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Evaluating TERRA-1 MODIS data for discrimination of tropical secondary forest regeneration stages in the Brazilian Legal Amazon

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[1] We establish the potential of TERRA-1 Moderate Resolution Imaging Spectrometer (MODIS) data for discriminating and mapping tropical secondary forest regeneration stages in the Brazilian Legal Amazon, in terms of both their age and pathway. In using MODIS data, many difficulties encountered in local to regional scale mapping and discrimination of regeneration stage using NOAA Advanced Very High Resolution Radiometer (AVHRR) and fine spatial resolution Landsat/SPOT sensor data can be largely overcome. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1640 Global Change: Remote sensing; 1851 Hydrology: Plant ecology

1. Introduction

[2] In the early 1990s, tropical secondary forests occupied between 31% and 37% of the total area deforested in Brazil's Legal Amazon [*Fearnside and Guimaraes*, 1996; *Lucas et al.*, 2000]. In future years, the area of secondary forest in the region is anticipated to increase substantially [*Fearnside*, 1996; *Laurance et al.*, 2001]. Since most deforestation occurred after the 1970s, the majority of secondary forests are young (less than 30 years in 2002) and at a stage where growth, and hence the rate of biomass (carbon) accumulation, is most rapid [*Brown and Lugo*, 1990]. For this reason, these forests are widely believed to fulfill an important role as a net carbon sink. Indeed, if deforestation of the Amazon continues as expected [*Laurance et al.*, 2001], secondary forests could represent a prime mechanism by which carbon is restored to the terrestrial system.

[3] To quantify the current and future magnitude of the carbon sink associated with tropical secondary forests in the Legal Amazon, spatial datasets that quantify the extent of different stages of regeneration across the region are required. In this study, regeneration stage is considered to be a function of age and pathway. Discrimination of regeneration pathway, in addition to age, is important, as forests of similar age may differ markedly in their species composition, particularly in the early stages of regeneration. Furthermore, rates of biomass accumulation differ between pathways, as a function of land use history prior to abandonment of agricultural lands, and in response to local/regional climate, soils and topography [*Ewel*, 1980; *Uhl et al.*, 1988; *Lucas et al.*, 2002a, 2002b].

[4] For the Legal Amazon, *Skole and Tucker* [1993] mapped the regional extent of secondary forest (one class) using Landsat TM data. For selected locations, discrimination of secondary forests of varying age and pathway has been also been achieved through comparison of multi-temporal Landsat and SPOT sensor data [e.g., *Lucas et al.*, 1993; *Moran et al.*, 1994; *Palubinskas et al.*, 1995]. However, the regional mapping of regeneration stage using fine spatial resolution Landsat and SPOT sensor data is unrealistic due largely to the vast quantities of data required and the lack of cloud-free images. An alternative approach, therefore, has been to use 1 km spatial resolution NOAA AVHRR data. For example, *Lucas et al.* [2000] developed and implemented a procedure for mapping the extent of up to four stages of tropical forest regeneration across the Legal Amazon from these data. However, although demonstrated in theory, discrimination of the four stages to acceptable levels of accuracy was not achieved in practice due largely to the coarse spatial resolution of the AVHRR, the limited number of waveband regions for observation, and the low dynamic range of the data for vegetated surfaces.

[5] In view of these limitations, we have investigated the use of TERRA-1 MODIS data for discriminating secondary forest regeneration stages in the Legal Amazon. Our results are based on an informed interpretation of land cover dynamics and temporal changes in spectral reflectance that occur as forests following different pathways regenerate. Our preliminary research indicates that many of the difficulties encountered in discriminating and mapping regeneration stage using NOAA AVHRR or fine spatial resolution Landsat or SPOT sensor data can be largely overcome using MODIS data. Furthermore, MODIS data can potentially be used to routinely deliver maps of secondary forest regeneration stages, including common pathways, across the Legal Amazon.

2. Spectral Characteristics of Regenerating Forests

[6] As tropical forests regenerate on abandoned lands, distinct temporal trends in reflectance, and also thermal emission, have been observed. Using 1 km spatial resolution AVHRR data for 475 forests in 7 locations across the Legal Amazon, *Lucas et al.* [2000] observed a rapid decline in both AVHRR channel 3 radiance and channel 1 reflectance from the larger values observed for non-forest (e.g., bare ground/grassland), with values merging with those typical to mature forest after approximately 5 and 10 years respectively. In contrast, AVHRR channel 2 (near infrared, NIR) reflectance increased from values typical to non-forest to a maximum at approximately 10 years, declining thereafter to merge with values typical to undisturbed forest after 20–25 years. These trends were most distinct where extensive areas of secondary forest of similar age were observed (e.g., on abandoned cattle pastures).

[7] The reflectance trajectories observed using AVHRR visible and NIR data were comparable to those observed using 30 m spatial resolution Landsat Thematic Mapper (TM) channel 3 (red) and 4 (NIR) reflectance data of regenerating forests north of Manaus, Brazil [*Lucas et al.*, 1996; *Foody et al.*, 1997]. Such trajectories were generated initially by relating estimates of the age of regenerating forests, derived from time-series comparisons of broad land cover classifications of Landsat and SPOT sensor data (1973–1995), to their red, NIR and also mid infrared (MIR;

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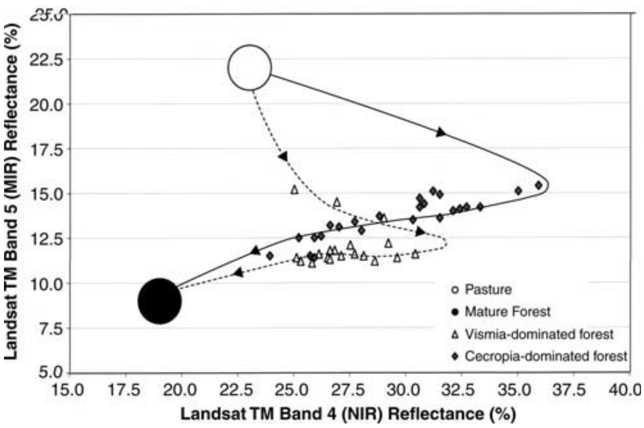

Figure 1. Landsat TM NIR/MIR reflectance trajectories observed at Manaus for regenerating forests of varying age and following regeneration pathways dominated by the pioneer genera *Cecropia* and *Vismia* respectively. Note the differences in the peak NIR reflectance and the rates of decline in MIR reflectance between the two pathways.

channel 5) reflectance, as extracted from a 1991 Landsat TM scene [*Lucas et al.*, 2002a]. These trajectories were refined subsequently by relating Landsat TM red, NIR and MIR data acquired for each of 15 forests in 1985, 1988, 1989, 1991, 1994 and 1995 to the age of these forests in their year of observation [*Lucas et al.*, 2002b]. As with AVHRR data, a rapid decline in visible (red) reflectance and a peak followed by a steady decline in NIR reflectance was observed as forests regenerated. A gradual decline in Landsat TM MIR reflectance data from values typical to non-forest was also evident.

[8] At Manaus, *Steininger* [1996, 2000] observed considerable scatter in relationships between forest age and Landsat TM red, NIR and MIR reflectance data. However, following analysis of floristic and structural data collected from 30 forests of known age at Manaus in 1993 and 1995, *Lucas et al.* [2002a, 2002b] attributed this variability in reflectance to differences in the structure and species composition of forests of varying age and following different regeneration pathways. Most early regenerating forests were dominated either by the pioneer genus *Cecropia* or *Vismia*, with the former occurring typically on land abandoned within a few years of use and the latter on land used for longer periods and experiencing burning during clearance of either mature or regenerating forests [*Mesquita et al.*, 2001]. These two pathways also exhibited distinct NIR and MIR reflectance trajectories (Figure 1). The maximum NIR reflectance was greater and the rate of decline in MIR reflectance from non-forest values was slower for *Cecropia*-dominated forests, whilst the greatest discrimination between pathways was observed using MIR reflectance data. These reflectance trajectories indicated that, using a combination of Landsat TM NIR and MIR reflectance data, forests of varying age and following these two regeneration pathways could be distinguished.

[9] The reflectance trajectories observed using either or both NOAA AVHRR or Landsat sensor data were explained by considering changes in the structure and species composition of secondary forests [*Steininger*, 1996; *Lucas et al.*, 2000, 2002a, 2002b]. The rapid increase in leaf and canopy cover as forests regenerated led to a decline in visible reflectance from values typical to non-forest but also a corresponding increase in NIR reflectance. The observed peak in NIR reflectance, which generally coincided with the merging of the visible reflectance of regenerating and mature forests, was associated with forests of maximum leaf cover but minimum structural development. The decline in reflectance from this peak was associated with an increase in radiation trapping as the canopy became more complex. The decrease in MIR reflectance with forest age was attributed to increases in vegetation moisture content and also trapping of MIR radiation as structural development of the forest occurred. Differences in the peak NIR reflectance and also the rate of decline in MIR reflectance observed between *Cecropia* and *Vismia* dominated forests were attributed largely to differences in canopy structure, which were most prominent during the first 10–15 years of regeneration.

3. Observations of Secondary Forests Using Landsat 7 Enhanced Thematic Mapper (ETM+) and MODIS Data

3.1. Methods

[10] In 1995, when field data were last collected at Manaus, few forests were older than 18 years and the majority, particularly those regenerating on more intensively used lands, were younger than 10 years. Therefore, in this current investigation, we updated the reflectance trajectories observed previously at Manaus using Landsat ETM+ data acquired on the 25th October and 26th November 1999, such that the reflectance characteristics of forests as old as 22 years could be considered. Data from a 33-year old forest dominated by *Vismia* was also included. We geometrically registered the ETM+ data to the existing database of Landsat TM data and derived classifications (e.g, forest age class) for Manaus [*Lucas et al.*, 1998] and calibrated the data to surface reflectance. For the 30 forests sampled in 1993 and 1995, we updated estimates of their age in 1999. NIR and MIR reflectance data were then extracted from the two Landsat ETM images. As several secondary forests had been cleared between 1995 and 1999, the associated reflectance data for these sites were omitted from the analysis.

[11] We also acquired MODIS data (product MOD09A1) over the Manaus study area between 20th and 26th July, 2000. This product consisted of 8-day composite surface reflectance data at 500 m spatial resolution and included 7 spectral bands centred at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm. The MODIS data were registered to the fine spatial resolution database for Manaus and, for forests of known age and regeneration pathway and exceeding 0.25 km^2 in area, MODIS NIR (Band 2, 858 nm) and MIR (Band 6, 1640 nm) reflectance data were extracted.

3.2. Results

[12] Using Landsat ETM+ data, differences in the NIR and MIR reflectance values of *Cecropia* and *Vismia*-dominated forests were similar to those observed using Landsat TM data (Figure 2). The

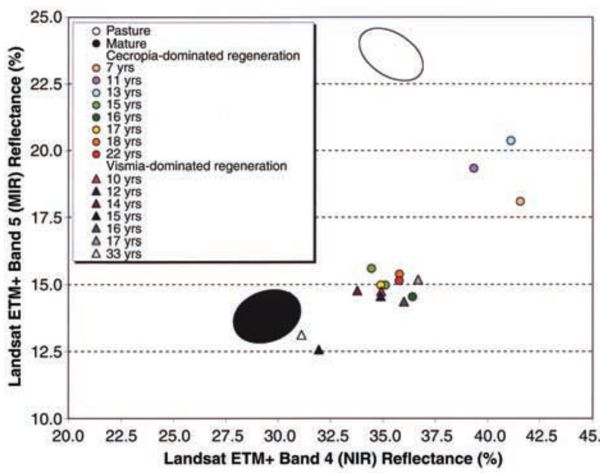

Figure 2. Reflectance trajectories observed using Landsat ETM+ data for 1999.

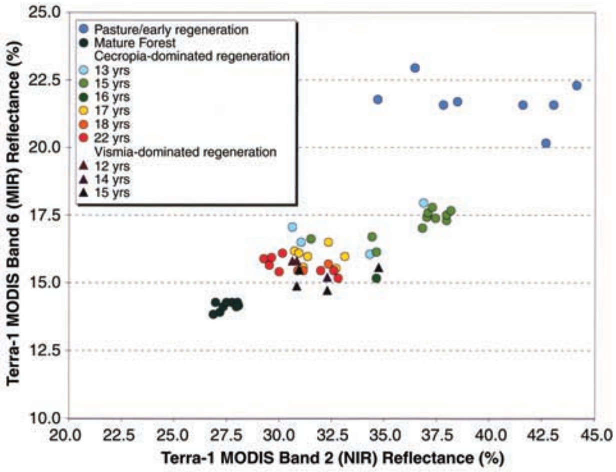

Figure 3. MODIS NIR/MIR reflectance trajectories observed for regenerating forests of varying age. The scatter in the relationship is attributed to the different sub-pixel proportions of land covers and the existence of different pathways of forest regeneration.

reflectance trajectories were not as distinct, due largely to the reduced number of data points and the lack of data for forests younger than 12 years. Even so, the same trends in NIR and MIR reflectance with forest age and pathway, as observed previously using Landsat TM data, were evident.

[13] Using MODIS, reflectance trajectories similar to those obtained using Landsat TM/ETM+ and also (in the case of the NIR region) NOAA AVHRR data were obtained (Figure 3). As no 'pure' areas of pasture or other non-forested surfaces could be located, the NIR and MIR reflectance for pixels considered to most representative of these surface types exceeded 33% and 20% respectively due to sub-pixel proportions of regenerating forest. With increasing forest age, a general decline in both NIR and MIR reflectance was evident. The characteristic peak in NIR reflectance was not observed, as the minimum age of forests was 12 years and, based on Landsat TM/ETM+ trajectories, the NIR reflectance of all forests would be declining from the peak. However, based on previous observations using NOAA AVHRR and Landsat sensor data, a peak in NIR reflectance can be expected.

[14] The influence of regeneration pathway on the NIR and MIR reflectance of forests was also evident in the MODIS data. In particular, 12–15 year old *Vismia*-dominated forests exhibited NIR and MIR reflectance values ranging from $<\sim 31-35\%$ and $\sim 14.5-16\%$ respectively which were lower than those observed for *Cecropia*-dominated forests of similar age (range from $\sim 30-38\%$ and $\sim 16-18\%$ respectively). These relative differences in reflectance between forests following different regeneration pathways agree with those observed using Landsat sensor data. However, as the *Cecropia*-forests age, the pathway becomes less distinguishable.

[15] Although the differences in reflectance appear to be small, it should be noted that the dynamic range of the MODIS data is far greater (12 bit) compared to both Landsat TM (8-bit) and NOAA AVHRR (10 bit). For this reason, MODIS is sensitive to even minor differences in NIR and MIR reflectance within and between forest regeneration pathways.

4. Discussion

[16] The study indicated that MODIS provides far greater potential for mapping and discriminating regeneration stage than the AVHRR due to:

- Provision of NIR and MIR wavebands well suited to discriminating forests of varying age and pathway.
- Regional coverage at 250 m and 500 m spatial resolution, allowing better registration of image data and resolving of ground features and a greater proportion of 'pure' pixels with regenerating forest to be observed; and greater potential than the fine spatial resolution Landsat or SPOT sensors due to:
- Acquisition of data on a daily basis, thereby alleviating the limitations associated with persistent cloud cover and facilitating multi-temporal comparison of reflectance values;

and greater potential than either AVHRR or Landsat/SPOT sensors because of

- Atmospherically corrected data of greater radiometric quality and dynamic range (12-bit), allowing better discrimination of multiple stages of regeneration.
- Consistent radiometric calibration/rectification allowing better intra- and inter-annual comparison of reflectance data.

[17] The accuracy to which secondary forests of varying age and following different pathways can be discriminated using MODIS data and the importance of spatial resolution has yet to be fully investigated, and is the subject of further study. However, discrimination is likely to be limited using single-date imagery unless spatial datasets relating to the age of regeneration at selected sites are available. For this reason, analysis of multi-temporal MODIS data, whereby the reflectance of individual or groups of pixels are compared over time, may be used to better indicate the age and also pathway of forests, particularly if the historical record starts with a non-forested surface or the age of secondary forests in a particular year has already been established.

[18] Although numerous pathways of regeneration occur across the Amazon, those dominated by *Cecropia* and *Vismia* species are particularly widespread [*Fearnside*, 1988] and are commonly, although not exclusively associated, with forests regenerating on abandoned agricultural land. Of significance to the regional carbon budget is that several studies [e.g., *Uhl et al.*, 1988; *Parrotta et al.*, 1997; *Mesquita et al.*, 2001; *Lucas et al.*, 2002b] have established that prior land use and management dictate whether pathways are dominated by *Vismia* or *Cecropia*, and that rates of biomass accumulation vary between and within pathways. The discrimination of *Cecropia* and *Vismia* from 'other' regeneration pathways using MODIS could therefore represent a major advance in land use change assessment and regional carbon budgeting.

5. Conclusions

[19] As tropical forests regenerate, distinct visible (red), NIR and MIR reflectance trajectories have been observed using a combination of Landsat sensor and NOAA AVHRR data. Such trajectories can be used to establish the age of secondary forests and discriminate common pathways from remotely sensed data. However, neither of these sensors alone, or even in combination, is ideally suited to the regional mapping of regeneration stage or pathway as each lacks one or several of the key attributes required (e.g., appropriate dynamic range, a MIR waveband, frequent regional coverage).

[20] In this paper, we have presented evidence that MODIS is currently the most suitable optical sensor for regional discrimination of multiple ages and even pathways of regeneration. The utility of this sensor for this purpose could be enhanced further if multi-temporal data were used. Our study is based on a comprehensive fine spatial resolution database of land use, forest age and reflectance data, generated from a time-series of Landsat and SPOT sensor data and interpreted with the aid of forest inventory data. For MODIS to be fully evaluated, however, such datasets need to be generated for other regions of the Amazon to establish consistencies in discriminating and mapping regenerating forests of varying age and pathway between sites and to provide appropriate calibration of algorithms for regional map-

ping of secondary forest regeneration stages and validation of output products.

[21] The study concludes that, given the wide area coverage provided by MODIS, the capacity exists to routinely generate maps of secondary forest regeneration stages (based on age and pathway) for the Brazilian Legal Amazon. Such capacity represents an important breakthrough in terms of refining carbon budgets and also better understanding the dynamics of tropical forest regeneration in response to land use.

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