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Supporting Online Material for

Comment on "Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009"

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This PDF file includes:

SOM Text

S1. Field NPP Measurements

The individual field sites are: KM67 (55.024° W; 2.863° S), ZF-2 (60.100° W; 2.375° S), UFAC (67.627° W; 10.077° S), BA712 (39.673° W; 17.287° S) and ZAR-01 (69.906° W; 4.007° S). The sites AGP, CAX and TAM represent two sites each: AGP-01, AGP-02, CAX-06, CAX-08, TAM-05 and TAM-06 (the coordinates for these sites can be found at http://www.geog.leeds.ac.uk/projects/rainfor/pages/fieldsites_eng.html). The NPP estimates published in ZR10 (*S1*) were compared with the experimentally derived up-scaled values of NPP for the following time periods: KM67 (2001 and 2004); ZF-2 (2001 and 2002); UFAC (2001 and 2002); BA712 (2006); AGP (2004-2006); CAX (2004-2006); TAM (2005) and ZAR-01 (2004-2006).

The KM67 site is situated in the 600,000 ha Tapajós National Forest, a dense tropical moist forest near the city of Belterra, Pará, Brazil. NPP estimates obtained for KM67 (2004 data) were calculated from measures of dead leaf biomass and the biomass increment of trunks (wood) and roots provided by the LBA project, for 4 "transects" installed in the site, three of which were composed of 10 parcels of 1 ha and 1 "transect" composed of 20 parcels of 1 ha (*S2*). The KM67 2001 data are from the same area (S3).

The ZF-2 site is located in the *Estação Experimental de Silvicultura Tropical* (Experimental Center of Tropical Silviculture) run by the Instituto Nacional de Pesquisa da Amazônia (INPA - National Institute of Amazon Research). This area is approximately 2,000 ha of dense tropical moist forest and is located between the km 21 and km 24 on the ZF-2 secondary road, approximately 90 km to the north of Manaus, in the state of Amazonas, Brazil (*S3*).

The UFAC site, a mosaic with small patches of dense moist forest and open forest (with bamboo), is located in the Experimental Farm Catuaba, of the Universidade Federal do Acre, has an area of approximately 860 ha, and is located in the eastern region of the state of Acre, Brazil, along the BR 364, 23 km from the city of Rio Branco (*S3*).

NPP estimates for sites ZF-2 (2001 and 2002), UFAC (2001 and 2002) and KM67 (2001) were estimated by assuming that wood biomass increment data from (*S3*) represent 20.62% of total NPP in accordance with other estimates for the Amazon (*S4*).

The Atlantic Forest site (BA712) is a permanent preservation area (1,136 ha) covered with tropical moist forest belonging to Aracruz Celulose SA, near Teixeira de Freitas, southern of the state of Bahia, Brazil. Two permanent parcels were installed, with 400 x 25 m (10,000 m^2 = 1 ha) in the BA712 site, with parcel 1 east-west oriented along its length, while parcel 2 was north-south oriented along its length, inside an area of 2 x 2 km. Inside these parcels, 16 sub-parcels with 25 x 25 m were established, where the trees with trunk diameters at breast height (DBH) greater than 10 cm, were mapped, numbered and measured, and they had dendrometric bands installed for the bi-annual monitoring of

the diametric increment of the trunks started on December 15, 2005 and continued till February 8, 2007. DBH was transformed using an allometric equation that relates wood biomass to DBH (*S5*) and the carbon was estimated to be 50% of the total biomass (*S6*).

We also used published data of field estimates of NPP compiled from four sites of Amazonian tropical forest of RAINFOR network (Amazon Forest Inventory Network, *(S4)*): two plots at Amacayacu, Colombia (AGP-01 and AGP-02); two at Caxiuanã, Brazil (CAX-06 and CAX-08); two at Tambopata, Peru (TAM-05 and TAM-06) and one at El Zafire, Colombia (ZAR-01).

The individual field sites are: KM67 (55.024° W; 2.863° S), ZF-2 (60.183° W; 2.967° S), UFAC (68.033° W; 10.117° S), BA712 (39.673° W; 17.287° S) and ZAR-01 (69.906° W; 4.007° S). The sites AGP, CAX and TAM represent two sites each: AGP-01, AGP-02, CAX-06, CAX-08, TAM-05 and TAM-06 (the coordinates for these sites can be found at http://www.geog.leeds.ac.uk/projects/rainfor/pages/fieldsites_eng.html. The NPP estimates published in ZR10 (*S1*) were compared with the experimentally derived up-scaled values of NPP for the following time periods: KM67 (2001 and 2004); ZF-2 (2001 and 2002); UFAC (2001 and 2002); BA712 (2006); AGP (2004-2006); CAX (2004-2006); TAM (2005) and ZAR-01 (2004-2006).

The KM67 site is situated in the 600,000 ha Tapajós National Forest, a perennial tropical forest near the city of Belterra, Pará, Brazil. NPP estimates obtained for KM67 (2004 data) were calculated from measures of dead leaf biomass and the biomass increment of trunks (wood) and roots provided by the LBA project, for 4 "transects" installed in the site, three of which were composed of 10 parcels of 1 ha and 1 "transect" composed of 20 parcels of 1 ha (*S2*).

The ZF-2 site is located in the Estação Experimental de Silvicultura Tropical (Experimental Center of Tropical Silviculture) run by the Instituto Nacional de Pesquisa da Amazônia (INPA - National Institute of Amazon Research). This area is approximately 2,000 ha and is located between the km 21 and km 24 on the ZF-2 secondary road, approximately 90 km to the north of Manaus, in the state of Amazonas, Brazil (*S3*).

The UFAC site is located in the Experimental Farm Catuaba, of the Universidade Federal do Acre, has an area of approximately 860 ha, and is located in the eastern region of the state of Acre, Brazil, along the BR 364, 23 km from the city of Rio Branco (*S3*).

NPP estimates for sites ZF-2 (2001 and 2002), UFAC (2001 and 2002) and KM67 (2001) were estimated by assuming that wood biomass increment data from (*S3*) represent 20.62% of total NPP in accordance with other estimates for the Amazon (*S4*).

The Atlantic Forest site (BA712) is a permanent preservation area (1,136 ha) belonging to Aracruz Celulose SA, near Teixeira de Freitas, southern of the state of Bahia, Brazil. Two permanent parcels were installed, with 400 x 25 m (10,000 m^2 = 1 ha) in the BA712 site, with parcel 1 east-west oriented along its length, while parcel 2 was north-south oriented along its length, inside an area of 2 x 2 km. Inside these parcels, 16

sub-parcels with 25 x 25 m were established, where the trees with trunk diameters at breast height (DBH) greater than 10 cm, were mapped, numbered and measured, and they had dendrometric bands installed for the bi-annual monitoring of the diametric increment of the trunks started on December 15, 2005 and continued till February 8, 2007. DBH was transformed using an allometric equation that relates wood biomass to DBH (*S5*) and the carbon was estimated to be 50% of the total biomass (*S6*).

We also used published data of field estimates of NPP compiled from four sites of Amazonian tropical forest of RAINFOR network (Amazon Forest Inventory Network, *(S4)*): two plots at Amacayacu, Colombia (AGP-01 and AGP-02); two at Caxiuanã, Brazil (CAX-06 and CAX-08); two at Tambopata, Peru (TAM-05 and TAM-06) and one at El Zafire, Colombia (ZAR-01).

S2. Matching Zhao and Running NPP Estimates to Field Measurements

Annual NPP values were extracted from (*S1*) for the same years in which the field measurements were carried out using the arithmetic average of the NPP values for a grid approximately corresponding to the size and position to the field sites (Table 1). For individual sites KM67, ZF-2, UFAC and ZAR-01 this meant an area of 25 km^2 centered on the site coordinates. For the remaining individual site, BA712, with an area of 4 km^2, a grid of 4 pixels of 1 km^2 was used. For sites AGP, CAX and TAM, which actually represent two sites each, ZR10 estimates for an area of 5x5 km^2 centered on each site were extracted and the average of the two sites is used to represent the site ZR10 estimate (Table 1). The NPP values reported in (*S1*) are available at ftp://ftp.ntsg.umt.edu/pub/MODIS/Mirror/MOD17_Science_2010/

S3. MODIS NDVI, EVI, LAI and FPAR Analysis

The latest versions of satellite-derived datasets of vegetation greenness are used in this study, which were developed by NASA with data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Terra satellite. Collection 5 (C5) is the latest version of MODIS land products and supersedes all previous versions.

S3.1 Collection 5 (C5) Vegetation Indices (VI)

These are satellite-sensed estimates of vegetation greenness produced by NASA using surface reflectance measurements in blue (459-479 nanometers (nm)), red (620-670 nm) and near-infrared (842-876 nm) bands made by the MODIS instrument (https://lpdaac.usgs.gov, *S7*). VI's consist of Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). NDVI is a radiometric measure of photosynthetically active radiation (400-700 nm) absorbed by canopy chlorophyll, and therefore, a good surrogate measure of the physiologically functioning surface greenness level in a region (*S8*). NDVI has been used in many studies of vegetation dynamics in the Amazon (e.g., *S9-S10*). EVI generally correlates well with ground measurements of

photosynthesis (e.g., *S11-S12*) and found to be especially useful in high biomass tropical broadleaf forests like the Amazon (*S13*). C5 MODIS Terra VI data are used in this study.

The dataset "Vegetation Indices 16-Day L3 Global 0.05Deg CMG" – MOD13C1 – contains EVI and NDVI at 0.05^{o}x0.05^{o} spatial resolution and 16-day frequency. This 16-day frequency arises from compositing, i.e. assigning one best-quality EVI value to represent a 16-day period (*S7*). The data are available as global files in geographic latitude/longitude projection. These are "cloud-free spatial composites" of the corresponding 1x1km^2 VI data (https://lpdaac.usgs.gov). These were obtained from the NASA Land Processes Data Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov) for the period February 2000-December 2009.

S3.1.1. VI data quality

The quality of 16-day VI (EVI and NDVI) data in each 0.05^{o}x0.05^{o} pixel can be assessed using the accompanying 16-bit quality flags. Sets of bits, from these 16 bits, are assigned to flags pertaining to clouds and aerosols, as well as, flags that provide aggregate measures of data quality called VI Usefulness Indices**.** Cloud quality flags are single bit (binary) flags indicating the presence (1) or absence (0) of clouds. There are two binary cloud quality flags – "Adjacent cloud detected" (bit 8) and "Mixed Clouds" (bit 10). Aerosol quality flag, 2 bits in precision, provides information on aerosol content, and is named "Aerosol quantity". It occupies the bit positions 6 through 7. The aerosol quality flag can assume one of four values – "Climatology" (00), "Low" (01), "Average" (10) and "High" (11). "Low", "Average" and "High" refer to aerosol optical thickness (AOT) at 550 nm less than 0.2, between 0.2 and 0.5, and greater than 0.5, respectively (*S14*). On the other hand, "Climatology" indicates that the actual AOT is unknown, most likely due to presence of clouds, and climatological (long-term average) AOT is used in the process of atmospheric correction (*S14*). The VI Usefulness flag, 4 bits in precision, provides an aggregate measure of VI quality. It occupies the same bit positions – bits 2 through 5 – in both MOD13A2 and MOD13C1, and can assume values from 0 (0000 – best quality) to 15 (1111 – not useful).

Determination of VI validity: The presence of clouds (adjacent clouds and mixed clouds) "obscures" the surface in a radiometric sense, thus corrupting inferred VI values. In addition, two types of aerosol loadings typically corrupt data – climatology and high aerosols. Use of aerosol climatology indicates that the actual aerosol content is unknown, most likely due to the presence of clouds, and aerosol correction was performed using historical or climatological aerosol optical thickness (AOT) data (*S14*). Moreover, atmospheric correction methods are ineffective for high aerosol loadings (AOT > 0.5) (*S15*), especially in the shorter red and blue spectral (*S16*).

Based on the above information, each 0.05^{o}x0.05^{o} 16-day VI pixel is considered valid when (a) VI data is produced – "MODLAND_QA" equals 0 (good quality) or 1 (check other QA), (b) VI Usefulness is between 0 and 11, (c) Clouds are absent – "Adjacent cloud detected" (0) and "Mixed Clouds" (0), and (d) Aerosol content is low or

average – "Aerosol Quantity" (1 or 2). Note that "MODLAND_QA" checks whether VI is produced or not, and if produced, its quality is good or whether other quality flags should also be checked. Besides, VI Usefulness Indices 0 to 11 essentially include all VI data. Thus, these two conditions serve as additional checks.

S3.2. Collection 5 (C5) Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR)

LAI is defined as the one-sided green leaf area per unit ground area in broadleaf canopies, and one-half the total surface area per unit ground area in needle-leaf canopies (coniferous) (e.g., *S17*). FPAR is the fraction of photosynthetically active radiation (400-700nm) absorbed by vegetation. LAI and FPAR are operationally derived from atmospherically corrected surface reflectance in the red and near-infrared bands measured by the MODIS sensor (https://lpdaac.usgs.gov) and have been extensively tested and validated (*S17-S22*). The dataset "Leaf Area Index – Fraction of Photosynthetically Active Radiation 8-Day L4 Global 1km" – MOD15A2 – contains LAI and FPAR at $1x1km^2$ spatial resolution and 8-day temporal frequency. This 8-day frequency arises from compositing, i.e. assigning one best-quality EVI value to represent an 8-day period. This dataset is available in tiles ($10^o x10^o$ at the equator) of Sinusoidal projection. The data were obtained from the NASA LP DAAC (https://lpdaac.usgs.nasa.gov) for the period February 2000-December 2009.

S3.2.1. LAI/FPAR data quality

The quality of LAI/FPAR data in each $1x1km^2$ 8-day pixel can be assessed using two accompanying 8-bit quality flags – FparLai_QC and FparExtra_QC. Within the FparLai_QC, information on clouds is contained in bits 3 through 4 ("CloudState") and on algorithm pathway in bits 5 through 7 ("SCF_QC"). The cloud flag can assume four values – clear (00), significant clouds were present (01), mixed clouds present on pixel (10) and assumed clear (11). The algorithm flag can assume five discrete values – main algorithm without saturation (000), main algorithm with saturation (001), backup algorithm (010 and 011) and LAI not retrieved (100). Values retrieved with the main algorithm are of best quality (*S17*). The main algorithm may fail due to the presence of clouds, aerosols as well as geometry problems, in such situations a biome-specific backup algorithm that is based on empirical LAI/FPAR-NDVI relationship is used to retrieve LAI/FPAR. Thus, backup values are generally incorrect. Additional information on clouds and aerosols is contained in the FparExtra_QC flag. Three binary cloud flags are "Cirrus", "MODAGAGG_Internal_CloudMask" and "MODAGAGG_Cloud_Shadow". The aerosol flag – "Aerosol" – is also binary, assuming values "No or low atmospheric aerosols detected" (0) and "Average or high aerosol levels detected".

Determination of LAI/FPAR validity: This is done through a two-stage process: (i) A $1x1km^2$ 8-day LAI/FPAR pixel is considered valid when (a) data is of good quality – "SCF_QC" equals 0 (main algorithm without saturation) or 1 (main algorithm with saturation), (b) Clouds are absent – "CloudState" (0), "Cirrus" (0), "MODAGAGG_Internal_CloudMask" (0) and "MODAGAGG_Cloud_Shadow" (0). (ii)

Since the 8-day LAI aerosol flag does not distinguish between average and high aerosol loadings nor reports climatology aerosols, valid 8-day values are averaged to 16-day LAI/FPAR whose validity is further determined using corresponding 1x1km^2 VI quality flags cloud and aerosol flags: (a) VI data is produced – "MODLAND_QA" equals 0 (good quality) or 1 (check other QA), (b) VI Usefulness is between 0 and 11, (c) Clouds are absent – "Adjacent cloud detected" (0), "Mixed Clouds" (0) and "Possible shadow" (0), and (d) Aerosol content is low or average – "Aerosol Quantity" (1 or 2). Valid 1x1km^2 16-day values are averaged to obtain monthly LAI/FPAR. (iii) Finally, valid 1x1km^2 monthly values are aggregated to 8x8km^2 spatial resolution, given the problems of missing data owing to atmospheric corruption with clouds and aerosols in the Amazon (*S23*). Both the 1x1km^2 16-day and the 8x8km^2 monthly LAI/FPAR datasets spanning February, 2000-December, 2009 are used in this study.

S3.3. Collection 5 (C5) Land cover

Land cover information was obtained from the "MODIS Terra Land Cover Type Yearly L3 Global 1 km SIN Grid" product – MOD12Q1. This is the official NASA C5 land cover data set (https://lpdaac.usgs.gov, *S24*). It consists of five land cover classification schemes at 1x1km^2 spatial resolution. The International Geosphere Biosphere Programme (IGBP) land cover classification scheme was used to identify forest pixels in the Amazon region. The data were obtained from the NASA LP DAAC (https://lpdaac.usgs.gov).

S3.4. Trend Analysis

Time trends in NDVI, EVI, LAI and FPAR are calculated pixel-by-pixel. For a given year, valid monthly VI (NDVI and EVI, 0.05^{o}x0.05^o) greater than 0.1, which excludes barren areas, water bodies and snow/ice-covered surfaces, are averaged to obtain annual mean values. Similarly, valid monthly LAI/FPAR (8x8km^2) greater than 0 are also averaged to annual mean values. These annual mean values are used to evaluate the trend estimates shown in Figs. 1 and S3.

S3.5. Standardized Anomaly

July to September (JAS) 2005 standardized anomalies (anomaly divided by the standard deviation) of LAI and FPAR are calculated pixel-by-pixel at 1x1km^2 spatial resolution as $a = (x-m)/s$, where a is the JAS 2005 standardized anomaly for LAI/FPAR, and x is the 2005 JAS mean LAI/FPAR. For a given year the JAS mean is the average of all 16-day LAI/FPAR values that are valid (cf. Section S3.2.1). The mean (m) and standard deviation (s) of JAS mean LAI/FPAR are evaluated over the reference period, 2000 to 2009, but excluding 2005. Pixels with standardized anomalies in the range -1 to +1 standard deviation (std. dev.) are classified as showing no changes. Pixels with standardized anomalies less than -1 std. dev. are classified as browning and greater than +1 std. dev. classified as greening (or green-up). The 2005 JAS LAI/FPAR standardized anomalies in the Amazon are shown in Fig. S2.

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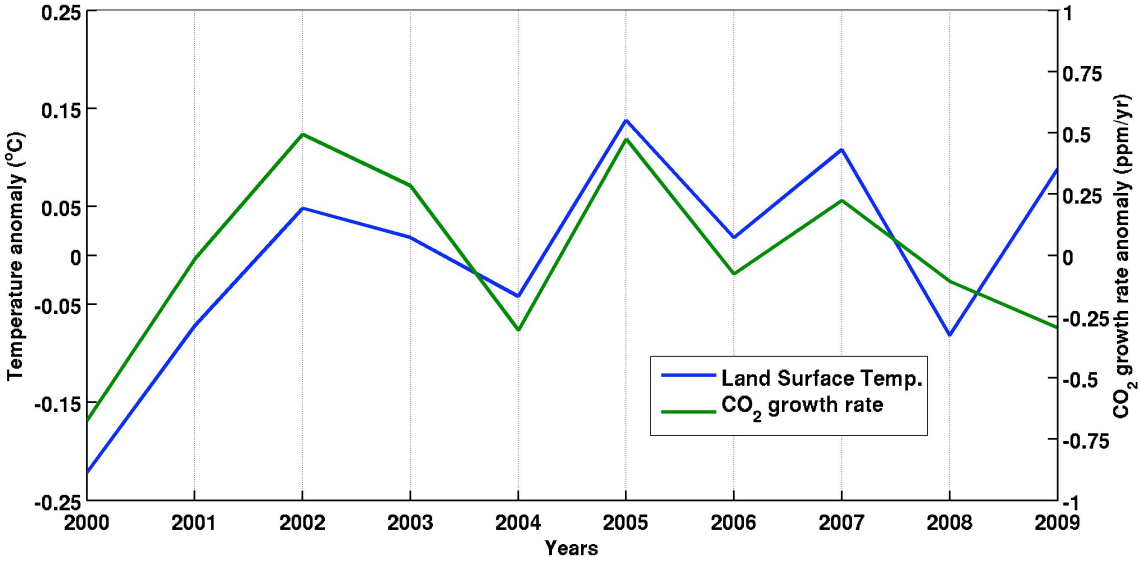

Fig. S1. Time-series of anomalies of annual mean global land surface temperature (°C, blue line), and atmospheric carbon dioxide (CO_2) growth rate (ppm/year, green line) (r=0.73, p=0.0168 (<0.05)). The land surface temperature anomaly data (relative to 1950-1981 mean) were obtained from NASA Goddard Institute for Space Studies. The CO2 growth rates were obtained from the Earth System Research Laboratory (ESRL) of the US National Oceanic and Atmospheric Administration. Note that the CO2 concentration data for 2009 have been revised by ESRL since ZR10.

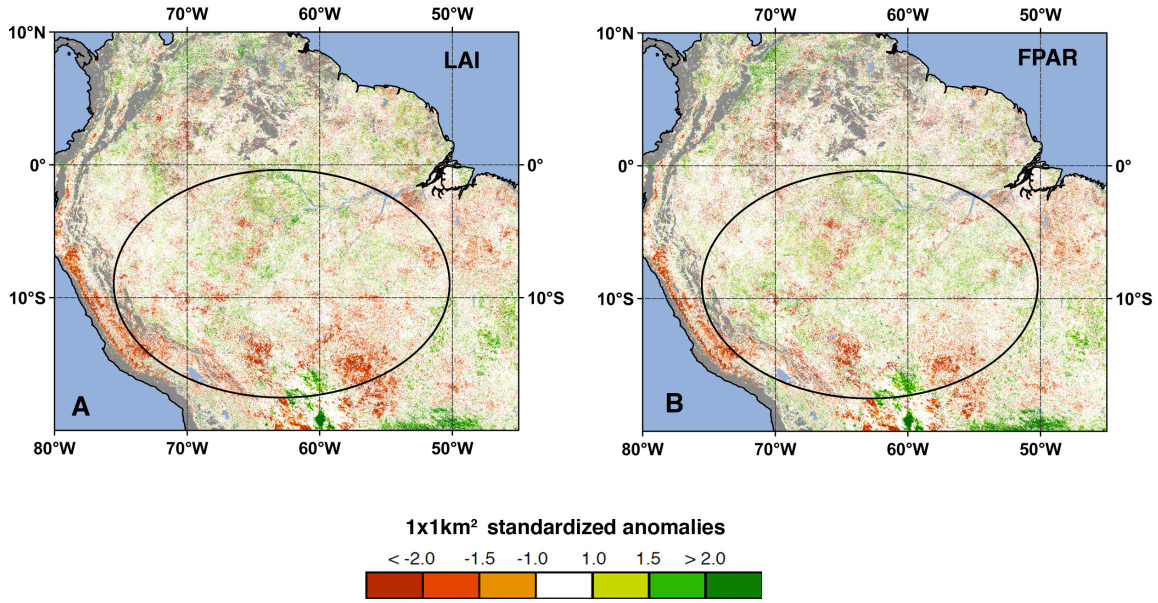

Fig. S2. Spatial patterns of Collection 5 Leaf Area Index (LAI) and Fraction of Photosynthetically Radiation absorbed by vegetation (FPAR) standardized anomalies during the 2005 dry season (July to September) at 1x1km^2 spatial resolution. Cloud-, shadow-, climatology aerosol- and high aerosol-contaminated data are screened from analysis (Supporting Online Material Section S3). Anomalies are calculated relative to 2000-2009, but excluding 2005. These data are from the Moderate Resolution Imaging Spectroradiometer (MODIS).

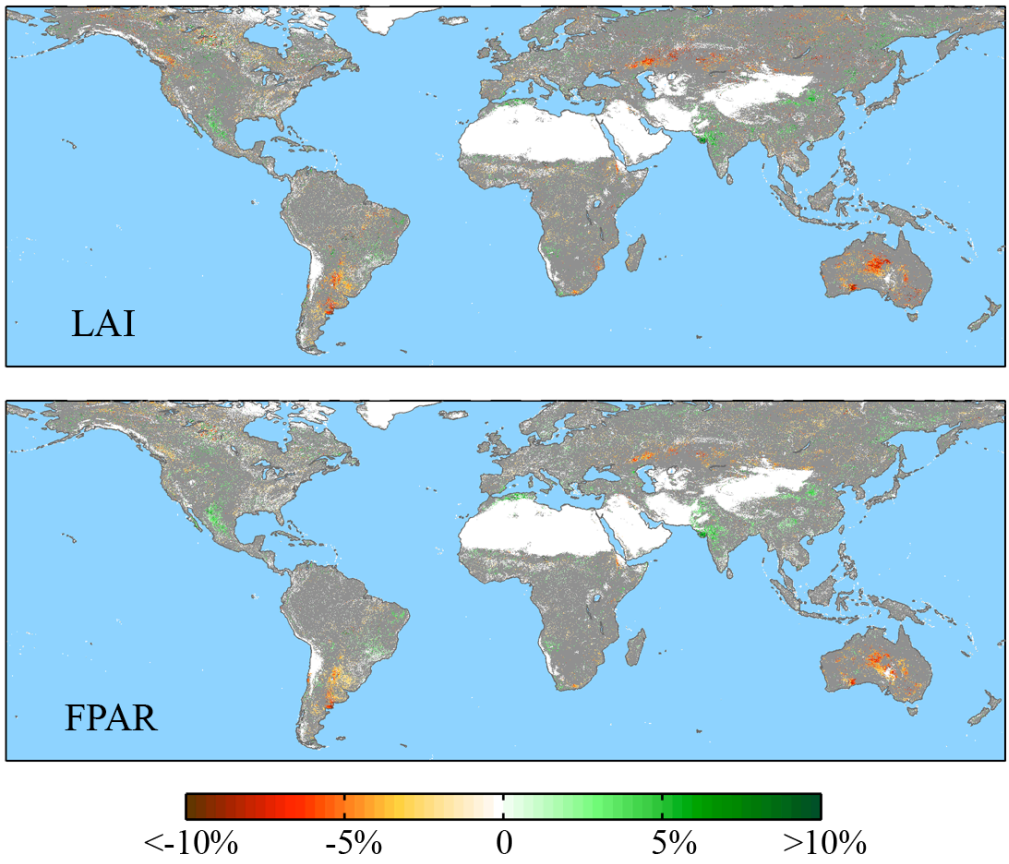

Fig. S3. Spatial patterns of statistically significant (p<0.05) trends (%/year) in annual mean Collection 5 (C5) Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation absorbed by vegetation (FPAR) at 8x8 km^2 spatial resolution during the decade 2000-2009. Cloud-, shadow-, climatology aerosol- and high aerosol-contaminated data are screened from analysis (Supporting Online Material S3). Areas with statistically insignificant trends are shaded grey, and barren areas are colored white. These data are from the Moderate Resolution Imaging Spectroradiometer (MODIS).