Auxiliary materials for Paper

Amazon forests did not green-up during the 2005 drought

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Introduction

This auxiliary section includes detailed information on data, methods to determine the validity of EVI and detailed description of methods to calculate standardized anomalies of EVI, precipitation and radiation not given in the main text. Also included are Figures S1-S3 and Tables S1-S3.

1. Data

1.1 Satellite Vegetation Data Sets

Collection 5 (C5) Enhanced Vegetation Index (EVI), Collection 4 (C4) EVI and C5 Landcover data sets are used in this study. The NASA wording "Collection" in this instance is synonymous with "Version". The EVI data sets were developed by NASA with data from the MODIS instrument aboard the Terra satellite. The EVI is a measure of vegetation greenness and generally correlates well with ground measurements of gross photosynthesis [*Huete et al.,* 2006].

Collection 5 (C5) EVI: We use the C5 EVI at 1x1 km^2 spatial resolution and 16-day frequency – this data set is named MOD13A2. It was obtained from the NASA LP DAAC [WWW1] for July-September of the period 2000-2008. Collection 5 is the latest version of MODIS land products and supersedes all previous versions.

Collection 4 (C4) EVI: This previous version of EVI data (1x1 km^2 spatial resolution and 16-day frequency) was used by [*Saleska et al.,* 2007, hereinafter SDHR07] – these data are now decommissioned and deleted from the NASA LPDAAC archives. We obtained a copy of the 2000 to 2005 July to September C4 EVI data from SDHR07. They did not provide year 2006 data. Also, the C4 EVI data lacked all quality flags. Hence, C5 quality flags were used in this analysis.

Collection 5 (C5) Landcover: A vegetation map at 1x1 km^2 spatial resolution (MOD12Q1) is used to identify forest pixels in the study area. This is the official NASA C5 Landcover data set [WWW1, *Friedl et al.,* 2010].

1.2 Precipitation Data

We use monthly precipitation data from the Tropical Rainfall Measuring Mission (TRMM) at quarter degree spatial resolution for July-September of the period 1998-2008 (3B43 – Version 6) [WWW2].

1.3 Aerosol Data

Aerosol Optical Thickness (AOT) data from the NASA MODIS instrument at 1^ox1^o spatial resolution for the period July to September 2005 [WWW3] are used in this study. We use the "Optical_Depth_Land_And_Ocean_Mean_Mean" data field from the product

MOD08_M3, which contains the AOT at 550 nm at monthly frequency. For daily AOT we use the "Corrected_Optical_Depth_Land_QA_Mean" data field from the product MOD08_D3, which contains the AOT at 550 nm at daily frequency.

1.4 Radiation Data

Monthly solar radiation data at 1^{o}x1^{o} spatial resolution for July-September of the period 2000-2005 are used in this study. These data were obtained from the NASA Langley Research Center Atmosphere Science Data Center [WWW4]. The Level 3 monthly Regional Radiative Fluxes and Clouds product (CER_AVG_Terra-FM1-MODIS-Edition2C & CER_AVG_Terra-FM2-MODIS-Edition2C) was generated from the Terra satellite's Clouds and the Earth's Radiant Energy System (CERES) data and Geostationary Operational Environmental Satellite 8 (GOES)-derived broadband fluxes [WWW5; *Wielicki et al.*, 1996]. We use the surface total sky short wave ("Total-Sky SW flux – Diffuse" and "Total-Sky SW flux – Direct") and photosynthetically active radiation (PAR, 400-700 nm) ("Total-Sky PAR Surface flux – Diffuse" and Total-Sky PAR Surface flux – Direct") data fields [WWW6]. These were retrieved from the Surface and Atmosphere Radiation Budget (SARB) component of CERES using detailed information on clouds and aerosols [WWW5; *Su et al.,* 2007].

2. Validity of EVI Values

Each 1x1 km^2 16-day composite EVI value is accompanied with explicit quality flags for clouds and aerosols (a 16-day EVI composite refers to one best-quality EVI value to represent a 16-day period). The binary cloud quality flags are "Adjacent cloud detected", "Mixed Clouds" and "Possible shadow". The aerosol quality flag is "Aerosol Quantity" which can assume one of four values – "Climatology", "Low", "Average" and "High". Positive AOT values less than 0.2 are labeled as "Low", between 0.2 and 0.5 as "Average" and greater than 0.5 as "High" [*Vermote and Vermeulen*, 1999]. Apart from clouds and shadows, the two categories of aerosol quantity – aerosol climatology and high aerosols – should be screened because of the following reasons. First, aerosol climatology indicates that the actual aerosol content is unknown, most likely due to the presence of clouds and, hence, the aerosol correction was performed using historical or climatological aerosol optical thickness (AOT) data [*Vermote and Vermuelen*, 1999]. Second, atmospheric correction methods are ineffective for high aerosol loadings (AOT > 0.5) [WWW7; WWW8; *Didan and Huete*, 2006], especially in the shorter red and blue spectral bands [*Vermote and Kotchenova*, 2008] used by EVI [*Huete et al.,* 2002].

According to SDHR07 "Properly filtered to remove atmospheric aerosol and cloud effects, EVI tracks variations in canopy photosynthesis". Therefore, in order to assess the impact of each source of data corruption, we examine the cloud, shadow and aerosol quality flags accompanying EVI data (Fig. S2). During the dry season the dominant sources of EVI data corruption are aerosols, particularly, over forests south of the

Equator (Fig. S2a-b) – three prominent patches (in Fig. 1b), that are missing (in Figs. 1a, 1c and 1d), are located in this region. Note that there is overlap between regions of cloud (and shadow) contamination, and climatology aerosol contamination. Aerosol contamination (high and climatology) was generally enhanced during the dry season of 2005 (Fig. S2b-c). For example, in 2005, daily EVI retrievals from days of high aerosol content (Aerosol Optical Thickness (AOT) > 0.5) constitute sizeable portions of 16-day EVI composites of August (at least 60%) and September (at least 50%) (Fig. S3a).

Given the above information, we determine the validity of each 16-day composite EVI value of a land pixel using the following methodology –

Pixel Quality Flags – Clouds, Cloud Shadows, Aerosol Climatology and High Aerosols Excluded. Pixels with following quality flags are deemed "valid" (ignore all other quality flags),

- "MODLAND_QA" flag must be equal to 0 (good quality) or 1 (check other QA).
- "VI usefulness" flags must be equal to 11 or less.
- "Adjacent cloud detected," "Mixed clouds" and "Possible shadow" flag values must be equal to 0.
- "Aerosol Quantity" flag must equal 1 (low aerosol) or 2 (average aerosol).

3. Standardized Anomaly

Standardized anomalies (anomaly divided by the standard deviation) of precipitation, EVI and radiation for the dry season (July, August and September) are calculated pixel-by-pixel. Pixels with precipitation anomalies less than -1 are classified as drought-

stricken or drought affected. Pixels with EVI anomalies in the range -1 to +1 standard deviation (std.) are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning and with EVI anomalies greater than +1 std. classified as greening. These designations conform to SDHR07. Note that, in the third quarter of 2005 approximately 2.19 km^2 of intact forests, south of the equator, were drought-stricken (precipitation anomalies relative to the mean for the 1998 to 2006 period, excluding 2005).

3.1 EVI Standardized Anomaly

For each year, we use six 16-day EVI composites covering the third quarter (July-September). More specifically, composites 177 and 193 pertain to July; 209 and 225 to August; and, 241 and 257 to September. The validity of EVI value at a pixel is determined by examining the corresponding quality flags (c.f. Section 2 of Auxiliary Materials). For each month, if both the 16-day EVI values are valid, then the mean of the two is the monthly value. If only one of the two is a valid EVI value, it represents the monthly value. If none are valid EVI values, the pixel is tagged and not used in further calculations. For each year, if all three EVI monthly means exist, then the mean of the three represents the quarterly value. If all six years (i.e., 2000, 2001, 2002, 2003, 2004 and 2006) have valid quarterly EVI values, the mean ($EVI^{JAS}_{mean,ref}$) and standard deviation of EVI (σ^{JAS}_{ref}) are evaluated. Finally, if the 2005 third quarter mean EVI exists, the 2005 third quarter standardized anomaly is calculated as:

$$EVI^{JAS}_{anomaly,2005} = \frac{EVI^{JAS}_{mean,2005} - EVI^{JAS}_{mean,ref}}{\sigma^{JAS}_{ref}} \quad (1)$$

where $EVI^{JAS}_{mean,2005}$ is the 2005 third quarter mean EVI. Overall, this method ensures that each pixel has at least 3 (i.e., 50% data) valid 16-day EVI values in a quarter, with one value in each of the three months. This is important because EVI in the Amazon forests increases sharply during the dry season [*Huete et al.,* 2006] and therefore, data from all three months – at least one valid 16-day EVI value per month – of the third quarter are needed for correct/unbiased estimation of the seasonal (JAS) mean. Moreover, this condition also ensures that the climatological season mean and standard deviation are correctly estimated (and consistent across pixels) in view of the short data record – 2000-2006 (excluding 2005). Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning and with EVI anomalies greater than +1 std. classified as greening. We use this method of anomaly calculation on valid (as described in Section 2 of Auxiliary Materials) C5 EVI data to generate Fig. 3 (main text), Fig. S1, Table S2 and Table S3.

3.2 Precipitation Standardized Anomaly

The monthly precipitation value is considered "valid" if it is not equal to -9999. If all three monthly precipitation values are valid, the total of the three represents the quarterly cumulative value. Else, the pixel is tagged and not used in further calculations. The rest

of the processing is similar to that described in Section 3.1 (Auxiliary Materials). The reference period for precipitation is 1998-2006, but excluding 2005.

3.3 Radiation Anomaly

Monthly surface radiation (SW and PAR) value is considered "valid" if it is in the range of 0-1400 W/m^2. If all three monthly surface radiation flux values are valid, the mean of the three represents the quarterly mean. Else, the pixel is not used in further calculations. The rest of the processing is similar to that described in Section 3.1 (Auxiliary Materials). The reference period is 2000-2004. Pixels with radiation anomaly less than -1 are classified as showing decline in radiation, while, those with radiation anomaly greater than 1 are classified as showing increase in radiation.

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WWW2: http://disc.sci.gsfc.nasa.gov/services/opendap/trmm.shtml

WWW3: http://ladsweb.nascom.nasa.gov

WWW4: http://eosweb.larc.nasa.gov/PRODOCS/ceres/table_ceres.html.

WWW5:http://eosweb.larc.nasa.gov/PRODOCS/ceres/SYN-AVG-ZAVG/Quality_Summaries/CER_SYN-AVG-ZAVG_Edition2.html.

WWW6: http://eosweb.larc.nasa.gov/PRODOCS/ceres/DPC/DPC_AVG_R5V1.pdf.

WWW7:http://modland.nascom.nasa.gov/cgi-bin/QA_WWW/detailInfo.cgi?prod_id=MOD13A1&ver=C5.

WWW8: http://modis-sr.ltdri.org/MAIN_VALIDATION/UNCERTAINTY_1.html.

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Figure Captions

Figure S1. Spatial patterns of July to September (JAS) 2005 standardized anomalies of Collection 5 (C5) Enhanced Vegetation Index (EVI) at 1x1 km^2 spatial resolution. Cloud, shadow, climatology aerosol and high aerosol contaminated data are screened (c. f. Section 2 of Auxiliary Materials) and EVI anomalies are calculated as described in Section 3.1 (Auxiliary Materials). Standardized EVI anomalies of intact forests in the drought-stricken region (July to September 2005 precipitation standardized anomalies that are less than -1) south of the equator are shown. EVI anomalies are calculated relative to the base period of 2000-2006, but excluding 2005. Note that the changes in greenness are insignificant north of the equator.

Figure S2. Spatial patterns of atmosphere corruption of EVI data. (a) Average number of 16-day EVI composites in the July to September quarter of 2000-2006, excluding 2005, with quality flags indicating clouds (adjacent cloud, mixed clouds and possible shadow). A 16-day EVI composite refers to one best-quality EVI value to represent a 16-day period. (b) Same as (a) but with quality flags indicating aerosols (climatology and high aerosols). (c) Same as (b) but for 2005 only. 19.03% pixels in the 2005 drought affected forests south of the equator have 2 or more 16-day composites with aerosol corruption during the July to September quarter of the period 2000-2006, excluding 2005. In 2005 this percentage increases to 36.84%.

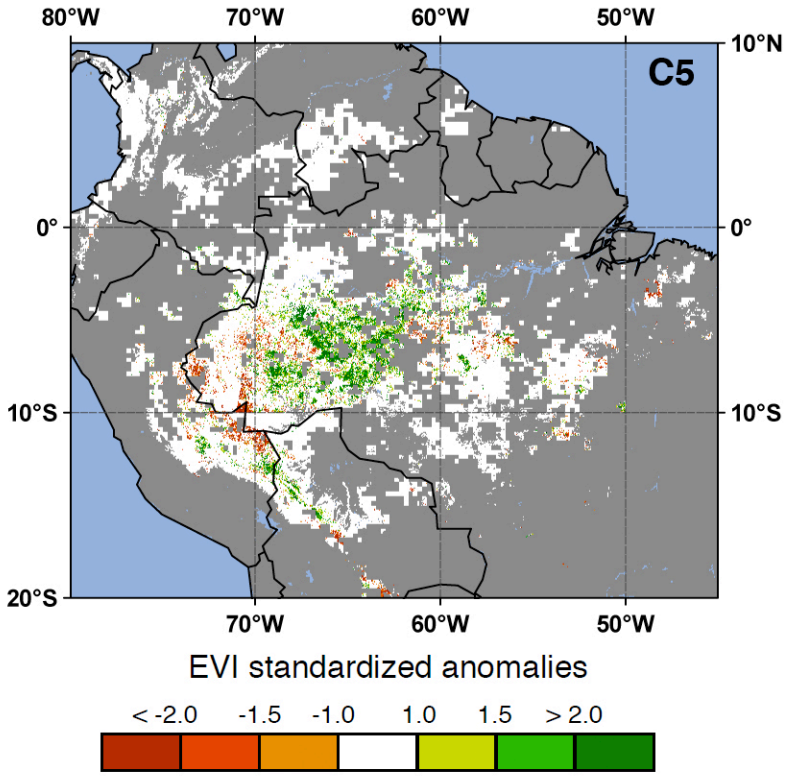
Figure S3. (a) Distribution (% pixels) of daily EVI retrievals in intact forests of the drought-stricken region below the equator for all six 16-day C5 EVI composites spanning JAS 2005 (left axis). Daily C5 Aerosol Optical Thickness (AOT) averaged over the same region (right axis) for JAS 2005. (b) JAS 2005 C5 mean Aerosol Optical Thickness (AOT, 1^{o}x1^{o} spatial resolution) at 550 nm. Pixels with invalid data are colored grey.

Table Captions

Table S1. Changes in spatial extent of EVI anomalies of drought-stricken forest areas in the Amazon region (0^o to 20^oS and 45^oW to 80^oW) in year 2005 during the July to September quarter. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. Pixels with precipitation deficit less than -1 are classified as drought-stricken. The changes in spatial extent of EVI anomalies (ΔGreening, ΔBrowning and ΔNo-change) are calculated for Figs. 1a, c and d, relative to Fig. 1b of main text (Our Fig. 1b is the same as Fig. 1B of SDHR07).

Table S2. Changes in spatial extent and magnitude of EVI anomalies of forest areas in the Amazon region (0^o to 20^oS and 45^oW to 80^oW) in year 2005 during the July to September quarter. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. The changes in spatial extent and magnitude of EVI anomalies are calculated for varying levels of precipitation deficit (anomaly) (PD). The average level of browning or greening is also shown in brackets.

Table S3. Changes in EVI anomalies and precipitation during the July to September (JAS) quarter of years 2000 to 2008. Only forest pixels, in the region 0^{o} to 20^{o}S and 45^{o}W to 80^{o}W, that are located in areas with JAS 2005 precipitation anomaly less than -1 std. (relative to the mean for the 1998 to 2006 period, excluding 2005) are considered. The EVI (1x1 km^2) anomalies are relative to the mean for the 2000 to 2008 period. The precipitation anomalies are relative to the mean for the 1998 to 2008 period. In both cases, year 2005 data are excluded. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. Note that the greening, browning, no-change and validity shown in the table are relevant to the kind of analysis presented here.



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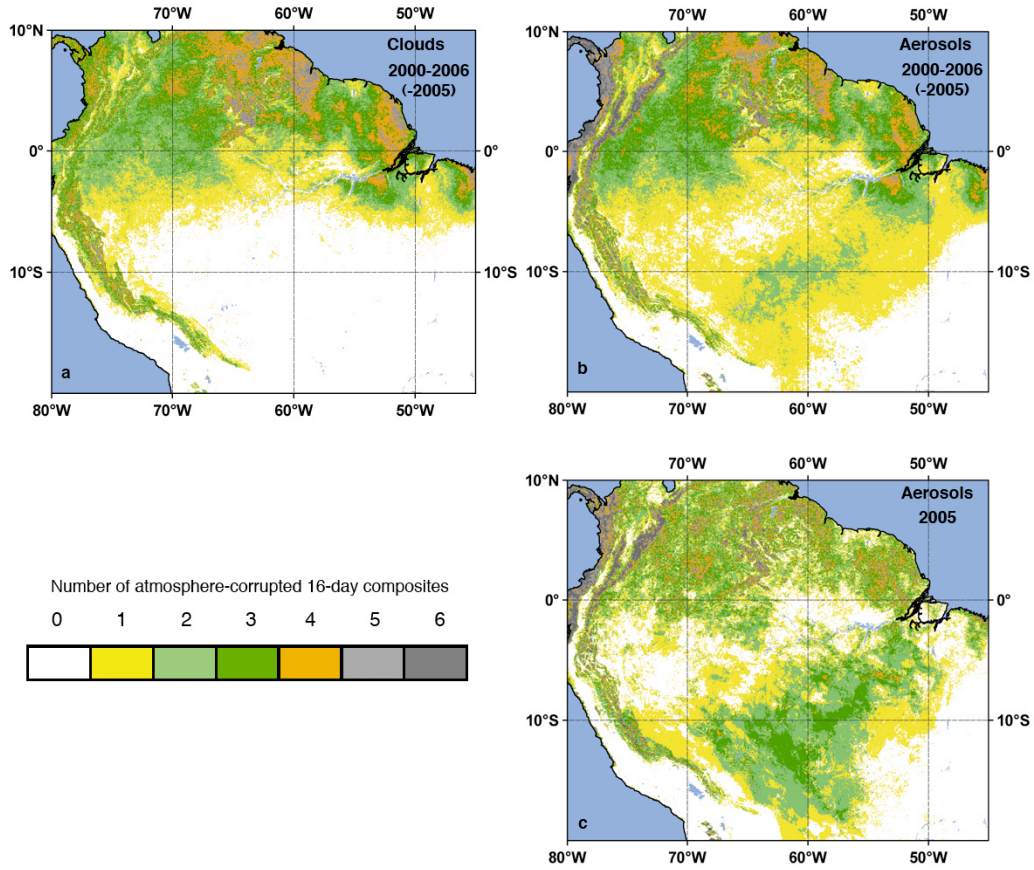

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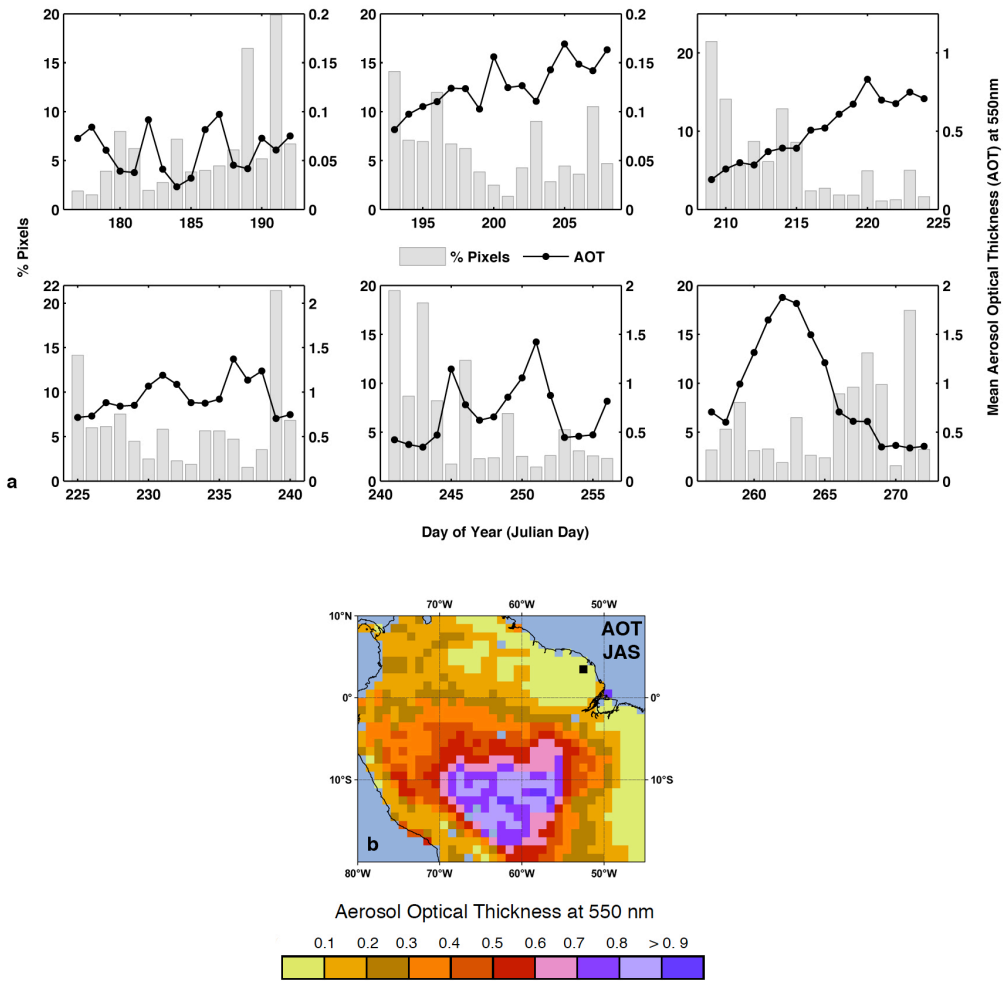

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Table S1. Changes in spatial extent of EVI anomalies of drought-stricken forest areas in the Amazon region (0^o to 20^oS and 45^oW to 80^oW) in year 2005 during the July to September quarter. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. Pixels with precipitation deficit less than -1 are classified as drought-stricken. The changes in spatial extent of EVI anomalies (ΔGreening, ΔBrowning and ΔNo-change) are calculated for Figs. 1a, c and d, relative to Fig. 1b of main text (Our Fig. 1b is the same as Fig. 1B of SDHR07).

Figure	ΔGreening (%)	ΔBrowning (%)	ΔNo-change (%)
1a	-33.57	55.26	12.63
1c	-32.23	68.19	8.93
1d	-28.36	72.00	6.03

Table S2. Changes in spatial extent and magnitude of EVI anomalies of forest areas in the Amazon region (0^o to 20^oS and 45^oW to 80^oW) in year 2005 during the July to September quarter. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. The changes in spatial extent and magnitude of EVI anomalies are calculated for varying levels of precipitation deficit (anomaly) (PD). The average level of browning or greening is also shown in brackets.

EVI Anomaly	**-1.5< PD< -1.0**	**-2.0< PD< -1.5**	**PD< -2.0**
Greening (%) [Magnitude (std)]	11.63 [1.99]	14.16 [1.98]	11.56 [1.91]
Browning (%) [Magnitude (std)]	4.99 [-1.87]	5.67 [-1.88]	6.40 [-1.90]
No Change (%)	19.12	23.63	24.24

Table S3. Changes in EVI anomalies and precipitation during the July to September (JAS) quarter of years 2000 to 2008. Only forest pixels, in the region 0^{o} to 20^{o}S and 45^{o}W to 80^{o}W, that are located in areas with JAS 2005 precipitation anomaly less than -1 std. (relative to the mean for the 1998 to 2006 period, excluding 2005) are considered. The EVI (1x1 km^2) anomalies are relative to the mean for the 2000 to 2008 period. The precipitation anomalies are relative to the mean for the 1998 to 2008 period. In both cases, year 2005 data are excluded. Pixels with EVI anomalies in the range -1 to +1 std. are classified as showing no changes. Pixels with EVI anomalies less than -1 std. are classified as browning. Pixels with EVI anomalies greater than +1 std. are classified as greening. Note that the greening, browning, no-change and validity shown in the table are relevant to the kind of analysis presented here.

Year	Precipitation Deficit Area (%)	Greening (%) [Magnitude (std)]	Browning (%) [Magnitude (std)]	No Change (%)	Valid Pixels (%)
2000	0.99	5.19 [1.37]	6.13 [-1.43]	23.75	35.09
2001	6.09	5.15 [1.38]	5.68 [-1.43]	24.24	35.09
2002	10.5	5.08 [1.38]	6.05 [-1.44]	23.95	35.09
2003	5.34	8.05 [1.43]	4.12 [-1.43]	22.90	35.09
2004	4.68	7.56 [1.46]	6.72 [-1.50]	20.80	35.09
2005	87.04	10.80 [1.88]	3.89 [-1.70]	18.98	33.68
2006	26.46	4.95 [1.35]	3.86 [-1.37]	26.27	35.09
2007	41.59	4.76 [1.37]	6.43 [-1.42]	23.88	35.09
2008	18.95	3.10 [1.34]	6.57 [-1.41]	25.40	35.09