The Use of Vegetation Indices in Forested Regions: Issues of Linearity and Saturation

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Abstract -- Numerous problems and difficulties have been reported with the use of vegetation indices in high biomass, forested regions. In this study we analyzed Landsat-5 Thematic Mapper (TM) scenes from various temperate and tropical forested biomes, representing needleleaf and broadleaf canopy structures in the Pacific Northwest (Oregon), Eastern U.S. (Harvard Forest), southern Chile, the Amazon, and Central America. The TM scenes were atmospherically corrected and reduced to MODIS surface reflectance data at 250 m pixel sizes. Various vegetation indices (VIs) were then computed including the normalized difference vegetation index (NDVI), simple ratio, soil-adjusted vegetation index (SAVI), enhanced vegetation index (EVI), and green vegetation index (GVI). The NDVI was also tested utilizing the green and middle-infrared (MIR) bands. All of the NDVIs were non-linear and were fairly saturated across the forested biomes. In contrast, the remaining indices remained sensitive to canopy structure variations over all of the forested biomes with minimal saturation problems. The high 'penetrating' capability of the near-infrared band through forested canopies was the dominant factor in vegetation index sensitivity and performance. We found that indices with higher weighing coefficients in the "near-infrared" to be the best approach in extending vegetation index performance over forested and dense vegetated canopies.

INTRODUCTION

The normalized difference vegetation index (NDVI), a non-linear transform of the near-infrared to red reflectance ratio, was developed to enhance the vegetation signal in low biomass conditions. Unfortunately, this enhancement is achieved at the expense of reduced sensitivity at the upper, or high biomass range of conditions. As a result, the NDVI often "saturates" in high biomass areas such as in forested biomes. Saturation occurs when the NDVI no longer responds to variations in green biomass. Changes in land use, land cover, biophysical vegetation parameters, and net primary production are difficult to detect in a 'saturated' mode. Studies have shown the NDVI to exhibit very little variation over canopies with low red reflectances (0.02 to 0.05) despite NIR reflectances which varied by over a factor of two [1].

This problem has been partially attributed to the highly-sensitive, chlorophyll-absorbing, "red" waveband, which saturates quickly with forest canopy closure. Several approaches have been proposed to improve upon the performance of vegetation indices (VI) and achieve greater sensitivity in high biomass situations. These include use of the "green" band instead of the "red" band in the NDVI equation; (2) use of the "middle infrared" band for the "red" band in the vegetation index equation; and (3) use of more linear vegetation indices such as the Green Vegetation Index (GVI).

Gitelson [2] found a 'green' based NDVI to have a wider dynamic range and be five times more sensitive to chlorophyll-a concentration than the standard NDVI, since the green waveband remains sensitive to chlorophyll-a over a wider range of concentrations. This is of particular interest to the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, which has a narrower, more chlorophyll-sensitive red band (620 - 670 nm) relative to that of the broader-band, NOAA-AVHRR (550 - 680 nm).

Others have utilized Landsat TM bands 5 (1.55 - 1.75 μm) and 7 (2.08 - 2.35 μm) for discrimination of land cover types as well as variations in canopy structure in high biomass forest/grassland conditions. Red band imagery has been shown to saturate over Brazilian tropical forests which contained both primary and secondary forests in initial through advanced stages of regrowth. [3] In this study, we investigate vegetation index sensitivity in high biomass, forested canopies. The objectives of this analysis were: (1) to determine if vegetation index saturation is inherent to all, and (2) to determine if the 'green' and 'MIR' bands can be used to increase sensitivity over dense canopies.

METHODS AND STUDY SITES

We include forests with both broadleaf and needleleaf structures and evergreen and deciduous phenologies. In this paper we present the results obtained over two rainforests, a temperate evergreen broadleaf forest in southern Chile and a tropical evergreen broadleaf forest near Manaus, Brazil.

The TM images were first converted to 250m imagery using a fourier transform based, TM to MODIS program. The 250m images were calibrated with updated, vicarious-based calibration factors and then atmospherically corrected by use of an atmospheric radiative transfer code based on dark objects. The following vegetation indices were then calculated:

$$NDVI = (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red}), \quad (1)$$

$$NDVI_{green} = (\rho_{nir} - \rho_{green}) / (\rho_{nir} + \rho_{green}), \quad (2)$$

$$NDVI_{MIR} = (\rho_{nir} - \rho_{MIR}) / (\rho_{nir} + \rho_{MIR}), \quad (3)$$

$$SAVI = (1 + L) (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red} + L), \quad (4)$$

$$EVI = 2.5 (\rho_{nir} - \rho_{red}) / (1 + \rho_{nir} + 6 \rho_{red} - 7.5 \rho_{blue}) \quad (5)$$

$$GVI\ (6\ band) = -0.214*\rho_{TM1} - 0.254*\rho_{TM2} - 0.414*\rho_{TM3} + 0.812*\rho_{TM4} + 0.046*\rho_{TM5} - 0.239*\rho_{TM7} \quad (6)$$

$$GVI\ (4\ band) = -0.5*\rho_{TM3} + 0.806*\rho_{TM4} - 0.02*\rho_{TM5} - 0.316*\rho_{TM7} \quad (7)$$

The linear-based, GVI coefficients were derived with the use of an 'n-space' program [4].

RESULTS

Fig. 1 shows that there was very little variation in the red reflectance values over the forests of Chile (Fig. 1a) and Brazil (Fig. 1b). Yet there is considerable variation in the NIR reflectance values, associated with canopy structural conditions due to differences in forest species, regeneration stage, and LAI. There is also only slight variations in green reflectance values and slightly more variable middle-infrared reflectances, despite NIR variations from 0.10 to 0.40 (Fig. 1). This indicated that the use of the green and MIR bands would not result in significant sensitivity differences in the NDVI over these forests. Fig. 2 shows the resulting VI behavior over these forests. The NDVI was nearly saturated over both of the forests, including with the use of the green and MIR based, NDVI equations. The green band lowered the NDVI values slightly, while the MIR band raised them slightly. Thus, these additional bands did not result in a more sensitive NDVI equation. In contrast the SAVI and EVI remained sensitive to the variations in NIR reflectances. Similarly, the GVI equations also did not saturate and maintain sensitivity over these dense forests. This is seen in a crossplot of the GVI equations with the SAVI (Fig. 3). There was very little difference between the 6 - band and 4 - band GVI equations. Fig. 4 shows the ratio itself (NIR/red), remained sensitive to variations in the canopy, although with such low red reflectance values, the ratio was somewhat unstable with much scatter.

CONCLUSION

The structure of the NDVI equation, which is a non-linear transform of the simple ratio (NIR/red), was found to be the major cause for non-linearity and saturation in high biomass situations. As a result of the non-linear nature of the NDVI equation, the substitution of the "green" or "MIR" channels for the "red" had only slight but minimal improvements on NDVI sensitivity. The simple ratio, which is insensitive at low amounts of vegetation was found to remain sensitive to high biomass conditions without saturation. The ratio showed that there is still a significant "vegetation" signal present over dense forests. The GVI, EVI, and SAVI reduced the saturation problem considerably, remaining sensitive to canopy variations over high biomass conditions. The high 'penetrating' capability of the near-infrared band through forested canopies was the dominant factor in vegetation index sensitivity and performance.

DISCUSSION

Although linear combination indices and other indices which are not "ratios" of wavebands performed better than the NDVI and NIR/red ratio indices, they would be more prone to noise associated with external factors such as calibration, cloud shadow, and topography than the ratio-based indices. However, in an era where atmospheric corrections and BRDF adjustments have progressed significantly, it is questionable whether we should still be relying on ratioing as a way to standardize data sets for routine, operational use.

ACKNOWLEDGMENTS

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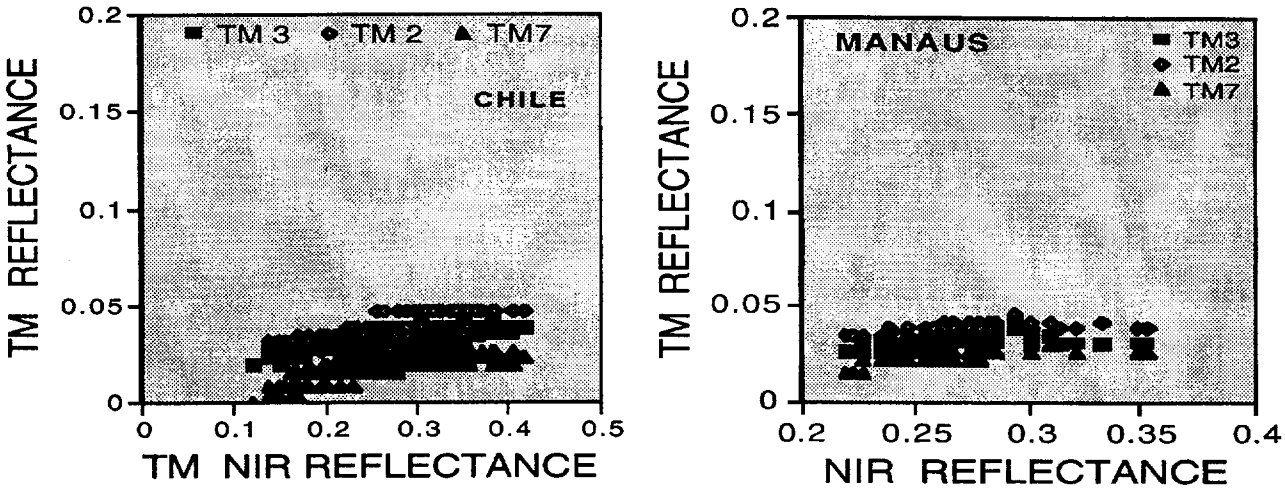

Fig. 1 Crossplots of green (TM2), red (TM3), and MIR (TM7) reflectances against NIR (TM4) reflectances for the (a) Chile forest and (b) Manaus forest.

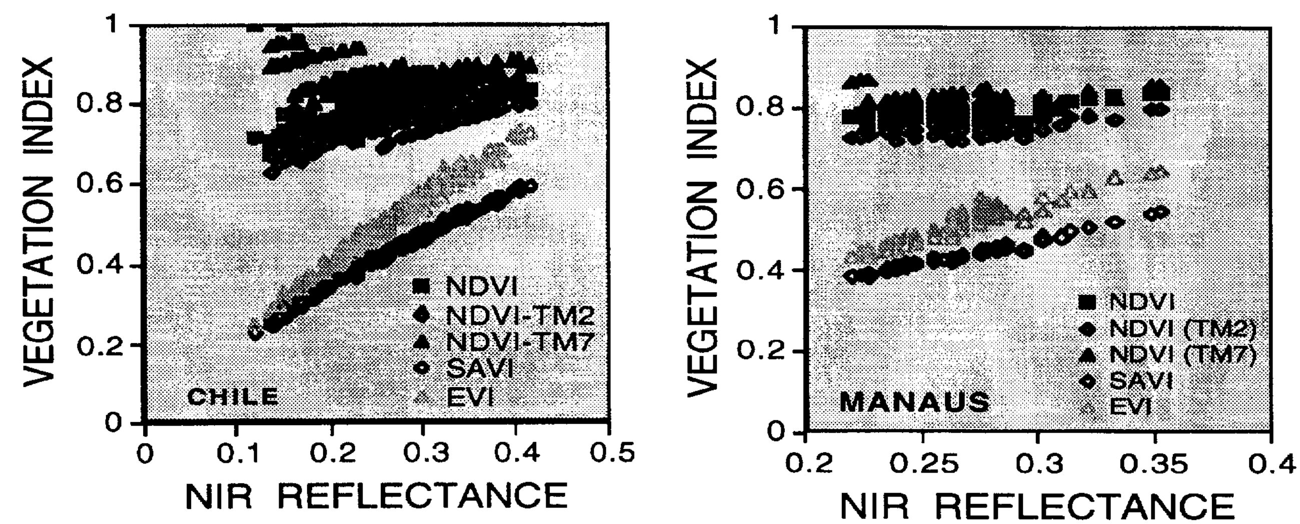

Fig. 2 Vegetation index behavior with NIR reflectance varaitions for (a) Chile and (b) Manaus.

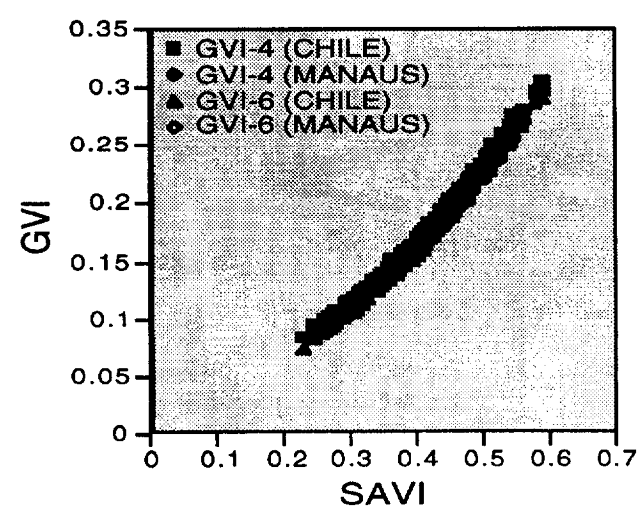

Fig. 3 4- and 6- band GVI equations plotted with the SAVI for Manaus and Chile.

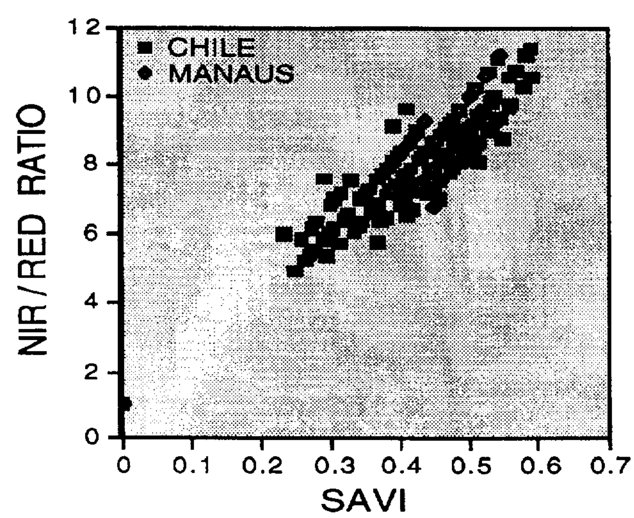

Fig. 4 NIR/red reflectance ratio plotted with the SAVI for Manaus and Chile.