What do vegetation indices tell us about the dynamics of the Amazon evergreen forests?

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Abstract. Our understanding of the response of satellite–based vegetation indices to the meteorological conditions in terms of temperature and precipitation conditions of the Amazon evergreen forest is arguably weaker than that of any other tropical continental region, despite the obvious connection. To assess such response, we have used different dataset of vegetation indices – the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and Fraction of Vegetation Cover (FVC) derived from SPOT 4 Satellite VEGETATION data and Meteosat Second Generation (MSG) satellite products. Based on the covers time scales from daily to dekadal, at spatial resolutions from 1 to 3 km, and provides temporal coverage for the period of extremely El Niño event (between 1998-2000). And the weather data were compiled from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) – HydroNet collection. The obtained results suggest that the combined effects of precipitation decrease and air temperature increase in the healthy Amazon evergreen forest is a possible explanation of the higher EVI values and the lower NDVI values during the dry season. On the other hand, FVC reflects the combined effects of precipitation and air temperature changes, shows the higher values for pasture and lower values during the wet season consistent with an increase in precipitation and a decrease in air temperature. Such distinct vegetation responses may be viewed as a function of the spatial scale.

Key words:.Vegetation indices, meteorological conditions, green-up, El Niño.

1. Introduction

The satellite–based vegetation index is one of the main research tools used to assess vegetation dynamics of the Earth's surface (Huete *et al.* 2006), yet persistent problems limit its full acceptance in ecological research. It can be somewhat difficult to know exactly what vegetation index is responding to depending on spatial scale. Different studies suggest that it correlates well with leaf area index, green leaf biomass and annual net primary productivity. Moreover, little is known quantitatively, regarding the degree to which spatial variation in vegetation index depends on rainfall seasonality in tropical rainforest at regional scale. While on the smaller spatial scales, it is partly associated with soil properties, rooting depth and vegetation types.

Special attention has been devoted to investigating the dependence of phenological variability in the healthy Amazon evergreen forest. Huete *et al.* (2006) found that higher vegetation index values in the dry than in the wet season. This unexpected pattern was initially linked to invalid data due to cloud- and water-vapor contamination in the wet season, and to aerosols due to slash and burn agriculture during the dry season. Others, such as Saleska *et al.* 2003 and Myneni *et al.* 2007, applied time series analyses based on MODIS and AVHRR vegetation data to reveal the same patterns. Evidence already exists that the increase in sunlight during the dry season causes a vegetation green-up. While this increase is consistent with ground-based measurements of carbon fluxes (Nemani *et al.*, 2003), there is widespread suspicions that water availability during the dry season is not the limiting factor, because the roots of trees may reach up to 20 m down into the soil and saprolite (Nepstad *et al.*, 1994).

In fact, the results above may be viewed in terms of the distinct responses of the disturbed forests and pasture with a shallow rooting system that shows green-up prevailing during the rainy season. These conditions, in turn, are confirmed by the increase in LAI of healthy Amazon evergreen forests. Locally, this increase is typically triggered by the rainy season. This is of particular interest within the scope of climate research. Because more leaves, evapotranspiration will also increase but, as decreased surface temperature favors lower evaporation. And hence the Amazon rain forest itself triggers the rainy season, which is a great example of surface-atmosphere interaction.

Based on the results of Huete *et al.* 2006, our central objective, is to explore some new daily Fractional Vegetation Cover (FVC) and dekadal NDVI S10 VEGETATION products received through EUMETCast service's EUMETSAT (Europe's meteorological satellite agency) to characterize the spatial and seasonal variations between undisturbed forests and pasture sites across the Amazonian region. We use the equivalent sites from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) Project in multiple years 1998, 1999 and 2007 to verify whether or not the green-up conditions prevailing during the dry season?

2. Material and Methods

The Amazonian region is very important in the global climate system. It consists of a mosaic of ecosystems and land cover types including grassland, shrubland, flooded forests, deciduous florets, seasonal forests, and rainforests. Primary rain forest is vertically structured into at least five layers: the overstory, the canopy, the understory, the shrub layer, and the forest floor (Figure 1). Changes of precipitation regime in the region are known to be associated with changes of path of storm-tracks that are partially controlled by a few specific large-scale modes of atmospheric circulation, such as the El Niño-Southern Oscillation (ENSO) events. Such El Niño changes in the precipitation regime are directly associated to major impacts in the vegetation dynamics and the frequency of wild fires. As precipitation is the main driver of land surface hydrological cycle, other major hydrological indicators will also change correspondingly. Soil moisture progressively decreases; so will runoff and river discharge, reducing the water available for Amazon evergreen forests. They are known to have deep rooting systems, which are thought to maintain evapotranspiration at high levels even during seasonal drought conditions (Nepstad *et al.*, 1994).

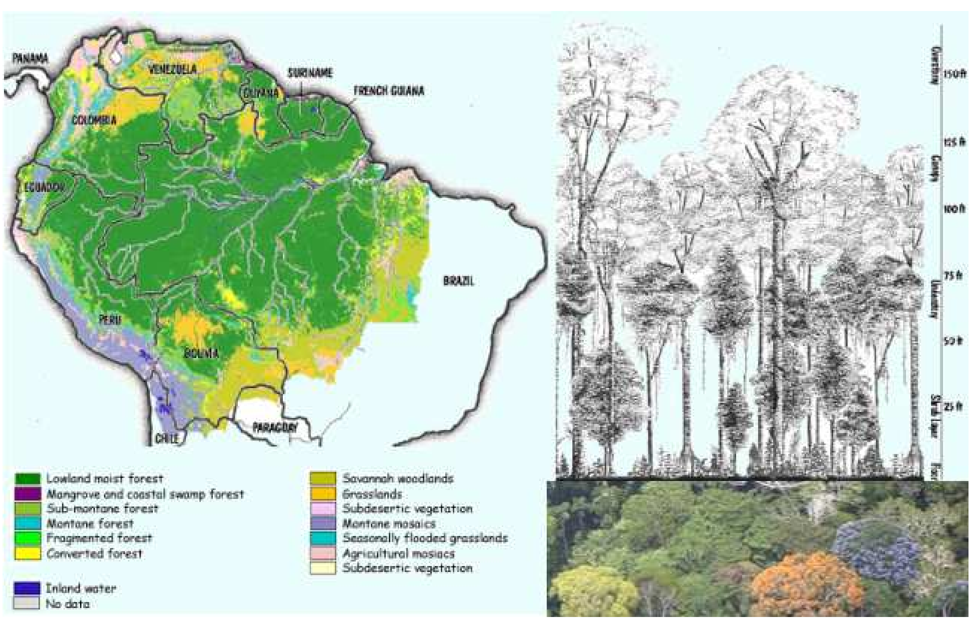

Figure 1. The Amazonian region and its land cover types.

The LAPIS (Laboratório de Análise e Processamento de Imagens de Satélites in Portuguese – http//www.lapismet.com) laboratory receives 10-day vegetation indices derived from SPOT-VEGETATION (VGT) and daily FVC derived from MSG-SEVIRI data products for the whole South America data by means of a satellite antenna pointed towards the NSS-806 satellite (EUMETCast service) in a GRIB (or HDF5) format which is not recognized by readily available remote sensing software packages. Three spectral bands: blue (0.43-0.47μm), red (0.61-0.68 μm), and NIR (0.78-0.89 μm) from VGT data are from http://free.vgt.vito.be, and then both the NDVI and Enhanced Vegetation Index (EVI) indices are derived from 10-day.

The main purpose of the LAPIS is to develop tools to retrieve parameters related with land, land-atmosphere interactions, and biospheric applications, using data from satellites, with special emphasis on Meteosat Second Generation (MSG) satellites. Due to the different spectral band definitions, also the influence of the atmospheric perturbations will be different for VGT and AVHRR. Due to their intrinsically different spatial and spectral bands, and also the influence of the atmospheric perturbations are regarded separately for both NDVI and Fraction Vegetation Cover (FVC). The VGT sensor was specifically designed for vegetation monitoring purposes, whereas MSG Spinning Enhanced Visible and InfraRed Image (SEVIRI) is mainly intended for operational meteorological monitoring.

The S10 VEGETATION product is a 10 day compositing obtained from the maximum composites values (MVC) of NDVI and EVI from all the images acquired of a location within a 10 day period. The VGT sensor on board the polar orbiting SPOT satellites captures data at a spatial resolution of approximately 1km with a daily repeat cycle at an altitude of around 820 km. The product was pre-processed by the Flemish Institute for Technological Research (VITO) using a consistent processing algorithm including geometric, radiometric, and atmospheric corrections.

The FVC product is an operational level product generated daily from SEVIRI data for the full MSG disk. The SEVIRI sensor operates with 12 spectral bands – two of which are especially useful for vegetation studies – which provides measurements with a ground resolution of 3×3 km^2 at the sub-satellite point every 15 minutes at 0°N, 0°W ~36 thousand km above the Earth's surface. The FVC product user manual, also available on the LSA – SAF website (http://landsaf.meteo.pt/) describes FVC as representative of the fraction of vegetation on a flat background covered by vegetation. This product is able to report a per pixel value which indicates the proportion of vegetation cover for that pixel. It is derived by a spectral mixture analysis which is designated by the difference vegetation index – rather than the NDVI that is the difference of the NIR and red channels (LSASAF 2008c). The FVC data range from 0 to 1.

Monthly rainfall data were extracted from LBA-HydroNet collection. The point data collected for the forest (10.09°S, 61.55°W) and pasture (10.45°S, 62.22° W) land covers to validate 10-day NDVI and EVI products. This data were downloaded from www.lba-hydronet.sr.unh.edu/. The processing analysis was carried out using Matlab 7.5. Further temporal profiles were generated for both monthly average 10–day NDVI (EVI) and monthly mean precipitation values for both forest and pasture land covers for the period April through December for the years 1998 and 1999. Monthly maximum and minimum air temperatures were computed as seasonal mean from the corresponding daily period (1982-1995) for the two land covers to show a possible explanation of the temperature and precipitation conditions in driving their seasonal variability.

We are interested in whether the healthy Amazon rain forest has higher vegetation values in the dry than in the wet season. To further investigate this issue, a temporal comparison of the monthly average NDVI (EVI) and the monthly average precipitation values for both forest and pasture land covers for the period April through December for the years 1998 and 1999 was carried out. Pearson's correlation was calculated for the comparisons, with NDVI (EVI) as the independent variable and its spatially standard deviation as the dependant for the period of 1998-2000.

We coupled daily plots of rainfall and 10-day NDVI (EVI) into monthly averages for the period April through December for the years 1998 and 1999. This effort, though, relied on daily changes in the FVC annual cycle at four sites for the year of 2007. The distribution of the four main land cover types is depicted in two Santarém forest sites, km 83 (3.03 S, 54.97W) (site plot #1) and km 67 (2.86 S, 54.96 W) (site plot #2) are in the Floresta Nacional do Tapajós in the state of Pará. Another forest site is in the Floresta Nacional do Caxiuanã (1.75 S, 51.45 W) (site plot #3) near the mouth of the Amazon River. The forest conversion sites Altamira (3.24 S, 52.3 W) (site plot #4). The reason for the selection of this period was to have a significant influence on humid and drought conditions in the region, with extreme El Niño years (i.e., 1998 and 2007) generally associated to below normal precipitation, whereas above normal precipitation is recorded during La Niña years (i.e., 1999). In order to draw a more conclusive picture for the green-up conditions prevailing during the dry season, the maps of NDVI and EVI (1998 and 1999) and FVC (2007) were also analyzed over the during the periods of the year characterized by more (less) intense vegetation activity.

3. Results

3.1 Seasonal 10-day SPOT NDVI, 10-day SPOT EVI, 10-day rainfall dynamics in the pasture and forest covers in Amazonian region

Figure 2 shows the seasonal evolution of rainfall, NDVI, and EVI values at the time scale from April through December of the El Niño/La Niña years in the pasture and forest covers. Despite the general similarity, differences exist between NDVI and EVI values (Fig 2 a-d). While the precipitation is the main driver of NDVI, with the highest values of NDVI associated to wet season (in July). On the contrary, the EVI values are actually higher during dry season (in October), as the higher mean air temperature values, as was also seen in the work of Huete *et al.* 2006. However, when both pasture and forested covers are mainly related to extreme phases of the El Niño (1998) and La Niña (1999), there are not noticeable differences in the NDVI values – but only in the EVI values.

The NDVI forest profile in Figure 2 (a-d) shows higher peaks than the pasture profile and overall is higher than pasture for the whole length of the profiles. This could be attributed to the fact that rainfall amount is higher in the forest than pasture. Overall, it is seen that the NDVI and EVI profiles are quite different between the two land covers, with less visual seasonal variations in the forest cover over the EVI values. Based on temporal profiles, NDVI appears to have higher visual seasonal variations in both pasture and forest covers than EVI. Atmospheric correction of data normally leads to an increase in NDVI values (Goetz 1997), due to the influence of the increase of atmospheric water vapour and aerosol (Holben 1986). Since NDVI has a tendency to lessen with them.

In particular, the regression in Figure 2 (e-f) is for the values retrieved by the same points as was used in Figure 2 (a-d), (on the shorter April 1998 – December 2000 period). The r values for both SPOT NDVI pasture and SPOT NDVI forest versus their spatial standard deviation are good overall (0.40 and 0.63 respectively) which indicates significant correlations and the regressions shown here in Figure 3(a) are all statically significant at the $\alpha = 0.05$ level. In contrast, the r values for both SPOT EVI pasture and SPOT EVI forest versus their spatial standard deviation are weakly to no significant correlated.

3.2 Seasonal daily-MSG FVC dynamics in the evergreen, pasture and forest covers in Amazonian region

The four key eco-LBA research sites of the Amazon evergreen-forests are shown in figure 3. These sites were depicted by same points as were used to Huete *et al.* (2006). The “Bezier smoother” was applied to the daily MSG FVC time series. The daily FVC forest profiles for the four sites peak in July-August, with high visual seasonal fluctuations over the year of 2007. These peaks in FVC profiles coincide with the peak of dry season. Some sections of the FVC profiles have concurrent sudden drops, particularly, around April and October. It is probable that both cloud masks and atmospheric correction of data used in generating the FVC product were not able to mask and to correct very thin cloud cover that occurred during these months. The pixel size of the MSG data is relatively coarse (higher than 3km) so the pixels in forested areas represent a mixture of forests.

Figure 4 displays the daily FVC profiles, over the year of 2007, of the pasture and forest covers. The daily oscillations for the two covers are broadly similar results represented in one major peak of FVC values during April through August. A couple of troughs in the FVC profiles (like around October and December) may be due to thin cloud cover, otherwise cannot be explained. Overall, MSG behavior is broadly similar to that depicted by the SPOT NDVI profiles (Fig. 2a and 2b); however seasonal variations of MSG FVC are higher than SPOT NDVI.

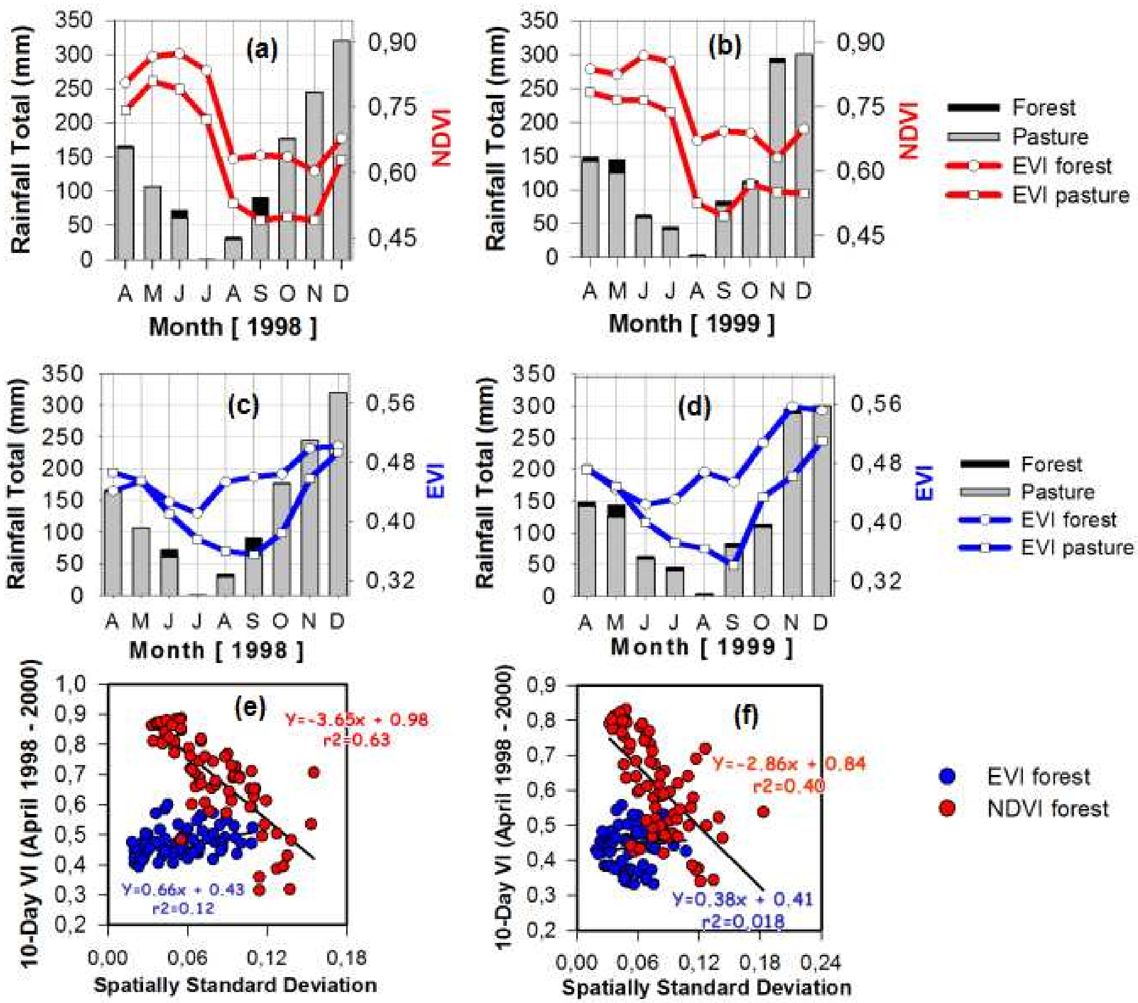

Figure 2. Comparison of10-day rainfall, 10 day SPOT NDVI and 10-day SPOT EVI temporal profiles for pasture and forest land covers (a, b, c, d). Scatterplots for 10-day (NDVI, EVI) versus their spatially standard deviation for pasture and forest land covers (e, f).

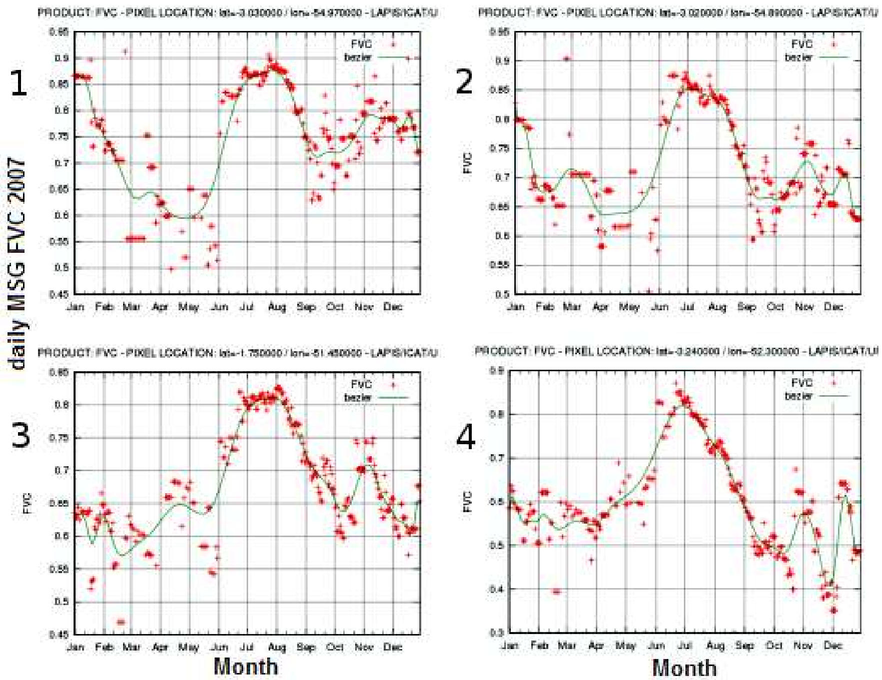

Figure 3. Temporal profile graphs of daily MSG FVC for pasture and forest covers. Two Santarém forest sites (#**1**) and (#**2**) are in the Floresta Nacional do Tapajós in the state of Pará. Another forest site is in the Floresta Nacional do Caxiuanã (#**3**) near the mouth of the Amazon River. The forest conversion sites Altamira (#**4**).

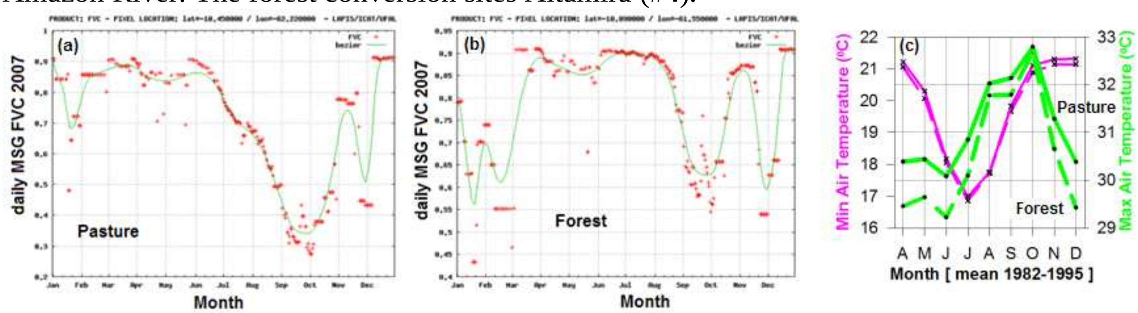

Figure 4. Daily MSG FVC profiles for both pasture (a) and forest (b) over the year of 2007. The climate conditions in terms of both minimum and maximum air temperature (c) located at pasture (10.45°S, 62.22° W) and the forest (10.09°S, 61.55°W).

3.2 Spatial patterns of SPOT NDVI, SPOT EVI and MSG FVC over a selected window in the Amazonian region

Figure 5 displays the spatial patterns, over a selected window of South America, of both 10-day SPOT NDVI and 10-day SPOT EVI for the months following springers with El Niño (1998) and La Niña (1999) years (from 21-30th September). Results show a large spatial diversity in the influence of both El Niño and La Niña events on the vegetation indices throughout the Amazonian region. The main difference is that SPOT EVI appears more sensitive to photosynthetic activity than SPOT NDVI data, but reversely, SPOT NDVI appears more sensitive to drought conditions than SPOT EVI data. The pattern of the El Niño impact on the SPOT NDVI data is clearly apparent with an East-West gradient. Contrasting with these figures, the spatial signature MSG SEVIRI FVC of the dry and the humid conditions affecting the vegetation activity for the year 2007 can be observed in Figure 6 (a selected window of the Amazonian region), suggesting that increasing temperatures (dry season) may lead to increased vegetation development. This pattern is apparently characteristic of the mid to high latitudes of the Northern Hemisphere. Although resulting from a daily basis, the image is still affected by cloud contaminated pixels. This is the case in the dry season, as suggested at Figure 3.

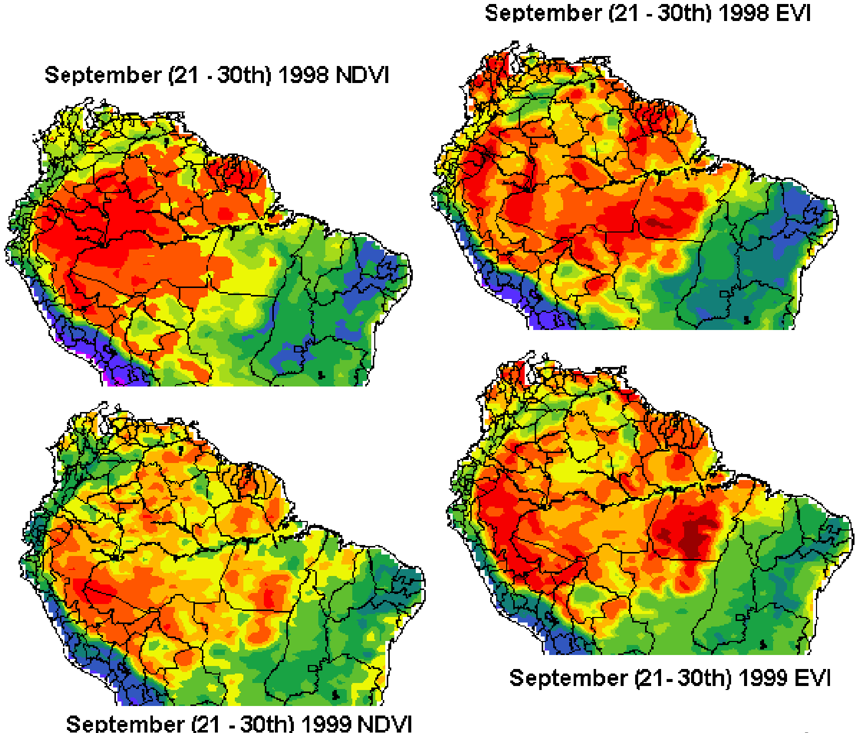

Figure 5. Spatial patterns of both SPOT NDVI and SPOT EVI from 21-30th September of both 1998 (El Niño) and 1999 (La Niña) years over a selected window of South America.

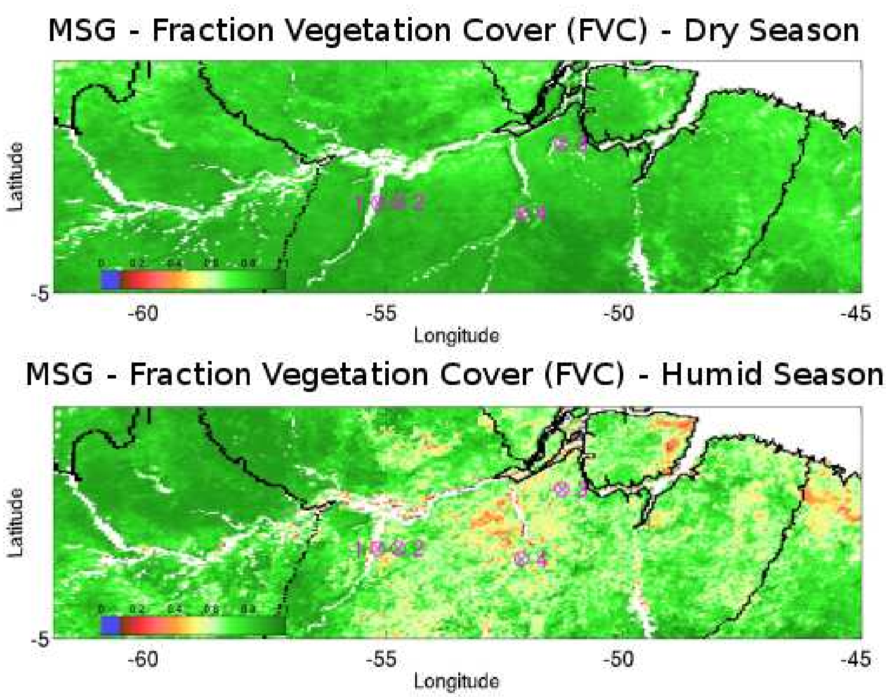

Figure 6. Spatial patterns of MSG FVC MSG SEVIRI FVC of the dry and the humid conditions of the year of 2007.

4. Conclusions

In this study, we evaluates whether there is empirical evidence to support the healthy Amazon evergreen forest has higher vegetation indices in the dry than in the humid season. Using satellite-derived SPOT NDVI, SPOT EVI and MSG FVC data over the period of April 1998 through December 2000, the obtained results suggest that the combined effects of precipitation decrease and air temperature increase in the healthy Amazon evergreen forest (at site plots) is a possible explanation of the higher EVI values and the lower NDVI values during the dry season. Furthermore, such a drier weather may be enhanced by El Niño years as reflecting the impact of drought conditions on the vegetation activity. The highest impact of El Niño occurs during the periods of the year characterized by more intense vegetation activity, i.e. around September in the case of central part of the Amazonian region. Because of the drier weather conditions, evapotranspiration will also decrease but, as increased surface temperature favors higher evaporation and hence the potential for forest activity. On the other hand, FVC reflects the combined effects of precipitation and air temperature changes, shows the higher values for pasture and lower values during the wet season consistent with an increase in precipitation and a decrease in air temperature. Despite its different methodology and its uncertainties associated with cloud contaminated pixels, the interpretation of FVC patterns is straightforward. Overall our results are in line with Huete *et al.* 2006, which have stressed the healthy Amazon evergreen forest has higher vegetation index values in the dry than in the wet season.

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