*Research review*

# Drought impacts on the Amazon forest: the remote sensing perspective

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## Summary

Drought varies spatially and temporally throughout the Amazon basin, challenging efforts to assess ecological impacts via field measurements alone. Remote sensing offers a range of regional insights into drought-mediated changes in cloud cover and rainfall, canopy physiology, and fire. Here, we summarize remote sensing studies of Amazônia which indicate that: fires and burn scars are more common during drought years; hydrological function including floodplain area is significantly affected by drought; and land use affects the sensitivity of the forest to dry conditions and increases fire susceptibility during drought. We highlight two controversial areas of research centering on canopy physiological responses to drought and changes in subcanopy fires during drought. By comparing findings from field and satellite studies, we contend that current remote sensing observations and techniques cannot resolve these controversies using current satellite observations. We conclude that studies integrating multiple lines of evidence from physiological, disturbance-fire, and hydrological remote sensing, as well as field measurements, are critically needed to narrow our uncertainty of basin-level responses to drought and climate change.

## Introduction

Precipitation varies spatially and temporally in the Amazon basin, but long-term station records indicate that annual rainfall is decreasing by an average 0.32% $yr^{-1}$ (Li *et al.*, 2008). Overlain on the long-term trend, there are El Nino–Southern Oscillation (ENSO) events and other sea surface temperature anomalies associated with intense drought in portions of Amazônia (Marengo, 1992; Costa & Foley, 1999; Aragao *et al.*, 2007). Droughts are expected to increase in frequency, extent and severity with climate change (Williams *et al.*, 2007; Malhi *et al.*, 2009), which will likely have an important impact on biosphere functioning and biodiversity (Meir *et al.*, 2008; Loarie *et al.*, 2009).

Independent of trends in drought occurrence, it remains a challenge to understand and predict the effects of precipitation change on the Amazon forest. These effects may be expressed at different ecological scales and among many processes ranging from leaf and canopy physiology to soil and river hydrology. Yet the spatial variability of drought is evident in maps derived from networks of precipitation gauges throughout the region or from satellite-based precipitation data (Aragao *et al.*, 2007; Villar *et al.*, 2009). ENSO-driven drought, the most common in the Amazon region, typically strikes hardest in the eastern and southern portions of the basin. Conversely the 2005 drought caused negative rainfall anomalies as far north as the Brazilian state of Roraima, along the Venezuelan border, and as far southwest as the Peruvian Amazon, the epicenter of the drought (Marengo *et al.*, 2008). This spatial variability makes it difficult to assess the ecological effects of drought from field measurements alone.

Remote sensing offers insight into the effects of drought in Amazônia, and it has been extensively used in this capacity. Most studies utilize satellite imagery (in contrast to airborne data) and the applications have ranged from very short-term, high-resolution experimental studies to low-resolution time series analysis spanning decades. Drought-related phenomena detected from satellites include changes in atmospheric properties such as cloud cover and rainfall, canopy physiological responses such as leaf loss and changes in photosynthetic radiation absorption, and disturbance feedbacks such as fire. Here we synthesize results and data from available remote sensing studies to answer the question: What do we know about Amazon responses to drought from spaceborne observations? The answer will prove to be clear in some respects and elusive in others.

## Canopy responses to dry season and drought

There is an important difference between the dry season and drought in the Amazon basin, and this difference relates to the geography, severity and persistence of precipitation deficit and cloud cover. Typically, there is a dry season lasting 4–5 months (when < 100 mm of rainfall are received per month) over much of the eastern and southern portions of the basin (Marengo, 1992; Marengo *et al.*, 1998). This dry season produces variation in vegetation phenology observable in field (Dantas & Phillipson, 1989; Meir *et al.*, 2009) and spaceborne reflectance measurements (Bohlman *et al.*, 1998; Asner *et al.*, 2000; Huete *et al.*, 2006) (Fig. 1). The proposed causes of this phenological cycle range from leaf flush that replaces aging or epiphyll-covered foliage (epiphylls decrease leaf reflectance in the near-infrared; Roberts *et al.*, 1998) to changes in canopy foliage content or leaf area index (LAI) (Myneni *et al.*, 2007). Given the pronounced dynamics of the system, it useful to first consider how remote sensing has been used to understand the typical dry-season effects on Amazon forest canopies, before addressing the impact of severe drought.

In a stand-level analysis in the central Amazon, Asner *et al.* (2004) used high spectral and spatial resolution Earth Observing-1 Hyperion satellite data to show that the reflectance of the canopy increases, described loosely in the literature as 'green-up', in a typical dry season (July–November 2001) (Fig. 2). This apparent green-up is caused by increases in near-infrared (NIR; 700–1300 nm) reflectance among some canopies within the forest (Fig. 3). Concurrent field observations indicated that new leaf production (leaf flush) at the top of the canopy was responsible for the apparent dry-season green-up in the satellite imagery, because newly flushing foliage displays much higher NIR reflectance relative to older, fully formed leaves (Roberts *et al.*, 1998; Kodani *et al.*, 2002).

The Hyperion result was corroborated and extended in a neighboring field-based study by Doughty & Goulden (2008). They found that although total canopy LAI increases negligibly in the dry season (*c.* 0.2 LAI units), new leaf production increases by one full LAI unit at the top of the canopy. That is, the net change in canopy LAI is small, but the gross amount of new-leaf LAI is large. Doughty & Goulden (2008) also showed that these increases in new-leaf LAI accompany major increases in NIR albedo and

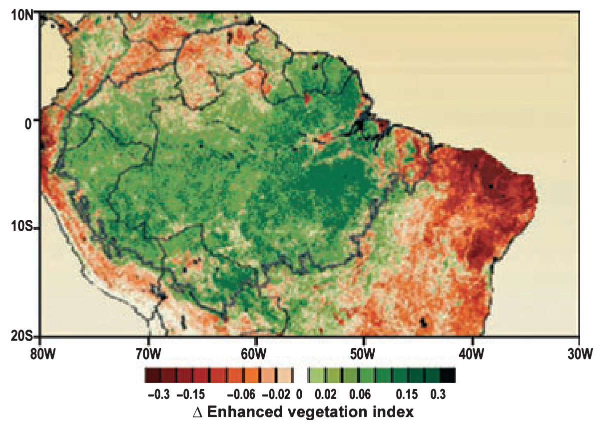


**Fig. 1** An apparent 'green-up' of the Amazon basin during the dry season: this image indicates changes in the NASA moderate resolution imaging spectroradiometer (MODIS) enhanced vegetation index (EVI) between the beginning (June) and end (October) of the typical dry season. From Huete *et al.* (2006), reproduced with permission from the American Geophysical Union.

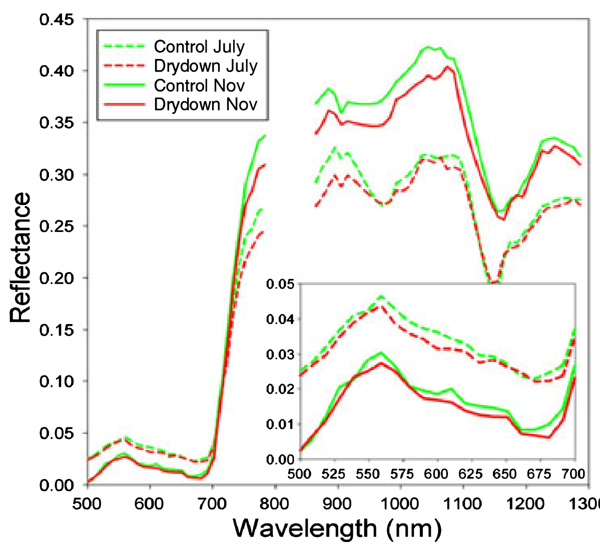


**Fig. 2** EO-1 Hyperion reflectance spectra collected over control (green) and drydown (red) forest plots in the central Brazilian Amazon. Dashed and solid lines indicate spectra collected at the beginning (July) and end (November) of the dry season in 2001, respectively. Inset shows zoom of visible wavelength region.

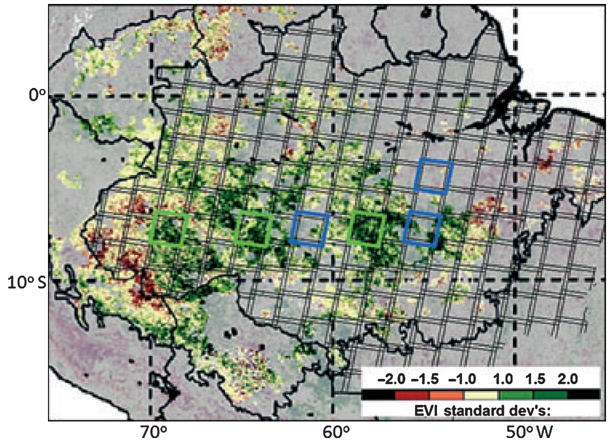


**Fig. 3** Apparent green-up of the Amazon basin during drought (Saleska *et al.*, 2007). The locations of our Landsat cloud time-series analysis (Fig. 4) are shown in green boxes for green-up and blue boxes for nongreen-up regions. Reproduced with permission from the American Association for the Advancement of Science.

reflectance values, results that match the study of Asner *et al.* (2004). The causal mechanisms for dry-season leaf flush remain unknown but the phenomenon seems relatively common, as it is reported in field and satellite studies of other humid tropical forests (Bohlman *et al.*, 1998; Roberts *et al.*, 1998; Condit *et al.*, 2000; Malhi *et al.*, 2002; Wright & Calderon, 2006; Bohlman, 2008). It is likely that leaf flush is coordinated with increased photosynthetic radiation associated with sunnier, dry-season (but not necessarily drought-stressed) conditions (Rascher *et al.*, 2004; Gamon *et al.*, 2005; Huete *et al.*, 2006).

In contrast to the studies of dry season conditions, two major field experiments in the Amazon basin have contributed important understanding on canopy responses and resilience to severe droughts (summarized by Meir *et al.*, 2009). For example, a 1-ha experimental plot was subjected to an 80% decrease in wet-season (December–June) (Nepstad *et al.*, 2002) throughfall inputs for 1 yr before Hyperion satellite measurements were taken (Asner *et al.*, 2004). This plot lost nearly 20% of its LAI from the wet to dry season during the simulated drought (Nepstad *et al.*, 2002). Such decreases in canopy LAI were also observed in another drought simulation study in Amazônia (Fisher *et al.*, 2007; Meir *et al.*, 2008). Leaf water potential was also highly sensitive to drought, decreasing by almost 30% compared with control forest. The net effect on remotely sensed spectral data was a measurable lowering of NIR reflectance in the dry-down plot compared with that of the control plot (Fig. 2), and thus a weakening of the green-up effect caused by new leaf flush.

In both Amazon field studies, LAI not only decreased by 10–20% from wet to dry season during simulated drought, but the long-term trend was one of decreasing LAI. After 4 yr of drought, canopy LAI was suppressed by *c.* 30% in comparison with control stands (Meir *et al.*, 2009). From the combined body of field and high-resolution remote sensing studies in the central Amazon basin, it appears that some canopy green-up can occur under sunnier, dry-season conditions, likely caused by leaf flush and not by LAI increases. These findings may explain results derived from low spatial resolution time-series data from the NASA moderate resolution imaging spectroradiometer (MODIS), which indicates a consistent seasonal cycle in canopy brightness during non-drought years (Fig. 1; Huete *et al.*, 2006).

These studies also suggest that severe drought can exceed the dry-season tolerance of Amazon forest canopies, resulting in decreased LAI and a lowering of spectral reflectance in the NIR. So, although Amazon forests are buffered to some degree from drought conditions by deep roots that maintain access to water when surface soil moisture levels are low (Nepstad *et al.*, 1994), there are thresholds across which persistently negative rainfall anomalies will cause losses in LAI and carbon storage (Brando *et al.*, 2008). However, this may not apply evenly in all forest types, of which there are at least 40 in the Brazilian Amazon (Instituto-Socioambiental, 2000).

Despite the understanding gained in plot-level field and remote sensing studies, Saleska *et al.* (2007) stated that forests green-up even during severe drought events in Amazonia such as the one that occurred in 2005. Their work indicated a large region of increased Enhanced Vegetation Index (EVI; similar to normalized difference vegetation index or NDVI) in MODIS data collected over the Amazon basin (Fig. 3). Based on these findings, they argued that Amazon forests might be more resilient to severe drought than previously thought, and thus there may be little basis for predicted drought-related losses in forest productivity or carbon storage as proposed by modeling studies (Cox *et al.*, 2004). However, despite the Saleska *et al.* results, a large network of field plots indicated that the 2005 drought caused an enormous 1.2–1.6 Pg carbon loss of forest biomass, mostly via tree mortality (Phillips *et al.*, 2009). These findings are difficult to reconcile with those drawn from the MODIS satellite observations.

One prevailing hypothesis is that the MODIS data, despite being processed to suppress atmospheric effects including aerosols and water vapor (both of which decrease the EVI and NDVI), are still subject to subpixel atmospheric effects, and apparent changes in the MODIS EVI may not be driven by variation in vegetation phenology. This problem is particularly acute when using low spectral and spatial resolution imagery such as from MODIS or its predecessor sensor the NOAA advanced very high resolution radiometer (AVHRR). In the 2005 MODIS case presented by Saleska *et al.* (2007), it could be that decreases in cloud cover and water vapor were responsible for increased MODIS EVI values over the western Amazon. However, this possibility is difficult to investigate because diminishing clouds increase the MODIS EVI even if there is no actual canopy green-up. However, fewer clouds may also be associated with an actual physiological response in leaf flush that would increase the EVI.

To illustrate the challenge in unraveling cause and effect in this case, we analysed cloud cover in time-series of > 300 Landsat images collected from 2003 to 2007 in three 34 000 $km^2$ regions representing the largest apparent MODIS green-up in the Saleska *et al.* (2007) study (Fig. 4). We repeated the analysis in three areas that did not undergo apparent green-up in their results. As Landsat data are 30 m spatial resolution, the cloud cover is directly observable at fine resolution, and thus we can capture sub-pixel cloud cover within the MODIS data.

The results show persistently clearer skies in the regions of the Amazon that displayed the largest increases in the MODIS EVI time-series compared with the nongreen-up areas (Fig. 4). Cloud cover was lower throughout most years in these apparent green-up regions independent of whether it was a drought year. An exception was the wet season of 2003 and 2004 (Julian days 0–60) when heavy cloud cover prevailed, but was followed by periods of clear sky over the green-up regions. Despite the added concern caused via our Landsat cloud cover study, our analysis also fails to prove causation: the higher apparent green-up in the MODIS time-series could result from less cloud cover as we mapped with concurrent Landsat or from increased leaf flush in response to sunnier conditions.

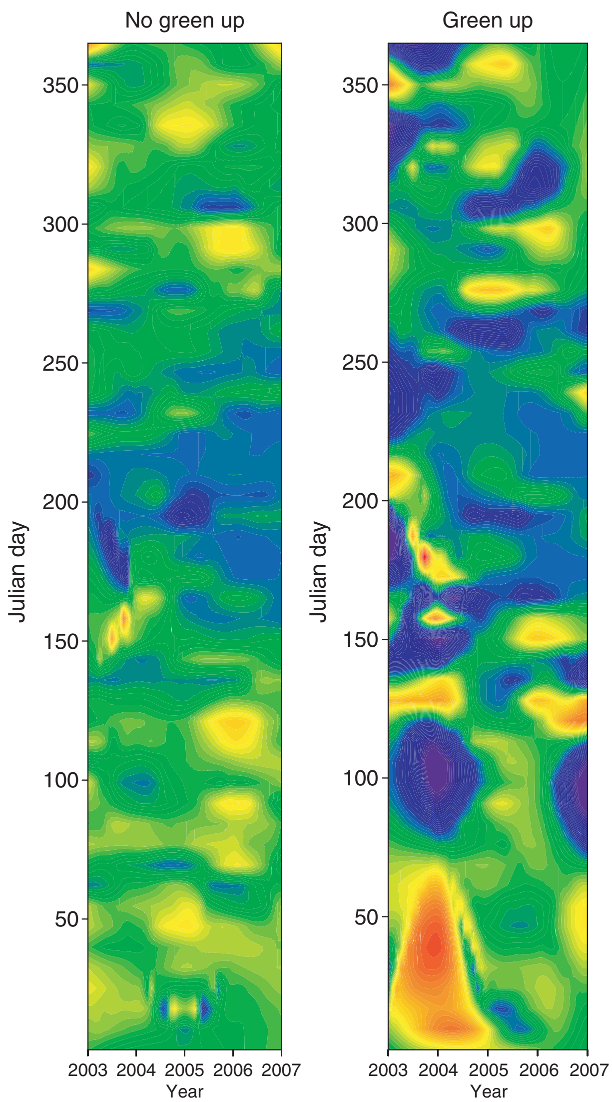


**Fig. 4** Contour plots of time-series Landsat data indicating percentage cloud cover in the six regions shown in blue and green in Fig. 3.

Recently, Samanta *et al.* (2010) reanalysed MODIS EVI data from 2005 and other years that had undergone reprocessing for improved atmospheric correction, along with additional observations of solar radiation throughout the Amazon basin. They found little evidence for green-up during the 2005 drought, and showed that the original work of Saleska *et al.* (2007) was irreproducible. Moreover, Samanta *et al.* (2010) reported a weak relationship between downwelling radiation and the MODIS EVI, stating that there is no observable relationship between illumination levels and apparent canopy green-up. These changes in results taken from the same satellite sensor highlight the challenges inherent to the use of coarse-resolution observations such as from MODIS that do not easily resolve the contributions of biospheric and atmospheric processes to the observed spatial and temporal patterns [paragraph updated after online publication 8 July 2010: URL references to a blog posting and a NASA presentation have been removed].

Other independent satellite-based evidence suggests a different set of possibilities for the Amazon during drought conditions. Asner *et al.* (2000) showed that seasonal patterns in AVHRR time-series taken over the Amazon basin from 1982 to 1992 are largely driven by subpixel cloud cover, water vapor and aerosol contaminants. Only following a series of highly conservative regional filtering and resampling steps could the AVHRR data be used to estimate the phenology of small portions of the Amazon forest, particularly only in the southeastern basin. This study indicated a dry-season increase in the NDVI in the eastern Amazon in some years, but a nearly flat seasonal NDVI cycle during the ENSO drought years of 1983, 1987 and 1991–92. Combined with a carbon cycle model, these results suggest suppressed growth rates during ENSO drought, parallel to the negative impacts found at the stand level (Nepstad *et al.*, 2002; Fisher *et al.*, 2007; Meir *et al.*, 2009) and observed in plot-network measurements during the 2005 drought (Phillips *et al.*, 2009).

One other very recent study made a direct link between forest use and phenological responses to dry conditions. Koltunov *et al.* (2009) used high temporal resolution MODIS data, combined with high spatial resolution maps of selective logging (Asner *et al.*, 2005), to show that just

5–10% canopy opening causes a significant decrease in dry-season green-up that lasts at least 3 yr following timber harvest. That is, selective logging may decrease the ability of the canopy to undergo seasonal leaf flush, possibly owing to increased desiccation. Given the extensive area of actively logged forest in the Amazon – *c*. 1.6 million km$^2$ mostly in the same regions as the proposed green-up (Asner *et al*., 2009), it is even less likely that forests are responding positively to dry or drought conditions.

## Fire and burn scars

Studies clearly show that fire is a major cause and consequence of forest degradation in Amazônia (Cochrane & Schulze, 1999; Cochrane *et al*., 1999; Nepstad *et al*., 1999; Cochrane & Laurance, 2002), and that the effects of fire on forest cover and condition can be remotely sensed (Souza *et al*., 2003, 2005; Chambers *et al*., 2007). In comparison with canopy physiology, remote sensing of fires, burn scars and forest degradation is less controversial.

Thermal remote sensing is commonly used to calculate the frequency and occurrence of temperature anomalies called 'hot pixels', which indicate the location of active fires. High temporal, low spatial resolution imagery is most often used, with MODIS, AVHRR and the Tropical Rainfall Measuring Mission (TRMM) being the most common data sources. Global studies indicate increases in tropical forest and savanna fires during droughts associated with ENSO (van der Werf *et al*., 2004), but it is the comprehensive analyses of Aragao *et al*. (2007, 2008) that provide the clearest evidence that fires are more common in Amazônia during drought conditions. Using AVHRR and MODIS fire count data from 1999 to 2005, they show that the 2005 drought resulted in a 33% increase in fire. Aragao *et al*. (2008) also describe a strong positive correlation between annual gross deforestation area and the number of hot pixels per year ($r^2$ = 0.84), but with the 2005 drought year producing more than a 43% increase in fire per unit deforestation over background levels. Clearly, there is a link between human activities, forest loss and fire occurrence (*sensu* Cochrane *et al*., 1999), but drought can push the system to extremes in fire susceptibility.

The most uncertain aspect of this type of work rests in forest understory fire detection: it is very challenging to detect small ground-covering fires from space because thermal anomalies at the ground level are masked by the moist, highly foliated canopy above. A good indication of this problem can be recognized by viewing an overlay of TRMM satellite fire detections on a map of deforestation (INPE, 2007) and selective logging (Asner *et al*., 2005) in the state of Mato Grosso from 1999 to 2002 (Fig. 5). The results indicate an annual mean (± SD) fire count density for deforested areas of 10.5 (± 3.8) per 100 km$^2$ yr$^{-1}$, while fire count densities within intact forest canopies were only 0.8 (± 0.1) per 100 km$^2$ yr$^{-1}$. However, studies of burn scars in the same region of Brazil indicate substantial areas of forest degradation caused by fire (Alencar *et al*., 2006), which were undetected in the TRMM fire data.

We also note that TRMM fire count densities for selectively logged forest average 2.4 (± 0.7) fires per 100 km$^2$ yr$^{-1}$

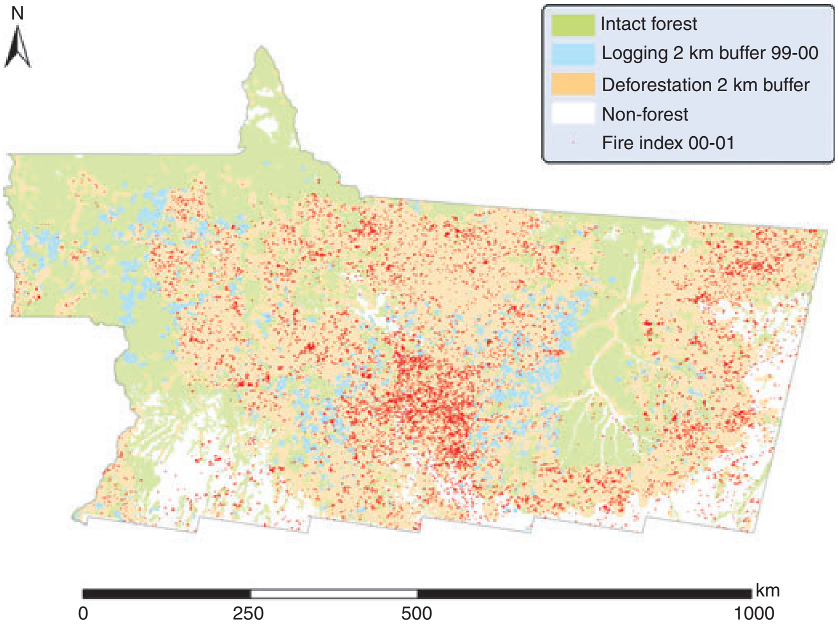


**Fig. 5** Spatial distribution of forest cover (green), deforested land (orange), selective logging extent in 1999–2000 (blue), and the Tropical Rainfall Measuring Mission (TRMM) satellite fire index for the period 2000–01 in the northern portion of Mato Grosso, Brazil.

in the same year of timber harvest and 2.4 (± 0.1) fires per 100 $km^2$ $yr^{-1}$ in subsequent years after harvest (Fig. 5). Thus forest disturbance (not just deforestation) is clearly associated with elevated fire frequency, as highlighted by others previously (Nepstad *et al.*, 1998, 1999; Cochrane & Laurance, 2002; Alencar *et al.*, 2004; Souza *et al.*, 2005).

Despite the difficulties in observing active understory fires from space, rapid advances in burn scar detection have made it possible to link fire to forest degradation. The methods rely on moderate to high spatial resolution data from sensors such as MODIS, Landsat and SPOT. In the first study of its kind in the Brazilian Amazon, Alencar *et al.* (2006) used Landsat imagery to estimate burn scar area in three regions in the states of Para and Mato Grosso (Fig. 6). They found that, during the 1998 ENSO drought, understory burn scars covered an area 13 times larger than in non-ENSO years, or 3.9 million ha compared with just 0.2 million ha. Surprisingly, fires were nearly twice as likely in dense forests compared with more open, fire-tolerant forests during the 1998 ENSO event, whereas the opposite trend was found for non-drought years. This hints at the possibility that drought-enhanced fire might have a disproportionately more negative impact on moist forests, with cascading effects on carbon emissions and biodiversity losses (Fearnside, 2000; Potter *et al.*, 2001; Alencar *et al.*, 2006; Barlow & Peres, 2008). Although this aspect remains speculative, it seems clear that forest fires increase in frequency across a range of forest types and forest conditions during drought in Amazônia.

## Hydrological dynamics

Although not the focus of this paper, we briefly summarize how satellites have improved our insight into climate conditions throughout the Amazon basin. MODIS, AVHRR and even Landsat time-series have provided cloud climatological data that indicate both dry-season and drought occurrence (Asner, 2001; Rickenbach, 2004). Since 1999, TRMM has provided critical spatial information on precipitation throughout the tropics (Haddad *et al.*, 2004).

Beyond these mainstream sensors, other orbital instruments have improved our understanding of hydrological processes in Amazônia, particularly with respect to river extent, volume and flooding associated with dry season and drought conditions across Amazônia (reviewed by Alsdorf & Lettenmaier, 2003; Alsdorf *et al.*, 2007). A number of studies have applied space shuttle and satellite synthetic aperture radar (SAR) to quantify the effects of dry season on the spatial distribution of flooding in the basin (Hess *et al.*, 1995; Mertes *et al.*, 1995; Alsdorf *et al.*, 2000). Sippel *et al.* (1998) used spaceborne 37 GHz microwave radiometer data to quantify inundation extent on the Amazon floodplain. Their results indicate interannual variation in flooded area, with the strong 1983 ENSO event causing a 30–40% decrease in flooded area compared with 1982 and 1984 (non-ENSO years).

Another particularly noteworthy technology has provided novel insight into dry-season and drought effects on Amazon floodplain inundation and extent. High resolution mapping of the Earth's gravity field using the NASA Gravity Recovery and Climate Experiment (GRACE) satellite has been used to quantify the geographic extent and magnitude of changes in the water storage in Amazônia and other tropical regions (Chen *et al.*, 2005). Fig. 7 highlights the enormous seasonal variation in water stocks in the wet season (April) and dry season (October) in the region. These types of newer observations, combined with radar and optical satellite data, will continue to advance our understanding of precipitation dynamics and drought response in the Amazon basin.

## Conclusions

Remote sensing has played a key role in efforts to understand the consequences of drought on ecological, hydrological and land-use processes in the Amazon basin. The major advantage with remote sensing is that the observations are made at a spatial scale and temporal resolution that captures the regional-level effects of drought on forest phenology and canopy stress, fire and hydrological dynamics. The disadvantage is that the apparent responses of vegetation to drought are difficult to validate at a scale that matches the patterns expressed in the satellite observations. As a result, it is often difficult to establish the causal mechanisms contributing to the remotely sensed patterns.

Remote sensing studies over Amazônia have suggested an apparent change in canopy greenness associated with the typical dry season in the eastern portion of the basin. Field and high-resolution remote sensing measurements further suggest that leaf flush is associated with the measured spectral changes, but the data nonetheless remain sparse and unconvincing. In the case of severe drought, the evidence for green-up is tenuous. Interpretation of the patterns in MODIS and AVHRR data remains a challenge because of persistent atmospheric aerosol, water vapor and sub-pixel cloud contamination. Moreover, the course-scale satellite observations provide contradictory results: one AVHRR-based study suggests a negative response to ENSO drought, while at least one MODIS EVI-based study suggests continued or even enhanced green-up during drought. Future studies will continue to grapple with these issues, but the integration of multiple lines of evidence from physiological, disturbance-fire, and hydrological remote sensing observations may help narrow the range of possible interpretations of any individual source of information (*sensu* Anderson *et al.*, 2010). This should continue as a focal research effort given the predictions for major climate changes in

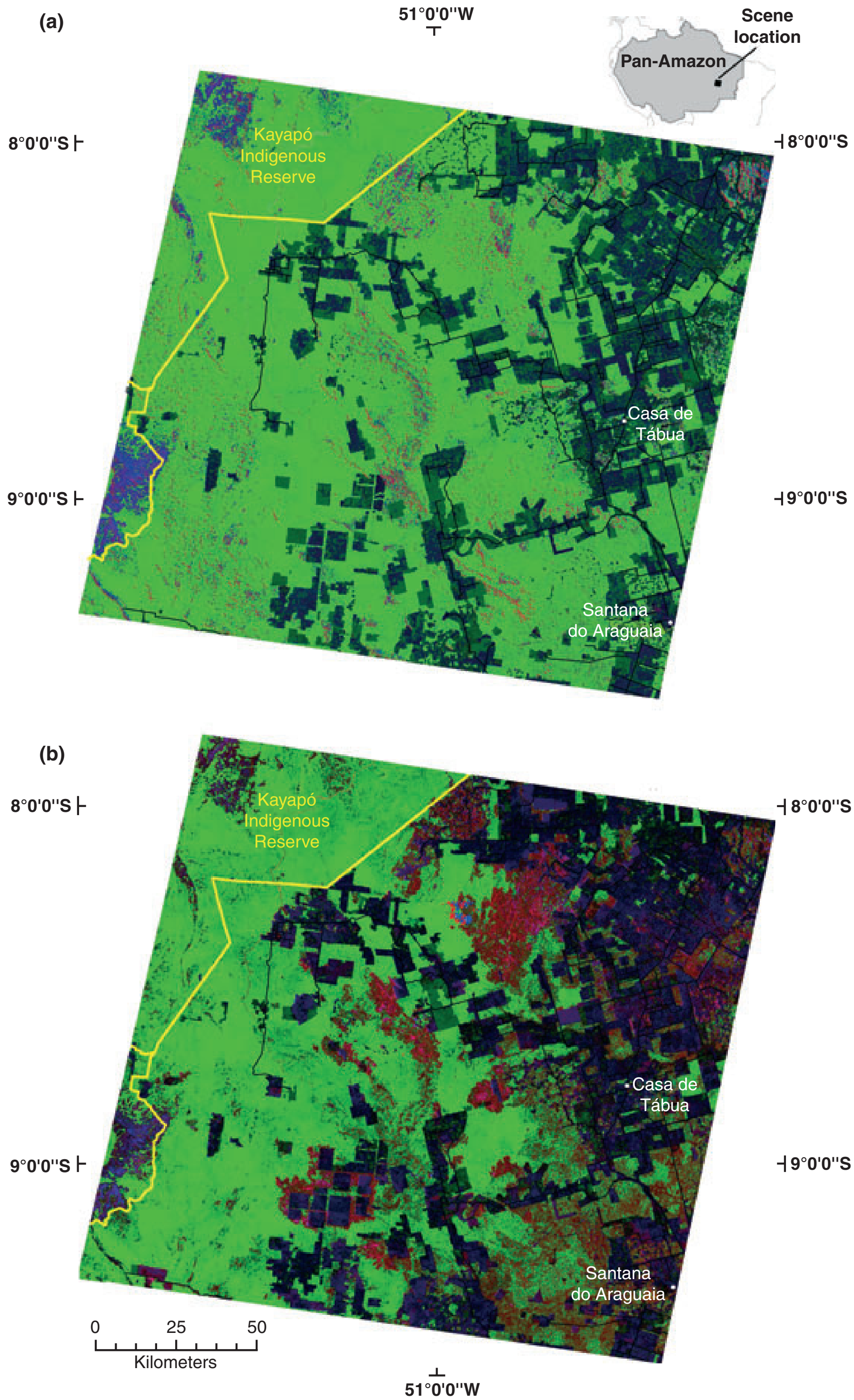


**Fig. 6** False color composite of photosynthetic vegetation (green), nonphotosynthetic vegetation (blue) and burn scars (red) derived from Landsat Thematic Mapper imagery. (a) No forest fire scars during the nonEl Nino–Southern Oscillation (ENSO) 1995 year; (b) shows the forest area affected by fire (in red) during the ENSO 1997 (light red) and 1998 (dark red). Adapted from Alencar *et al.* (2006).

Amazonia and throughout the humid tropics (Cox *et al.*, 2004; Williams *et al.*, 2007).

Fires in deforested areas are more common during drought events, but the most dramatic differences between drought and nondrought years are observed as understory forest fire that is hard to detect from satellites. One emerging solution focuses on detection of burn scars rather than fires directly. This approach has the advantage of working

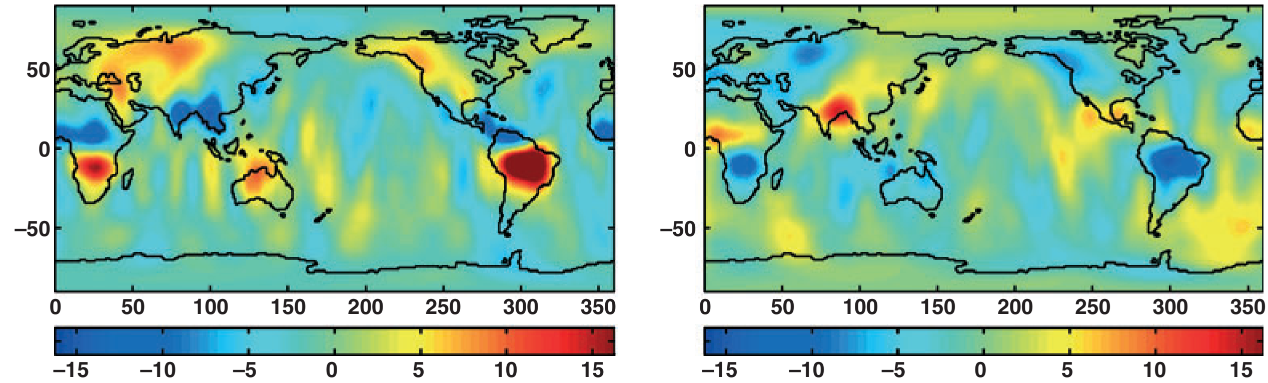


**Fig. 7** Changes in water storage in the wet (April; left panel) and dry (October; right panel) season in Amazonia, derived from the NASA Gravity Recovery and Climate Experiment (GRACE). From Chen *et al.* (2005), reproduced with permission from the America Geophysical Union.

well with Landsat imagery, which has higher spatial resolution than that of AVHRR, MODIS and TRMM. In turn, this allows for more detailed studies of how fire relates to drought and land-use change. Current studies suggest a need for an increased use of these methods to evaluate longer time-series of forest fire occurrence in different parts of Amazônia, especially in the drier eastern compared with the wetter western portions of the basin. In addition, there is a need for increased study of how land-use decisions interact with drought to cause fire. Recent work suggests that continued changes in forest structure and composition results in increased herbaceous cover along forest edges, which increases susceptibility to fire (Balch *et al.*, 2009).

Little controversy seems to exist for basin hydrological remote sensing: the observations show that seasonal variation of flood inundation can be measured using multiple techniques and that drought effects are expressed in satellite observations of flood area and water levels. Still, we found no synthetic studies that bring together multiple satellite observations – for example from microwave, synthetic aperture radar, and gravity sensors – to fully diagnose the effects of drought on basin hydrological flows. This area appears ripe for study.

Future spaceborne sensors will bring far more capable observations to the problem of drought response in the Amazon basin. The European Union and the USA are developing new imaging spectrometer missions which will greatly increase our ability to detect physiological responses to changing climate conditions via high-fidelity measurements of canopy chemistry (e.g. http://hyspiri.jpl.nasa.gov, Stuffler *et al.*, 2006). Spaceborne measurements of forest structure are also rapidly improving (Lefsky *et al.*, 2005; Saatchi *et al.*, 2007), and with the development of the NASA Desdyni mission, monitoring for forest carbon losses and gains will become ever more tractable in the face of climate change in Amazônia. With a trend of decreasing precipitation and continuing episodic drought in the region there is an acute need for these and other spaceborne observations to complement and integrate field and modeling studies.

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