations in estimating these two variables for the Shenandoah National Park:

Without forest age discrimination

$$C = A \times D \quad (1)$$

where C = magnitude of carbon stock
A = forest area
D =carbon density

$$S = A \times R \quad (2)$$

where in turn

S = sink capacity
R = rate of change in carbon density

With forest age discrimination, the above formulas (1) and (2) become

$$C = \Sigma A(i) \times D(i) \quad (3)$$

$$S = \Sigma A(i) \times R(i) \quad (4)$$

where i = forest age group

3. RESULTS

Based on the MISR image analysis, the forest areas at different growing stages in the Shenandoah National Park are estimated as: 1) forest with ages less than 20 years, 1225.73km^2, 2) forest with ages between 20 and 50 years, 1141.03km^2, 3) forest with ages over 50 years, 244.42km^2. Assessed by the ground truth data, this age estimation accuracy is 83% (n=18) for the ages between 20 and 50 years.

If we do not discriminate between different forest growing stages, the average carbon density is 23.755kg/m^2, and the rate of change in carbon density is 0.29kg/m^2/yr. Using formula (1) and (2), the current carbon stock is 62.0TgC and the carbon sink capacity is 0.8TgC/yr in the Shenandoah National Park forest.

If we consider the age differentiation, using formula (3) and (4), the current carbon stock is only 43.3TgC while the carbon sink capacity is 1.1TgC/yr in Shenandoah National Park forest.

Based on these estimates, without age differentiation, the carbon stock is overestimated by 30% while the sink capacity is underestimated by 38%.

4. DISCUSSION AND CONCLUSIONS

Multi-angular remote sensing can be very useful in the characterization of forest ecosystems at large spatial scales for global environmental change research. It provides more spectral information for the characterization of not only land cover land use types but also forest growing stages. With respect to forest age characterization and classification, the accuracy is quite satisfactory.

When combining this remote sensing based growing-stage characterization with forest inventory data, the current carbon stock and sink capacity in the temperate forest ecosystems can be more accurately estimated.

While this is an experimental study in a small region, it does demonstrate that incomplete characterization of forest ecosystems can have significant effects on carbon source and sink estimation thus on the understanding of the role of terrestrial biosphere in the global carbon cycle and climate system.

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