Persistent effects of a severe drought on Amazonian forest canopy

Sassan Saatchi[a,b,1], Salvi Asefi-Najafabady[b], Yadvinder Malhi[c], Luiz E. O. C. Aragão[d], Liana O. Anderson[c,e], Ranga B. Myneni[f], and Ramakrishna Nemani[g]

[a]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [b]Institute of Environment, University of California, Los Angeles, CA 90045; [c]Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford OX1 3QY, United Kingdom; [d]College of Life and Environmental Sciences, University of Exeter, Devon EX4 4RJ, United Kingdom; [e]Remote Sensing Division, National Institute for Space Research (INPE), Sao Jose dos Campos, Sao Paulo 12227-010, Brazil; [f]Department of Geography and Environment, Boston University, Boston, MA 02215; and [g]Biospheric Sciences Branch, National Aeronautics and Space Administration/Ames Research Center, Moffett Field, CA 94035

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Recent Amazonian droughts have drawn attention to the vulnerability of tropical forests to climate perturbations. Satellite and in situ observations have shown an increase in fire occurrence during drought years and tree mortality following severe droughts, but to date there has been no assessment of long-term impacts of these droughts across landscapes in Amazonia. Here, we use satellite microwave observations of rainfall and canopy backscatter to show that more than 70 million hectares of forest in western Amazonia experienced a strong water deficit during the dry season of 2005 and a closely corresponding decline in canopy structure and moisture. Remarkably, and despite the gradual recovery in total rainfall in subsequent years, the decrease in canopy backscatter persisted until the next major drought, in 2010. The decline in backscatter is attributed to changes in structure and water content associated with the forest upper canopy. The persistence of low backscatter supports the slow recovery (>4 y) of forest canopy structure after the severe drought in 2005. The result suggests that the occurrence of droughts in Amazonia at 5–10 y frequency may lead to persistent alteration of the forest canopy.

radar | canopy water content | rainforest | QSCAT | canopy disturbance

In the past decade, Amazonia has experienced two major droughts, as highlighted by the water level of the Rio Negro recorded at Manaus in central Amazonia, the longest (109 y) available time series record. The first occurred in 2005 (1, 2), with the minimum river level at 14.75 m, the lowest in the past 40 y, and the second in 2010, with the river at 13.63 m, the lowest in the record (3). Severe droughts, often associated with the El Niño–Southern Oscillation (ENSO), cause a decline in soil moisture, pushing the plant-available water below a critical threshold level for a prolonged period, resulting in higher rates of tree mortality and increased forest flammability (4–7). The drought of 2005 was unlike the ENSO-related droughts because of its temporal and spatial extent: its peak of intensity during the dry season and its center of impact in southwestern Amazonia, rather than the central and eastern regions, which are associated more with El Niño droughts (1).

Warming of the tropical North Atlantic sea surface temperature is considered a major contributing factor in the 2005 drought, which resulted in the lowest river levels recorded to that date in southern and western tributaries (1, 8, 9). Observations from ground stations show that precipitation over the southern region of Amazonia declined by almost 3.2% per year in the period before this decade (1970–1998) (10). The same region experienced several negative precipitation anomalies during the last decade, indicating an increase in dry conditions that culminated in severe 2005 drought (1–3, 11). Climate model predictions also suggest that the intensity of dry seasons and extreme dry events may increase with climate change, affecting the ecosystem function and health of forests in Amazonia (11, 12).

The short-term consequences of drought events are well established through ground and satellite observations (3–6, 13). However, the extent and severity of longer-term impacts of droughts on the Amazonian rainforest and its functioning are not known. Measurements of forest structure and density from inventory plots over humid tropical forests have shown an increase in tree mortality and a decline in the aboveground biomass that may persist for several years (4, 14, 15). A relationship found between a simple measure of moisture stress and changes in forest biomass was used recently to predict the potential impacts of droughts on the Amazon carbon dynamics (6). Direct evidence of long-term impacts of droughts on the Amazon vegetation has been demonstrated only in controlled small-scale (1-ha plot) field experiments (16). The study showed the most important forest response to severe droughts was the mortality of large trees with crowns in the upper canopy when plant-available soil water declined below a critical threshold (16, 17). Similar drought effects have been observed in Amazonia and other regions in research plots (4, 18).

Sensitivity of satellite spectral observations to the forest's upper-canopy characteristics (greenness, leaf area), particularly at optical wavelengths, potentially may provide the necessary information to assess the long-term impacts of droughts (18). However, recent results from optical satellites monitoring changes in vegetation greenness after the 2005 drought have been contradictory because of severe impacts of clouds and atmospheric aerosols on spectral observations (3, 19–22) over Amazonia. No study has examined the potential changes of vegetation detectable at microwave frequencies.

Here, we analyze data from two microwave satellite sensors measuring precipitation and canopy water content to quantify the relative severity of recent droughts and potential impacts on Amazonian vegetation (*Methods*). First, we characterize the drought over Amazonia by calculating three indices derived from monthly precipitation measured by the Tropical Rainfall Measuring Mission (TRMM; 1998–2010): the dry-season precipitation anomaly (DPA), dry season water deficit anomaly (DWDA), and maximum climatological water deficit (MCWD) (*SI Methods*). These indices are complementary in their information content and provide spatially specific indicators about the extent and severity of moisture deficit in Amazonia.

Second, we examine the impact of the water deficit on the Amazon forest by using observations from the SeaWinds Scatterometer onboard QuickSCAT (QSCAT: 2000–2009). QSCAT operates in microwave frequency (13.4 GHz), providing backscatter measurements strongly affected by the temporal and spatial variations of water content and structure of the forest canopy (Fig. S1) (13, 22).

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[1]To whom correspondence should be addressed. E-mail: saatchi@jpl.nasa.gov.

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QSCAT signal propagating at 2.1-cm wavelength and incidence angles of about 50° penetrates a few meters (1–5 m) into the forest canopy, depending on forest gaps, and scatters from leaves and branches of the upper canopy of trees. The backscatter measurements capture biophysical properties of forests, such as the water content in leaves and branches, and canopy structure (i.e., volume or biomass) (*SI Materials and Methods*). Temporal changes (diurnal and seasonal) of canopy water content (i.e., leaves and branches) and seasonal leaf phenology have the largest impact on the radar backscatter (23). Structural changes such as large-scale forest degradation and deforestation that may change the canopy roughness (layering of tree crowns), create gaps, and affect the water content or biomass of the upper canopy of forests can change the backscatter signal significantly (Fig. S1). However, because of the incidence angle and large footprint of QSCAT radar, other factors, such as soil moisture and variations in leaf clumping or orientation of branches, have less impact on the QSCAT backscatter (23).

In November 2009, QSCAT sensor scanning capability failed and the sensor stopped collecting systematic data globally, limiting our analysis of the changes in canopy characteristics when the 2010 drought occurred. However, before its scanning failure, throughout its mission (1999–2009) QSCAT provided reliable data over ocean and land surface without any bias or sensor degradation and continued providing limited data along its orbital passes (*SI Materials and Methods*). To examine the impact of the 2010 drought, we analyzed TRMM precipitation radar (TRMM-PR) backscatter data operating at the same frequency as QSCAT but with nadir-looking incidence angle and surface backscatter measurements for periods of no rain. TRMM-PR backscatter responds to the surface moisture by penetrating deeper into the canopy and scattering from soil and understory vegetation through forest gaps (*SI Materials and Methods*).

We used time series of QSCAT backscatter data from dawn orbits to monitor vegetation in its least-stressed time of day by studying its monthly and seasonal normalized anomaly and spatial variations over Amazonia. Throughout the time-series analysis, the QSCAT backscatter measurement was used as a direct representation of the upper-canopy forest structure and water content to avoid any indirect estimation and validation of water content or structure (13).

Results

Patterns of Water Deficit. The three indices derived from TRMM data show a strong negative anomaly over southwestern Amazonia in 2005 (Fig. S2). Of the total current forested area of the Amazon basin (~5.5 M/km^2), about 30% (1.7 M/km^2) experienced standardized DWDA less than −1.0 σ (σ: SD) in 2005, and more than 5% of total area (0.27 M/km^2) was subject to severe anomalies (DWDA less than −2.0 σ). Both the spatial extent and the severity of drought increased in 2010, resulting in more than 48% (2.6 M/km^2) of the forest area subject to DWDA less than −1.0 σ, and about 20% (1.1 M/km^2) at DWDA less than −2.0 σ (Fig. S2). In south and southwestern regions of Amazonia, this anomaly was superimposed on a dry season that is fairly strong in normal years, resulting in the forests experiencing a very large water deficit (MCWD less than −300 mm) by the end of the dry season. The generally wetter forests in central Amazonia with the largest negative DPA and DWDA experienced low to moderate water deficit (MCWD less than −100 mm) in 2005 and 2010. Data show that precipitation anomalies over these regions lasted only over a relatively short time span within the last decade. However, the spatial extent of precipitation anomaly (DPA) and MCWD in southwestern Amazonia reached to the foothills of the Andes in 2005 and extended to northern regions of Peru, Ecuador, and Colombia, suggesting a pattern approximately consistent with the low river stage measured in Rio Negro and other rivers in the southwestern Amazon basin (2, 9).

Patterns of Drought Impact on Forest Canopy. The impact of this extensive water deficit on the Amazon forest was captured by the QSCAT (2000–2009) backscatter time series (*SI Materials and Methods*). The dry season standardized anomaly in 2005 showed widespread (2.1 M/km^2) decline in forest canopy backscatter (anomaly less than −1.0 σ) in southwestern Amazonia (Fig. 1*A*). Nearly 40% of this area (0.77 M/km^2) indicated a major decline in backscatter (anomaly less than −2.0 σ). The backscatter anomaly on a monthly or seasonal basis calculated for 2000–2009 shows a strong spatial correlation with the water deficit anomaly (WDA) observed by TRMM for the same period, indicating that water stress is the likely cause of the change in forest canopy properties. The region affected by the QSCAT anomaly covered a variety of old-growth forests, from transitional semideciduous and bamboo forests in southwestern Brazil, northern Bolivia, and areas in southern Peru and along the Andean flank in western Amazonia to a variety of inundated and *terra firme* forests in the north (24). All nonforested areas were excluded from the analysis using a global land cover type (*SI Materials and Methods*).

We performed cross-correlation between the QSCAT and TRMM anomaly averaged over Amazonia and found correlation was significant with 1–3 mo lag, but varied over the basin depending on the rainfall patterns (Fig. 1 *B* and *C*). In the southwestern region, with a longer dry season, the correlation was lagged significantly by about 3 mo. However, in the northeastern region, where the dry season is moderate and short, the correlation was strong, with no time lag. Spatial variations of QSCAT and TRMM anomaly in 2005 show that areas captured by highly negative QSCAT anomaly (less than −3.0 σ) are larger in extent than similar areas captured by WDA. The difference is explained by closely examining areas where maximum water deficit (MCWD) in 2005 exceeded 300 mm and/or there was a strong water deficit during the entire driest quarter (DWDA less than −3.0 σ). The reduction in QSCAT backscatter, causing the anomaly in the southwest region, is closely associated with the WDA gradually developing through the dry season in 2005 (Fig. S3).

Slow Recovery of Forest Canopy. We used the time series of TRMM and QSCAT anomaly averaged over the area affected by the drought in southwestern Amazonia (4°S–12°S, 76°W–66°W) to examine the temporal patterns of the 2005 drought and its impacts. After 2005, the area affected by the drought had a recovery of total rainfall, but WDA stayed negative on the average during the 2006 and 2007 dry seasons. Recovery of water deficit started in 2008 followed by an anomalously wet year in 2009 that extended over all of Amazonia except the northeastern region (Fig. S4). From late 2009, the water deficit increased before it rapidly reached its highest value in the decade in southwestern region (Fig. 2*A*). However, most remarkably, forest pixels affected by the water deficit over southwestern Amazonia continued to show low values in the QSCAT backscatter (about 20% below previous mean) from 2005 through to the end of the record in November 2009 (Fig. 2*B*). We used an autoregressive moving-average (ARMA) model with an order of about 5% of the data points (>6 mo) to highlight the longer-term trends and cycles in the data. The time series of the QSCAT anomaly suggests that the 2005 drought caused a step change in the backscatter properties of the canopy, with little recovery in the subsequent years (*SI Materials and Methods*). The response is very localized to regions in western Amazonia that experienced the strongest water deficit anomalies, hence cannot be attributed to hypothetical changes in sensor performance. We tested the sensor performance in other regions of Amazonia and the world to ensure the stability of the backscatter signal and its calibration (Fig. S5). Spatial patterns of annual QSCAT anomaly for the dry season support the long-term reduction in backscatter after the 2005 drought until the end of 2009, when the positive anomaly of

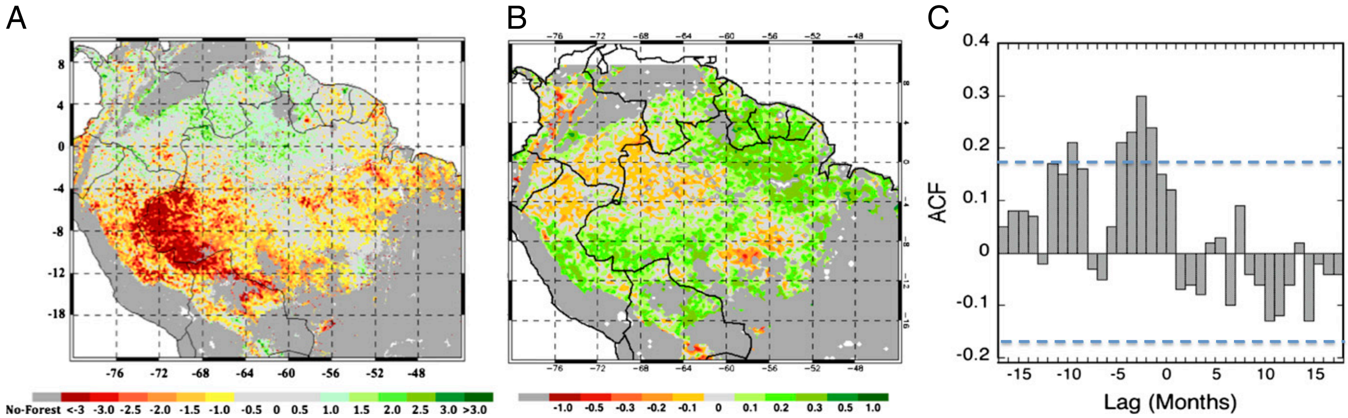

Fig. 1. Spatial extent and severity of the 2005 Amazonian drought using seasonal (JAS) standardized anomaly of QSCAT backscatter data at H polarization for ascending orbits (acquired at dawn), capturing the forest canopy water stress and spatial patterns. (*A*) Magnitudes of QSCAT anomaly beyond ±1.0 σ. (*B*) Spatial cross-correlation between the TRMM monthly WDA and the QSCAT monthly anomaly with 1 mo lag over the period 2000–2009. (*C*) ACF developed between the two datasets averaged over forested pixels in Amazonia with time lags ranging from 0 to 18 mo in either direction. Dashed lines represent the 95% confidence interval as $\pm 2/\sqrt{N}$.

precipitation slightly changed the trend before the 2010 drought (Fig. S5).

The intensity of the anomaly in 2005 and its gradual shift toward recovery lagging the water deficit also is evident in the distributions of normalized anomalies for the dry season water deficit and the canopy backscatter power over pixels in southwestern Amazonia (Fig. S6). The distribution of the QSCAT anomaly peaked at a value between −2 and −2.5 σ in 2005 but stayed significantly negative and different from the distribution of the entire time series for years before 2005 that peaked at about zero ($P < 0.01$ from a two-sided t test). During this period, the distribution of water deficit over the same region alternated between negative and positive, with a strong negative in 2005

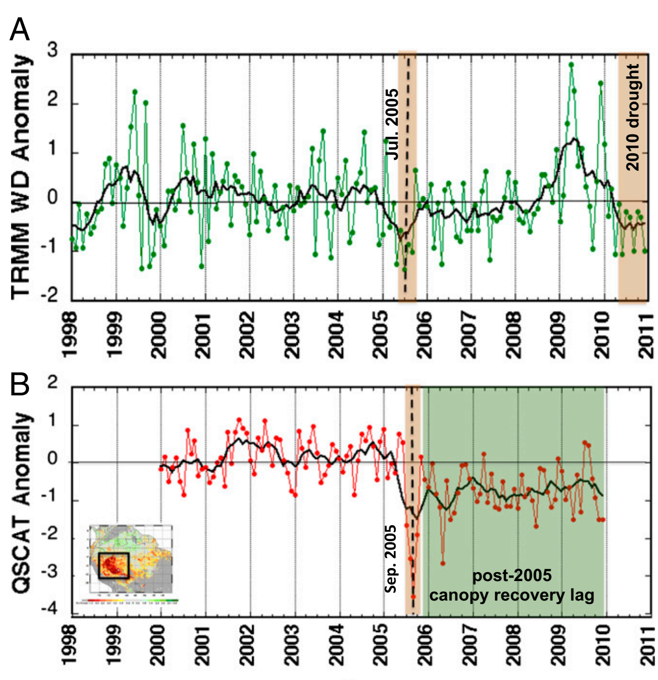

Fig. 2. Time series of (*A*) TRMM and (*B*) QSCAT monthly anomaly over western Amazonia (window: 4°S–12°S, 76°W–66°W). Solid lines show the result of the ARMA of the order of 6 mo.

(approximately −1.5 σ), relatively significant water deficit anomalies in summer of 2006 and 2007 (approximately −1.2 σ), and a strong anomaly in 2010 (peaked between −1.5 and −2.0 σ).

The variation of QSCAT anomaly before and after the 2005 drought was tested through statistical time-series analysis to quantify significance of the step change and trends in the data (*SI Materials and Methods*). Using an ARMA analysis over 120 mo (2000–2009), we found that the QSCAT time series was piecewise stationary because of changes in the mean and, to some extent, the variance over time caused by the 2005 drought. The autocorrelation function (ACF) and partial ACF (PACF) suggested that the time series had a lag of 1–3 mo with PACF cutoff after lag 1 (95% confidence interval), allowing the process to be represented by autoregressive (AR) model (1) on the monthly but not annual time scale (Fig. S7). The detection of the step change in the QSCAT time series was performed using the Breaks in Additive Season and Trend (BFAST) algorithm based on the iterative decomposition of time-series data (25). The results show that a significant step change in QSCAT data was detected in June 2005 with root-mean-square error (RMSE) of 1 mo under the assumption of 97.5% (3 σ) of the noise range in the data (Fig. 3). The noise level did not influence the RMSE of the detection, indicating a low commission error in the detection performance (*SI Materials and Methods*). The BFAST algorithm also detected the seasonality of QSCAT anomaly and showed that it did not influence the accuracy of detecting the breakpoint in the time-series data. The post-2005 trend in the time series was not significant, although it showed the slow recovery of QSCAT signal that lasted about 4 y after the 2005 drought (Fig. 3).

To demonstrate the changes in QSCAT signal relative to TRMM water deficit, we used the average monthly normalized anomalies for southwestern Amazonia and calculated the relative difference between QSCAT anomaly and TRMM monthly WDA (both are normalized and unitless). On average, the difference in anomalies stayed at zero (zero slope) before the 2005 drought and had a negative slope after 2005, suggesting a lag in recovery of QSCAT anomaly relative to the TRMM WDA in southwestern Amazonia. The largest decline in QSCAT backscatter occurred in September 2005 from gradual development of negative anomalies during the driest quarter in July, August, and September (JAS). We extended the analysis over the entire Amazonia by mapping the spatial distribution of the pixels with negative anomalies in both QSCAT and TRMM data (less than −1.0 σ) and with significantly ($P < 0.01$) negative slopes (*SI Materials and Methods*) between QSCAT anomaly and WDA

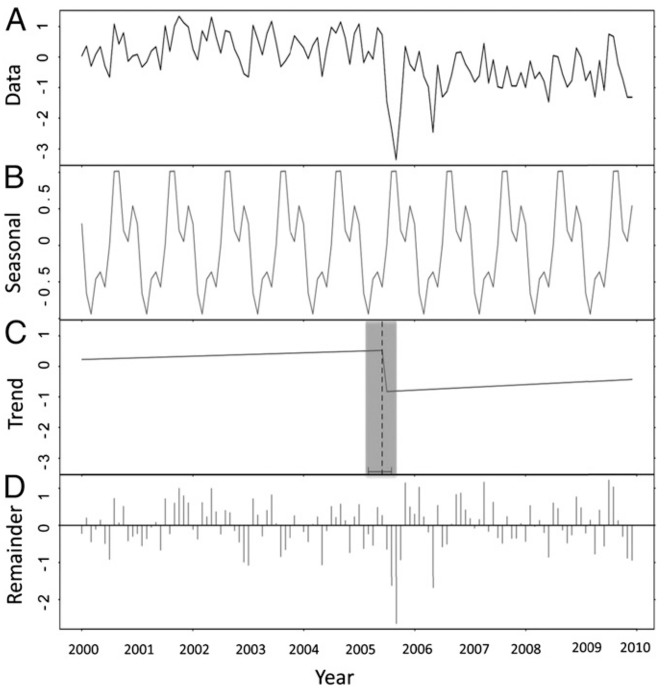

Fig. 3. (*A*) BFAST seasonal trend decomposition of the QSCAT monthly normalized anomaly time series of southwestern Amazonia (window: 4°S–12°S, 76°W–66°W) into seasonal, trend, and remainder components. (*B*) The seasonal component is estimated by taking the mean of all seasonal subcomponents starting from January 2000. The range of seasonal amplitude is less than 20% of the range of QSCAT anomaly. (*C*) One abrupt change in the trend component of the time series is detected on June 2005. The shaded bar indicates the 97.5% (3 σ) confidence interval. (*D*) The remainder shows the variation of the signal after the removal of the trend capturing the temporal variations in the time series.

after the 2005 drought (Fig. 4*A*). Pixels with larger negative slopes represent areas with a longer lag in canopy recovery relative to the recovery of the water deficit and showing persistent drought impacts on canopy characteristics. Regions A and B, respectively, show the old-growth forests of southern Peru and the states of Acre and Rondônia in the western Amazon of Brazil. Region C covers a mosaic of undisturbed and disturbed forests in the state of Mato Grosso and southern Pará (both in Brazil). All three regions were reported to have an anomalously higher number of fires in 2005 and subsequent years, suggesting a potential lower canopy water content and higher fuel loads (4, 22). The 2005–2009 forest loss and degradation from deforestation and fire impacts did not change the persistent QSCAT negative anomaly (Fig. S8). However, a significantly large number of fires during 2005–2009 (>35%) occurred in QSCAT pixels with strong negative anomaly (less than −1.0 σ) in 2005, and more than 78% of fires in 2010 occurred in pixels with large negative slopes (less than −0.01). The occurrence of fires and the areas with slow recovery after the drought coincided with regions with large seasonality of backscatter in QSCAT data, pointing predominantly to transitional and seasonal forests of Amazonia (Fig. 4*B*) (*SI Materials and Methods*).

Discussion

Overall, the results of QSCAT analysis indicate two important conclusions. First, the QSCAT anomaly captures the extent and intensity of the 2005 drought impact on the Amazon forest and provides patterns consistent with areas that experienced the largest water deficit in the driest quarter. Changes in QSCAT backscatter are the result of changes in the properties of the top layer of the canopy, consisting of emergent crowns that often are exposed to higher vapor-pressure deficits and consequently are more sensitive to droughts (4, 16). Theoretically, the widespread decline in radar backscatter suggests changes in canopy water content and structure (e.g., fresh biomass), unlike what was observed in optical sensing (3, 20). The decline in backscatter suggests a reduction of upper-canopy biomass or canopy roughness attributed to potential drought-driven disturbance. The magnitude of the decline in 2005 is significantly larger than seasonal amplitude of the QSCAT backscatter caused by phenology and changes of canopy water content from natural cycles of dry and wet seasons.

Second, the QSCAT anomaly remained negative after the 2005 drought over a large area in western Amazonia, suggesting the persistent effect of the drought on the forest canopy. The severity of the disturbance caused a slow recovery of the forest canopy to its predrought condition in terms of biomass or roughness (canopy layering), lagging the precipitation recovery of subsequent years until the 2010 drought. Notably, more than 0.6×10^6 km^2 of areas affected by the 2005 drought (QSCAT anomaly less than −2.0 σ) coincided with the areas affected by the 2010 water deficit (TRMM DWDA less than −2.0 σ), suggesting a potentially widespread exacerbation of stress on forests of south and western Amazonia.

Without extensive surveys and perhaps airborne observations and validations, the interpretation of the decline of backscatter and its direct relation to the forest disturbance remain challenging. A simple wilting or shedding of leaves during the peak drought, resulting in a temporary decline of net primary production, would be expected to be followed by recovery of canopy properties within a year. Such recovery is apparent in central Amazonia, where the backscatter anomaly recovered rapidly, despite experiencing a strong water deficit and QSCAT anomaly in 2005 (Figs. S2 and S3). The delayed recovery of QSCAT in southwestern Amazonia suggests a decline in more long-lived aspects of canopy structure with recovery timescales greater than 3–4 y, such as loss of leaves or dieback of branches, or potential tree falls creating large gaps.

We found no in situ observations over the region affected by the 2005 drought that could be used to directly verify our results. However, in most tropical drought studies, there is strong evidence that large-diameter or emergent trees have significantly higher mortality than small trees (16–18, 26, 27). The effects of extreme droughts on the understory light environment of tropical forests may be compared with the effects of tree-fall gaps, although on much larger scales (27). With the recovery of rainfall and potential increase in light availability due to gaps from canopy disturbance, the understory vegetation and pioneer species may increase productivity a few months after severe droughts (22). These changes may affect nadir-looking optical satellite observations with sensitivity to vegetation greenness and photosynthesis capacity (3, 21, 22). In situ measurements show that the mortality of large trees remains elevated even a few years after the drought (4), suggesting a decline in canopy structure or biomass followed by gradual development of canopy emergent trees (4, 22). The recovery of canopy trees after the drought event is a slower process and may take longer to reach the predrought state (18, 22, 25, 26). Based on the results from this study and the evidence reported in the literature, we hypothesize that western Amazonia experienced a large-scale canopy disturbance from the 2005 drought, resulting in the decline of emergent and canopy tree structure and biomass that continued with a slow recovery for the next few years. We expect future field campaigns directed to examine the effect of severe droughts and analysis of existing in situ data from permanent research plots in western Amazonia (4) to test the hypothesis and potentially verify the results of satellite observations.

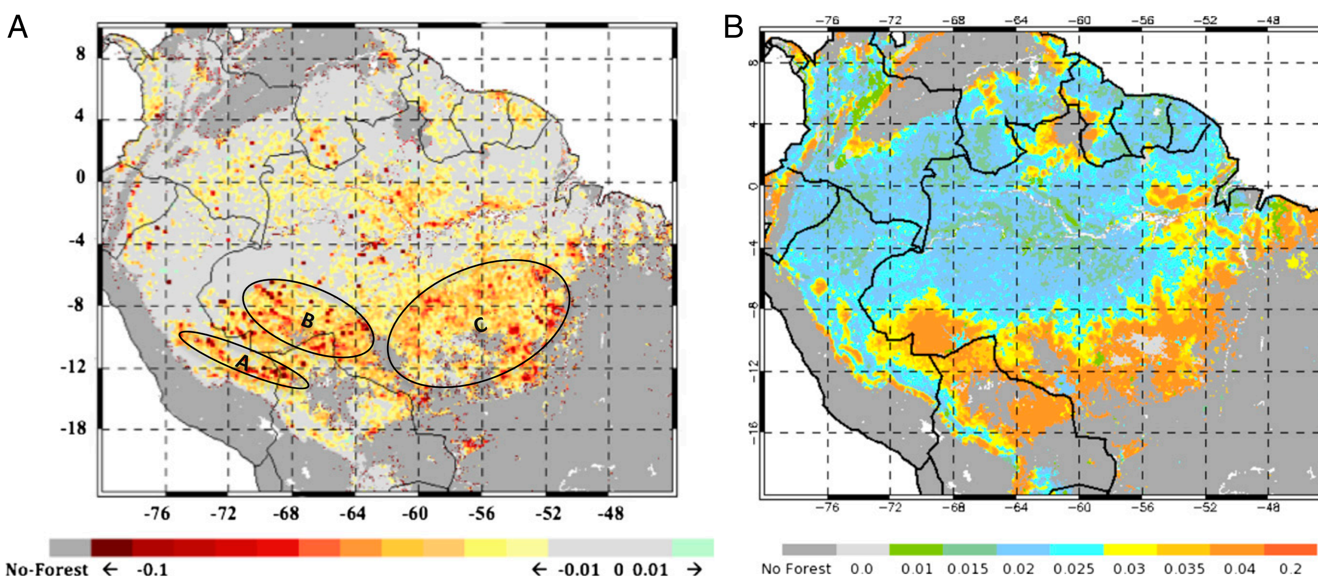

Fig. 4. (*A*) Spatial representation of the rate of recovery of pixels affected by QSCAT-negative anomaly (less than −1.0 σ) calculated by the slope of the difference in QSCAT and TRMM monthly anomalies from September 2005 to November 2009 (*SI Materials and Methods*). Pixels with significantly large negative slopes represent forests with slower recovery and cover an area of ∼4 × 10^5 km^2. Areas delineated in highlighted areas as A, B, and C represent regions in southeastern Peru, the state of Acre in Brazil, and areas in the state of Mato Grosso, respectively, showing areas with potentially the largest impacts of the 2005 drought. (*B*) Spatial representation of areas with strongest seasonality in canopy properties detected by the QSCAT backscatter measurements (2000–2009).

A large-scale drought disturbance of forest structure from mortality of large trees and, to some extent, a drop in the leaf area of the forest (16, 28) may lead to a sustained efflux of carbon dioxide from the decay of wood, with the process significantly perturbing the net ecosystem exchange and carbon fluxes (11, 12, 14). Results from climate analysis for the period 1995–2005 demonstrate a steady decline in plant water availability over the same region, suggesting a decade of moderate water stress before the 2005 drought (10, 22), helping to trigger a large-scale canopy disturbance after the 2005 drought. A higher water deficit in subsequent years, together with another strong local drought in 2007, suggests that soils from a large portion of southwestern Amazonia may not have reached the field capacity, which would favor canopy recovery (29). Other factors, such as a decline in rainfall and larger variability in the dry season over southwestern Amazonia since the late 1980s and early 1990s (Fig. S9), may have contributed to an increasingly drier condition in this region. We show that these recent negative anomalies and year-to-year variations are strongly linked to both the warming and variations in the sea surface temperature (1, 2). The most recent droughts are related to higher temperatures in the tropical Atlantic, showing a strong regional sensitivity of WDA to the tropical North Atlantic index (Fig. S10).

Our analysis ends in 2009. It seems likely that the observed canopy response was repeated in the more severe drought of 2010 (Fig. S11), for which QSCAT data are not available; hence, a new wave of disturbance may have affected forest canopies not yet recovered from the previous droughts and water deficit. The TRMM-PR backscatter anomaly suggests that the surface moisture in western and southern Amazonia dropped significantly in 2010 and lasted longer than the dry season (Fig. S11), potentially causing more stress on the forest canopy. If droughts continue to occur at 5–10-y frequency, or increase in frequency, large areas of Amazonian forest canopy likely will be exposed to the persistent effect of droughts and the slow recovery of forest canopy structure and function. In particular, areas of south and western Amazonia have been shown to be affected severely by increasing rainfall variability in the past decade, suggesting that this region may be witnessing the first signs of potential large-scale degradation of Amazonian rainforest from climate change (10, 11, 30).

Materials and Methods

This study is based on the use of various microwave satellite observations of Amazonia to detect the regional and potential severity of the impact of the 2005 drought on the Amazon forests. Our approach includes five steps: (*i*) spatial analysis of monthly TRMM rainfall data to calculate the standardized anomaly of rainfall during the dry season, maximum water deficit, and anomaly of monthly water deficit; (*ii*) spatial analysis of monthly QSCAT backscatter data to computer pixel-level standardized anomaly from the satellite dawn orbits to monitor vegetation in its least-stressed time of day and its spatial correlation with TRMM water deficit; (*iii*) time-series analysis of QSCAT monthly backscatter anomaly over western Amazonia using the ARMA model, testing ACF and PACF with time lags, and iterative application of the additive decomposition algorithm BFAST to detect a significant breakpoint and trend in the QSCAT data associated with the 2005 drought; (*iv*) quantifying the impact of deforestation and fire occurrence on the QSCAT anomaly and trend results and showing the independence of the results from canopy disturbances that may have been caused by fire and degradation during and after the 2005 drought; and (*v*) testing the regional impacts of variations in the historical climate data on the patterns of rainfall anomaly in Amazonia to explain the climatic cause of recent droughts in Amazonia. Our analysis of the QSCAT data was limited to the period 2000–2009 and could not provide information about the 2010 drought. We included the TRMM-PR backscatter anomaly to demonstrate the changes in surface moisture during the 2005 and 2010 droughts as evidence of the potential impact of the 2010 drought on forests in southwestern Amazonia already affected.

We used the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover map of 2005, GlobCover land cover map of 2009, and MODIS-derived pixel fire counts from 2001 to 2010 to exclude nonforest pixels from our analysis and to quantify the percentage of pixels with a large QSCAT-negative anomaly affected by fires after the 2005 drought (2005–2009) and during the 2010 drought. We had no independent ground measurements to verify our results because of the large pixel size of the satellite observations and the recentness of the drought event. However, we provided biophysical interpretation of the satellite observations and evidence from in situ measurements and ecological studies to corroborate our findings of the persistent effect of droughts on forest canopy. We provide detailed information about the data in *SI Materials and Methods*.

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