# Amazon vegetation greenness as measured by satellite sensors over the last decade

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[1] During the last decade two major drought events, one in 2005 and another in 2010, occurred in the Amazon basin. Several studies have claimed the ability to detect the effect of these droughts on Amazon vegetation response, measured through satellite sensor vegetation indices (VIs). Such monitoring capability is important as it potentially links climate changes (increasing frequency and severity of drought), vegetation response as observed through vegetation greenness, and land-atmosphere carbon fluxes which directly feedback into global climate change. However, we show conclusively that it is not possible to detect the response of vegetation to drought from space using VIs. We analysed 11 years of dry season (July–September) Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) and normalised difference vegetation index (NDVI) images. The VI standardised anomaly was analysed alongside the absolute value of EVI and NDVI, and the VI values for drought years were compared with those for non-drought years. Through a series of analyses, the standardised anomalies and VI values for drought years were shown to be of similar magnitude to those for non-drought years. Thus, while Amazon vegetation may respond to drought, this is not detectable through satellite-observed changes in vegetation greenness. A significant long-term decadal decline in VI values is reported, which is independent of the occurrence of drought. This trend may be caused by environmental or noise-related factors which require further investigation. **Citation:** Atkinson, P. M., J. Dash, and C. Jeganathan (2011), Amazon vegetation greenness as measured by satellite sensors over the last decade, *Geophys. Res. Lett.*, *38*, L19105, doi:10.1029/2011GL049118.

## 1. Introduction

[2] The Amazon region contains around 54% of the world's rainforest and stores more than 100 billion tonnes of carbon [*Malhi et al.*, 2006]. A general increase in temperature since the 1970s, and decadal-scale variation in rainfall, have been recorded for the Amazon rainforest [*New et al.*, 2000], while *Li et al.* [2008] reported a 0.32 per decade decline in the standard precipitation index between 1970 and 1999, suggesting increasingly dry conditions in the Amazon in recent years. Several global circulation models (GCMs) have projected these trends into the future [*Marengo*, 2005] leading to concerns over the effects of increased frequency and severity of drought on net primary productivity and biomass carbon storage in the Amazon basin [*Lewis et al.*, 2011] and possible feedback effects of biomass loss on climate change.

[3] Changes in precipitation amount and duration may affect photosynthetic activity and the functioning and condition of the forest which, in turn, may affect overall carbon fluxes to the atmosphere. In a normal year, the Amazon rainforest absorbs approximately 1.5 billion tonnes of carbon from the atmosphere. However, *Lewis et al.* [2011] predicted, based on a model, a net transfer of 2.2 billion tonnes of carbon to the atmosphere in 2010, a drought year. Thus, the prospect of increasingly dry conditions, and an increasing frequency of drought years, is of great concern as such conditions have the potential to turn the Amazon from a sink of carbon into a source of carbon, greatly affecting rates of global climate change [*Lewis et al.*, 2011].

[4] For an area as vast as the Amazon, satellite remote sensing provides the only possible means of monitoring the impact of droughts on vegetation at the basin scale. Such remote sensing approaches generally rely upon the use of vegetation indices (VIs) to measure vegetation "greenness". The ability to detect from space the effect of drought on vegetation response, in the form of vegetation greenness, is potentially of crucial importance in monitoring the effects of drought on carbon flux in the Amazon.

[5] During the last decade two severe drought events affected the Amazon basin; one in 2005 and the other in 2010. The drought in 2010 was spatially more extensive than that in 2005 and affected more than 3 million $km^2$ [*Lewis et al.*, 2011]. *Saleska et al.* [2007] were the first to report a significant *increase* in vegetation greenness over the Amazon during the 2005 drought using the enhanced vegetation index (EVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. However, this was later challenged by *Samanta et al.* [2010] on the basis of poor data quality and processing methodology. They suggested greater vegetation browning (or no change) than greening during the 2005 drought. Moreover, *Anderson et al.* [2010] reported positive EVI anomalies associated with higher tree mortality and questioned *Saleska et al.*'s [2007] interpretation of the observed changes in VIs. *Brando et al.* [2010], using climate, satellite and field data found no relationship between the inter-annual variability in plant available water (PAW) and EVI for densely forested areas in the Amazon, but observed a decline in EVI with decline in PAW for areas with low vegetation cover. Recently, a key paper published in this journal by *Xu et al.* [2011] suggested, using MODIS VIs, that vegetation browning in 2010 was four times greater than in 2005 affecting more than 50% of the forested area in the Amazon and, thus, that the increased browning was a response to the 2010 drought. Thus, controversy exists in the literature about the effects of

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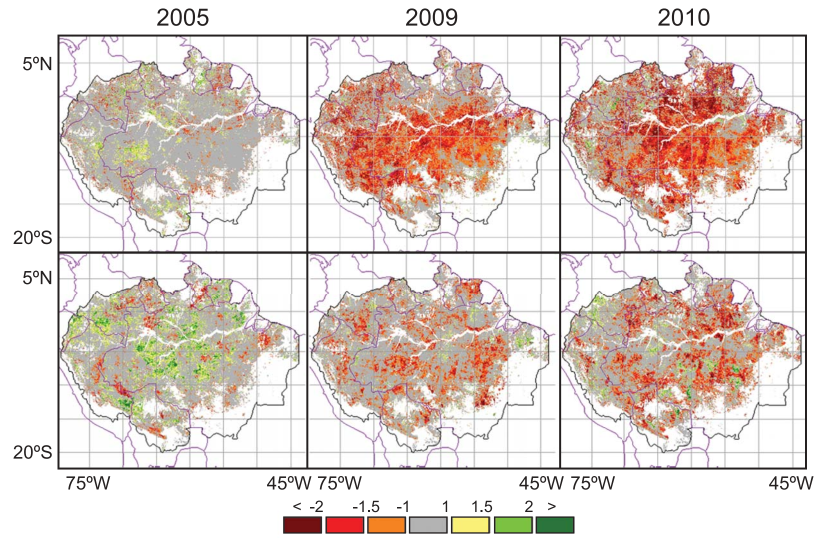


**Figure 1.** Spatial distribution of the standardised anomaly for (top) NDVI and (bottom) EVI for 2005, 2009 and 2010. In 2005, many areas in the Amazon basin show no change (gray). However, areas in the central basin show a positive standardised anomaly in EVI. Both 2009 (non-drought) and 2010 (drought) show large areas with negative standardised anomalies.

drought on Amazon vegetation greenness and its spatial manifestation across the basin.

[6] All of the above studies used the VI standardised anomaly (drought year VI subtracted from the mean VI for the study period divided by the standard deviation of the VI for the study period) to quantify changes in vegetation greenness (i.e., vegetation green up or brown down). In most cases [e.g., *Saleska et al.*, 2007; *Xu et al.*, 2011], researchers reported anomalies for the drought year in question without considering the values for non-drought years. We question the use of satellite VI anomalies to infer the response of Amazonian vegetation to drought. We show that, if the results are to be robust, researchers should, as a minimum, consider anomalies for drought years alongside the same measures in non-drought years. Moreover, in addition to the standardised anomaly (a relative measure) other *absolute* measures of change in VI value should be considered. We present some alternative methods in this paper. Finally, before linking vegetation index anomalies to processes such as changes in photosynthesis, and carbon sequestration and release, care should be taken to interpret them relative to the expected measurement uncertainty of the data products.

[7] If VIs are to be used to infer the response of Amazonian vegetation to drought then the observed changes should be (i) greater than the expected inter-annual variation, (ii) greater in drought years compared to non-drought years and (iii) larger than the expected error of the data product. Therefore, we re-visited the impacts of the 2005 and 2010 droughts on changes in MODIS-derived VIs and compared these changes to non-drought years to question whether the declines previously reported as associated with drought events could be substantiated. In addition to the standardised anomaly other methods were explored to detect changes in VI values.

## 2. Data and Methodology

[8] Satellite-derived data were used to investigate trends in vegetation greenness in the Amazon rainforest. Specifically, 16 day composites of MODIS EVI and normalised difference vegetation index (NDVI) (MOD13C1, C5) at a spatial resolution of 5.6 km from 2000 to 2010 and tropical rainfall measuring mission (TRMM) monthly surface rain rate at a spatial resolution of 55 km for the same period were used. The six (MODIS) or three (TRMM) composite images for July to September were averaged to provide a single dry season image for each VI and dry season images of surface rain rate, for each year. For MODIS products, only the highest quality pixels were considered (pixel reliability flag = 0). The data were analysed within the Amazon forested area only to avoid false inferences. Forested pixels were defined using the recently published fine spatial resolution (300 m) global land cover map (GLOBCOVER2009 Ver.2; class: closed to open [15%] broadleaved evergreen and/or semi-deciduous forest [>5 m]; available from www.ionia1.esrin.esa.int) and were upscaled using a majority filter to a common spatial resolution.

[9] For each year, the annual dry season mean for each VI was calculated using valid pixels only. It was noticed that for a few composites of the MODIS EVI and NDVI products, even for the highest quality pixels, many areas had unexpectedly low VI values (NDVI < 0.5) for dense Amazon forest. These low values of NDVI may be due to noise in the data not detected by the quality flags. Thus, only VI values greater than 0.7 for NDVI, and 0.4 for EVI were considered, for all calculations.

[10] Four different methods were analysed to investigate the potential effects of drought on vegetation response as detected through VIs. First, to characterize the temporal variation in VI anomaly we calculated the dry season VI anomaly for 11 years (2000 to 2010). The standard anomaly (SA) of the dry-season annual mean ($\overline{X}$) was calculated for every pixel for every year, with reference to the long-term mean ($\overline{L}$) and standard deviation ($\sigma_L$) over 2000–2010:

$$SA = \left( \frac{\overline{X} - \overline{L}}{\sigma_L} \right) \quad (1)$$

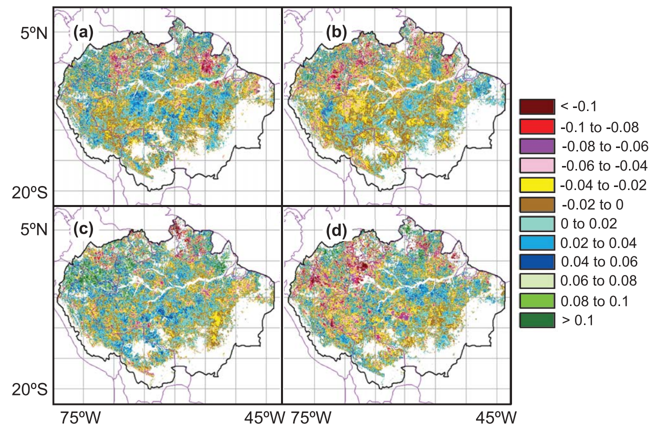


**Figure 2.** The inter-annual differences in mean dry season EVI between the years (a) 2010 and 2009, (b) 2009 and 2008, (c) 2005 and 2004 and (d) 2004 and 2003. In Figure 2a, an area in the north–east shows a decline in EVI (purple colour). Interestingly, that area is associated with positive rainfall anomaly [*Lewis et al.*, 2011]. In Figure 2b, the magnitude of absolute EVI change is similar to Figure 2a, but varies spatially. In Figure 2c, many areas in the north–west showed an increase in EVI value of up to 0.1, but these areas do not match with areas of increasing greenness as reported by *Saleska et al.* [2007]. In all figures, the inter-annual changes in the majority of the areas are within the error limit of the vegetation index.

[11] For this research, each year was included in the calculation of the mean, rather than excluding drought years (the distributions of NDVI and EVI during drought years (2005 and 2010) were not significantly different to those of non-drought years; Figure S1 in the auxiliary material).[1]

[12] Second, the inter-annual differences in the VI values were estimated between (i) a given drought year and the preceding non-drought year and (ii) two consecutive non-drought years. Third, we estimated the year of maximum decline in VI values with the expectation that drought years would produce the largest decline. The differences in annual mean VI for the time-series were calculated and these were then ranked in descending order to identify the year corresponding to the maximum change in VI. Finally, the decadal temporal correlation ($r$) and rate of change (slope) were calculated spatially for each variable.

## 3. Results and Discussion

### 3.1. Standardised Anomaly

[13] The standardised anomaly was analysed for 11 years. For both VIs, areas of positive anomaly declined and areas of negative anomaly increased over this time period (Figures S2 and S3). Though both NDVI and EVI showed a larger proportion of negative anomaly in 2010 (a drought year; NDVI = −51.9% and EVI = −29.1% for all forested areas), other non-drought years such as 2009 produced a similar proportion of areas showing negative anomaly (NDVI = −47.1%, EVI = −25.3% for all forested areas) (Figures 1 and S4). In fact, all years after 2005 (drought year) produced a larger proportion of areas with negative anomaly compared to 2005 (a drought year) in both EVI and NDVI. A gradual decline in the area of positive anomaly was observed from around 2 million $km^2$ in year 2000 to 0.5 million $km^2$ in year 2010. The area of negative anomaly was relatively small in the earlier part of this decade (between 2000 and 2006) with around 0.5 to 1 million $km^2$ of forested area showing a negative anomaly. However, post-2006 a rapid increasing trend was observed in the area of negative anomaly with a maximum in 2010. Hence, it is not possible to attribute drought as causing the observed negative anomalies. Other factors must be causing these changes, since equally extensive negative anomalies occur in non-drought years (e.g., 2009) while positive anomalies occur in a drought year (2005). Such alternative factors may be related to long-term changes in either environmental conditions or sensor characteristics.

### 3.2. Inter-annual Differences in Dry Season VI Values

[14] It was found that a small change in the NDVI or EVI absolute value (less than 0.05) compared to the long-term mean could produce a large anomaly of greater than 2 or less than −2. Such changes are small both in absolute terms and in relation to the expected error of the products. Hence, to further investigate the claimed effect of drought on dry season VI, the change in VI value between consecutive years was considered, relative to the expected error of the data products.

[15] Validation stage 3 has been undertaken for both of the MODIS VI products (NDVI and EVI). The accuracy of the NDVI product is ±0.025 and of the EVI product is ±0.01 units (http://landval.gsfc.nasa.gov/ProductStatus.php?ProductID=MOD13). Thus, it is reasonable to argue that differences between consecutive years should be larger than 0.05 (NDVI) and 0.02 (EVI) to reliably infer real changes (i.e., twice the expected error). If drought results in an observable decline in vegetation growth then the absolute observed change in VI should be larger than this.

[16] Given that the only known drought years are 2005 and 2010, and no two drought years follow consecutively, the absolute differences in dry season NDVI (and EVI) between consecutive years were analysed. Specifically, the spatial distribution of the inter-annual difference in VI was analysed (a) between consecutive drought and non-drought years (2010–2009; 2005–2004) and (b) between consecutive non-drought and non-drought years (2009–2008; 2004–2003).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL049118.

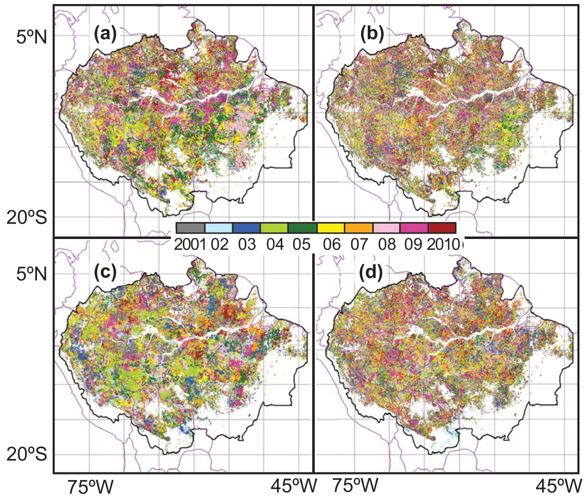


**Figure 3.** The year of (a, c) greatest decline and (b, d) second largest decline for NDVI (Figures 3a and 3b) and EVI (Figures 3c and 3d). During the 11 years of study the drought years (2005 and 2010) were not the year of greatest decline in the vegetation indices. Even for the severe drought in 2010 only 6.6% of the area showed the maximum decline in the EVI.

The difference between 2010 and 2009 is referred to as "Δ2010" and similarly for other years. Irrespective of the rainfall deficiency during the drought years [*Lewis et al.*, 2011] the majority of the area for the drought years did not show a larger decline in NDVI values than for non-drought years. In fact, for drought and non-drought years the spatial distribution of the NDVI difference was similar (Figure 2).

[17] Interestingly, for Δ2010 the percentage area (14.8%) with an increase in EVI (0.02 to 0.08) was larger than in Δ2009 (7.3%), and the percentage area with a decrease in EVI in Δ2009 (−0.02 to −0.08) was larger (32.6%) than in Δ2010 (23.3%). Moreover, in Δ2010, some areas in the north east Amazon (upper part) (Figure 2) showed a decrease in EVI, and these were identified as areas of positive rainfall anomaly in earlier work [*Lewis et al.*, 2011]. Similarly, for Δ2005 (drought year) the percentage area (21.6%) with an increase in EVI (0.02 to 0.08) was larger than in Δ2004 (non-drought year) (14%), and the percentage area with a decrease in EVI in Δ2004 was larger (33.8%) than for Δ2005 (22.2%). Moreover, the most spatially extensive decrease was observed for 2004 (a non-drought year) relative to 2003 (a non-drought year) (Figure 3d). This implies that there is no definitive browning detected by these VIs as an outcome of drought, although the observed variation may be due to other factors which need to be explored.

### 3.3. Year of Maximum Decline

[18] If the effect of drought causes a decline in VI value, then the drought years are expected to exhibit the largest decline. Moreover, within the study period, the year 2010 with the greatest severity of drought should be expected to show the largest decline followed by 2005. Therefore, the inter-annual changes in VI value for each year in each pixel were sorted in descending order to identify the year with the largest decline in VI value. Contrary to expectation, in both EVI and NDVI, neither 2005 nor 2010 was identified as the year with the maximum decline in VI value over the Amazon basin. Rather, all years showed a maximum decline over different parts of the basin (Figure 3). For EVI, only 6.6% of the forested area showed the greatest decline in 2010 (8.9% in 2005). For NDVI, 9.8% of the forested area showed the greatest decline in 2010 (17.4% in 2005). Even for the year with the second largest decline, the years 2005 and 2010 were not prominent (e.g., only 8% of the forested area in 2005 and 8.6% in 2010 showed the second largest decline for EVI) (Figure 3). Interestingly, the spatial pattern in the year of greatest decline is patchy, with no large homogeneous areas for drought years or indeed for any year.

### 3.4. Long-Term Trend

[19] The temporal correlation coefficient was estimated per pixel for the time-series of dry season VI images (Figure 4). The images for NDVI and EVI reveal an overall decline in greenness in Amazonian vegetation over the decade, con-

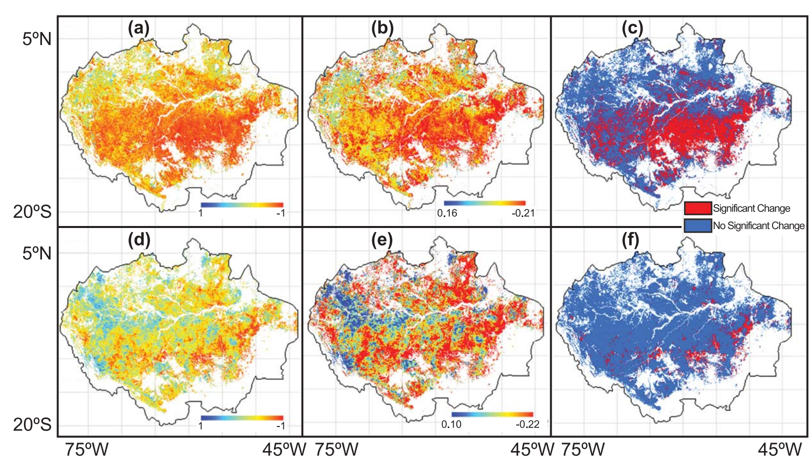


**Figure 4.** Spatial distribution of decadal temporal correlation coefficient in the Amazon for (a) NDVI and (d) EVI; rate of decline for (b) NDVI and (e) EVI; significance ($p < 0.001$) for (c) NDVI and (f) EVI. Non-forested areas (Globcover2009) are masked out. The southern part of the basin showed a negative trend in NDVI over the time period, with areas of significant declining trend in the south–east region. There was no consistent spatial pattern in EVI trend. However, some areas towards the edge (east and south–east) of the forest showed a significant declining trend.

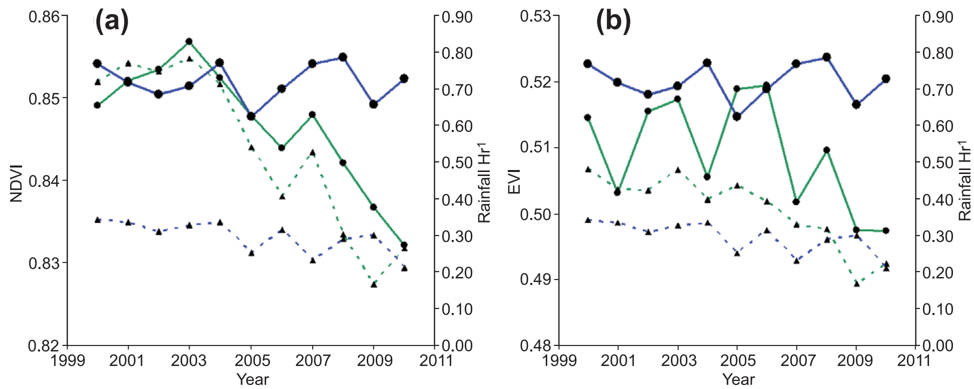


**Figure 5.** Temporal variation in spatial mean of (a) NDVI and (b) EVI in relation to rainfall in the northern and southern Amazon regions. Legend is as follows: green = VI, blue = rainfall, solid line = north and dashed line = south. A strong decline in mean NDVI was observed in both the northern and southern parts of the Amazon basin. In the southern part this was associated with a decadal decline in rainfall. For EVI, the decline was smaller, but still correlated with rainfall in the southern part of the basin.

centrated in the southern two-thirds of the Amazon, south of the Amazon river. The TRMM rainfall data reveal spatially coincident patterns of decline, concentrated in the south and south–east Amazon (Figure S5). Unlike the temporal correlation, the rate of decline was not large across the whole basin, but clustered in certain regions. A small proportion of forested areas, notably towards the south and south–east, showed a significantly ($p < 0.01$, 2-tailed $t$-test) large rate of decline (slope = 0.2). In the EVI images, these areas are situated towards the edge of the intact forest and these declines are likely to be attributed to anthropogenic causes such as deforestation [*Broadbent et al.*, 2008].

[20] Individual pixels may have a low signal-to-noise ratio and, thus, may not be reliable. Therefore, we evaluated the long-term decline at an aggregated level to provide more sample points and increase the signal-to-noise ratio. A similar approach has been used in many other studies investigating long-term trends in vegetation greenness. For example, *Jeong et al.* [2011] used the average of all northern hemisphere vegetation to study changes in phenology. The Amazon basin was divided into one area north (2.6 million $km^2$) and one area south (5.2 million $km^2$) of the Amazon river, and the image data were spatially averaged for each. For the south, a significant negative temporal trend was found for NDVI ( $r = -0.92$; $p < 0.001$) and EVI ($r = -0.88$; $p < 0.001$) with lower greenness at the end of the decade (Figure 5). For the north, the NDVI showed a significant negative decline ($r = -0.83$; $p < 0.001$), but for the EVI the decline was non-significant. Similarly, a decreasing marginally significant trend was observed in rainfall in the south ($r = -0.72$; $p < 0.05$) and no trend was observed for the north. Thus, there exists some evidence for a decadal-scale decline in vegetation greenness in the southern Amazon and over the same period declining trends in rainfall. However, this research demonstrates clearly that there exists no such relation between *drought* and VI greenness on an inter-annual basis.

## 4. Summary and Discussion

[21] We analysed 11 years (2000 to 2010) of satellite-derived VIs to investigate the potential change in their values due to recent droughts. We applied four different techniques to identify the impact of two widely reported droughts (2005 and 2010) on vegetation greenness over the Amazon. In summary,

[22] 1. An analysis of standardised anomalies revealed a lack of correspondence between drought years and negative anomalies. 2009 (a non-drought year) had a similar magnitude of negative anomaly (for both NDVI and EVI) to that for 2010 (Figure 1). Moreover, 2005 (a drought year) overall showed a positive anomaly.

[23] 2. The area showing a decline in VI value between consecutive years, was similar for consecutive non-drought to drought and non-drought to non-drought years (Figure 2).

[24] 3. The years 2010 and 2005 were not the years of maximum decline for the majority of the forested areas. Hence, there was no widespread decline in vegetation greenness (for both NDVI and EVI) due to drought (Figure 3).

[25] 4. There exists an overall declining trend in vegetation greenness over the period 2000 to 2010 (Figures 4 and 5). However, the declining trends in greenness (NDVI and EVI) are not significant for the majority of the Amazon basin except at the edges of the intact forest and towards the south and south east where disturbance and deforestation are known to have taken place. This is particularly the case for the more reliable EVI.

[26] In addition to the above, if the impact of drought results in a detectable decline in VI value then this change should be larger than the accepted error limit of the data product. However, for the majority of the Amazon forested area the changes in absolute VI value were within the error limit of the NDVI and EVI products.

[27] Given the above, the increase in vegetation greenness observed by *Saleska et al.* [2007] in 2005 and the decline in vegetation greenness observed by *Xu et al.* [2011] in 2010 cannot be explained by drought. Other climate-related factors such as inter-annual fluctuations in received sunlight (as argued by *Saleska et al.* [2007]) or cloud cover, or noise-related factors such as inter-annual variation in dry season atmospheric condition and change in sensitivity of the sensor over the study period may be responsible for the observed variation. In addition, inconsistency in data availability could also lead to false interpretation: as noted

by *Samanta et al.* [2010], in the 2005 dry season 60% of the drought affected area had no valid EVI data. Although MODIS data are subjected to atmospheric correction processes, there is a greater chance that sub-pixel cloud contamination and aerosols, which are hard to detect and correct at the MODIS spatial resolution, could alter vegetation index values without any change in the ground condition [*Asner and Alencar*, 2010]. From a physiological perspective, there appears to be an increase in leaf flushing during the dry season to synchronise with events such as increases in radiation and herbivory avoidance [*Asner and Alencar*, 2010; *Brando et al.*, 2010], which could result in an increase in VI values. However, field data to support this suggestion are limited.

[28] It is important to note that the results presented here do not show that Amazon vegetation functioning and productivity do not respond to drought. It has been reported previously that drought results in decreases in gross and net primary productivity in Amazon vegetation [*Zhao and Running*, 2010; *Lewis et al.*, 2011]. Rather, the results demonstrate the inability of remote sensing VIs to detect the response of Amazon vegetation to a drought event.

[29] Broadband vegetation indices (such as NDVI and EVI) tend to be saturated with greenness in the multi-layered dense canopy structure of humid tropical rainforests such as the Amazon [*Asner et al.*, 2004]. The loss of canopy cover due to drought is unlikely to be sufficient to produce detectable changes in the greenness signal. Thus, while productivity may be reduced, greenness remains very high.

[30] A significant decadal-scale reduction in vegetation greenness was observed that is consistent with long-term increases in temperature. This long-term change in observed vegetation greenness is of potential concern, especially given GCM forecasts of savannah conditions in Amazonia by 2050 [*Cox et al.*, 2004]. However, given the above results, the observed trend should be interpreted as a decline in vegetation greenness and not necessarily a decline in productivity. Moreover, the factors affecting the observed decline in vegetation greenness are not known, and may include atmospheric and sensor noise, and so interpretation is necessarily limited and the result should be treated with caution.

## 5. Conclusion

[31] Our findings refute claims for the ability of remote sensing VIs to detect the effects of drought on Amazon biomass [*Xu et al.*, 2011] and help to explain the controversy between moisture-constrained growth [*Xu et al.*, 2011] and sunlight-enhanced growth [*Saleska et al.*, 2007]. At the inter-annual scale, local climate factors (e.g., sunlight, reduced cloud cover) or noise-related factors (atmospheric fluctuations, temporal changes in sensor sensitivity), but not drought, may affect greenness within year.

[32] A significant decadal-scale reduction in vegetation greenness was observed. However, drought is not a driver of this decline and further research is required to investigate the factors causing the observed changes, which may include atmospheric and sensor noise.

[33] **Acknowledgments.** Authors are grateful to Geography and Environment Academic Unit, University of Southampton for funding. Data used in this study were provided by the Land Processes Distributed Active Archive Center (LPDAAC), Goddard Earth Sciences Data and Information Services Center (GESDISC) and the European Space Agency (ESA).

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