

Response to Comments on “Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009”

Maosheng Zhao* and Steven W. Running

Samanta *et al.* and Medlyn challenge our report of reduced global terrestrial net primary production (NPP) from 2000 through 2009. Our new tests show that other vegetation indices had even stronger negative changes through the decade, and weakening temperature controls on water stress and respiration still did not produce a positive trend in NPP. These analyses strengthen the conclusion of drought-induced reduction in global NPP over the past decade.

We (hereafter ZR10) used satellite data to estimate global terrestrial net primary production (NPP) over the past decade and found that large-scale regional droughts and a general drying trend over the Southern Hemisphere have caused a decline in NPP (*1*). Samanta *et al.* (*2*) and Medlyn (*3*) challenge our results, and their critiques focus on four areas. First, how reliable are spectral vegetation indices for quantifying terrestrial biospheric dynamics and anomalies? Second, can a simple globally generalized carbon balance algorithm using daily incident radiation, temperature, and vapor pressure deficit (VPD) adequately reflect ecosystem physiology of photosynthesis-respiration controls? Third, can ground measurements be used to validate a global-satellite-derived data set? Fourth, was the decadal global trend illustrated in ZR10 significant? We address these issues below.

Samanta *et al.* (*2*) argue that there were not any large-scale declines in global annual mean MODIS vegetation indices [VIs; including the normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), fraction of photosynthetically active radiation (FPAR), and leaf area index (LAI)] over the past decade and concluded there should be no NPP change as well. However, the authors used less precise data processing in two ways. First, because we are quantifying plant growth, we screen out dormant season data [as explained in supporting online material (SOM) text S1] using the Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover data set and process VIs only during the growing season. Samanta *et al.* used annual average VIs, which add many snow-covered pixels with corrupted spectral reflectances. Although they further screened out low values of VIs, some

values above their defined thresholds may still be in dormant seasons, especially for evergreen needleleaf forests.

Second, Samanta *et al.* used the MODIS CMG (Climate Modeling Grid aggregated to 0.05°) rather than the native 1-km data, introducing potential inconsistency to their NDVI and EVI data sets from within cell heterogeneity and making direct comparison with our analysis more difficult. To explore the potential differences in processing details, we replicated their processing of filtering out cloud- or aerosol-contaminated MODIS 1-km VIs and then aggregated reliable VIs into a 0.05° CMG grid (SOM text S1). However, instead of their annual average, we calculated growing-season average reliable VIs [SOM text S1 and (*1*)]. We found that more than 60% (58%) of global vegetated areas had a negative trajectory in NDVI (EVI) for the 2000 to 2009 period (Fig. 1 and Table 1). For the Southern Hemisphere (SH), all VIs show many more areas with significant decreased trends than those with significant increased trends (table S1). The reduced NPP for the tropical rainforests are further confirmed by 40.58% (16.69%) of areas with significant decreased NDVI (EVI) compared with 1.35% (1.86%) with significant increased NDVI (EVI) (table S1 and fig. S2).

Our NPP decadal trend agrees in direction (positive or negative) with each of the three considered spectral VIs over 62.4% of global vegetated land area (Fig. 1 and Table 1). Geographically, the most coherent region of disagreement is central Africa, where the spectral indices show a negative decadal trend but our NPP shows a positive trend. This region has the sparsest density of weather stations in the tropics, so our confidence in the gridded meteorology is low (*4*). However, if the trends in the VIs are more correct, it would strengthen our main conclusion, that NPP has declined over the past decade.

FPAR, an input to the MODIS NPP algorithm, provides essential information on ground vegetation dynamics, and hence its trajectory can

partially influence NPP change. In contrast to the negative trends in NDVI and EVI, the FPAR trend is virtually flat, except in the SH (fig. S2 and table S1). This FPAR anomaly is also exhibited in the 2005 Amazon drought, with 28.5% of rainforests greener versus 16.8% browner over the dry season compared with the previous 5 years over rainforests south of the equator (fig. S4). This FPAR anomaly is different from changes in EVI (*5*) but consistent with our previous report on FPAR [figure S13 in (*1*)]. Despite the weakly positive FPAR anomaly, our NPP captured the reduction of NPP (*6*) because the model incorporates biophysical constraints from meteorological data, suggesting the usefulness of the model. If we had used MODIS NDVI or EVI, instead of FPAR, as an input to our NPP model, global NPP would have exhibited a stronger decadal reduction.

As to the second critique by Samanta *et al.* (*2*), gap-filling or temporally smoothing satellite-based vegetation indices is a common practice and an accepted method for unifying time-series satellite data in cloudy climates (*7*). To calculate annual total MODIS NPP using our model, gap-filling must be employed to fill cloud-contaminated satellite data periods simply because photosynthesis occurs in rainforests during daylight hours regardless of cloud cover (fig. S3).

Samanta *et al.* (*2*) and Medlyn (*3*) argue that our results are an artifact of an overly sensitive temperature dependence in the NPP algorithm because autotrophic respiration and VPD are sensitive to temperature change. Medlyn also suggests that a significant positive correlation between NPP and Palmer Drought Severity Index (PDSI) over the SH is caused by the sensitivity of PDSI to temperature. Plant respiration is sensitive to air temperature (*8, 9*). Our respiration calculation follows the common ecological modeling approach for estimating autotrophic respiration, a Q_{10} function assuming an exponential relationship with temperature in which Q_{10} is the ratio of the rate at one temperature to that at a temperature 10°C lower (*10*). In ZR10 (*1*), we adopted a temperature-corrected Q_{10} for foliage across diverse plant taxa to replace a constant Q_{10} value of 2.0 in earlier algorithms, which had been found to be biased (*10*). A recent global-scale analysis of autotrophic respiration reveals that Q_{10} ranges from 1.9 to 2.5 for forests (*11*). A study of total ecosystem respiration based on data from 60 FLUXNET sites found that Q_{10} averaged ~1.4 (*12*). However, these lower Q_{10} values include heterotrophic respiration from dead tissue, whereas we compute only autotrophic respiration of live tissue.

We performed four sensitivity tests to examine the response of our NPP algorithm to temperature by modifying Q_{10} alone (two tests with constant 2.0 or 1.4) and both Q_{10} (constant 1.4) and daytime maximum VPD (VPD_{max}). VPD_{max} is the threshold where stomatal conductance reduces to zero (two tests with $VPD_{max} = 5000$ or 10,000 Pa) and photosynthesis halts (Table 2 and

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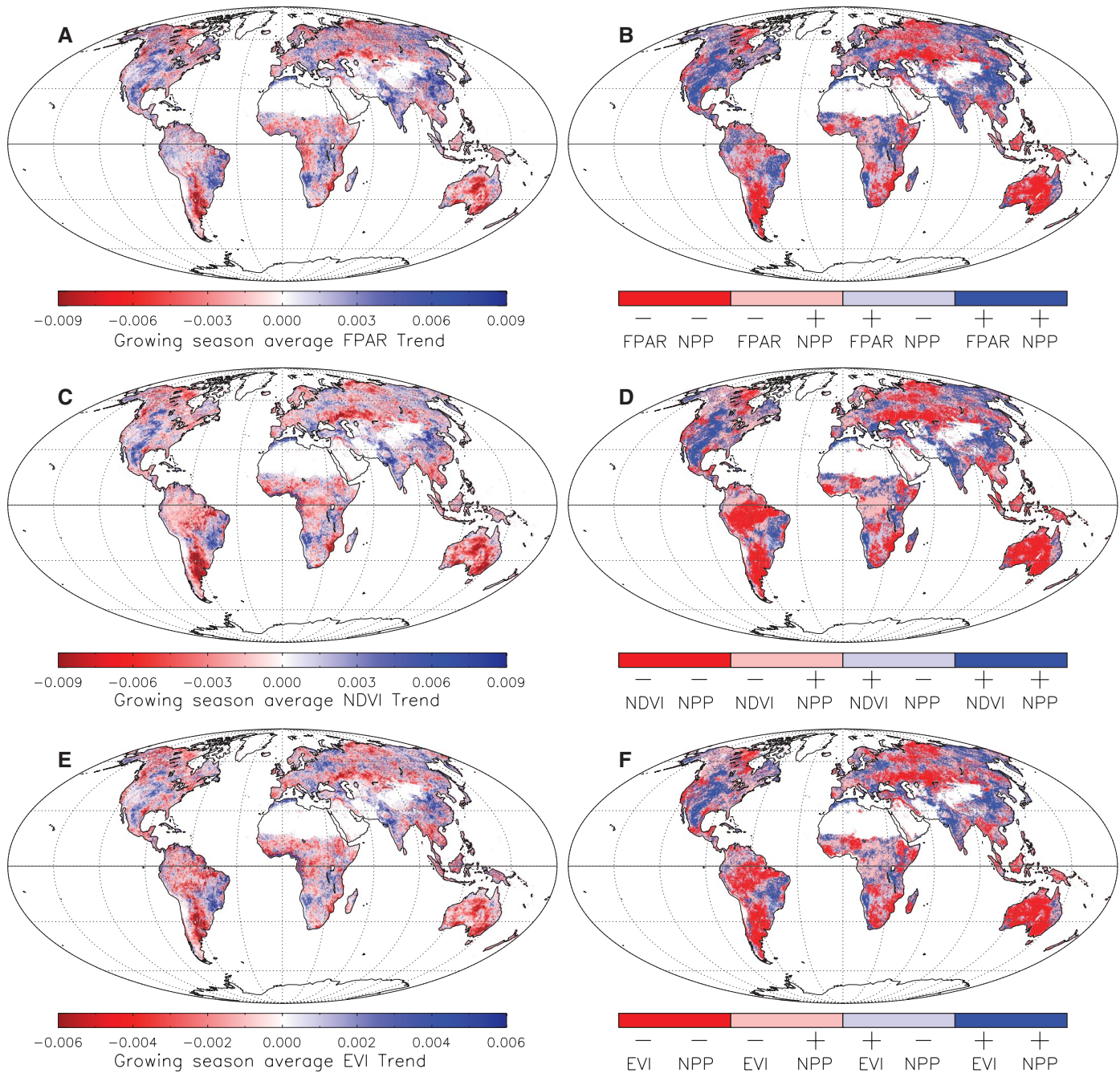


Fig. 1. For the period from 2000 through 2009, the spatial pattern of trends in the growing season average reliable Collection 5 MODIS vegetation indices at 0.05°, FPAR (A), NDVI (C), and EVI (E) and the agreement and disagreement in the change directions between MODIS NPP and FPAR (B), NDVI (D), and EVI (F). For (B), (D), and (F), the plus sign refers to an upward trend, whereas the

minus sign denotes a downward trend. For the three vegetation indices, we followed exactly the same method as used by Samanta *et al.* (2) to screen out contaminated FPAR, NDVI, and EVI by cloudiness and aerosols without temporal filling before calculating growing season average (SOM text S1). Results are listed in Table 1. Spatial pattern of NPP change was shown in Fig. 2 in (1).

Fig. 3). We also performed bootstrap tests for the global total NPP to examine the percentage of negative NPP trends (Table 2). As expected by Medlyn (3), if the respiration and water stress algorithms had weaker temperature dependence, the calculated reduction in NPP would generally decrease. However, none of these parameter combinations produce a positive NPP trend through our time period (Table 2). In addition, relaxed VPD control doesn't necessarily induce a smaller

reduction (Table 2). Relaxed control of VPD and a lower Q_{10} increased average global NPP from 55.1 to 67.6 Pg C/year (Table 2), a value considered unrealistically high by a synthesized ground NPP data set (13) (Fig. 2) and flux towers (14). Our current knowledge of long-term climatic adaptation in respiratory traits of leaves, stems, and roots among diverse plant taxa remain inadequate, as well as scaling these physiological processes to global carbon components (15).

Satellite-based global data sets must be validated against ground data, although one must be acutely aware of the scale mismatches of the data sets. Samanta *et al.* (2) compared isolated pixels from our global MODIS NPP data set with 14 small plots of field-measured NPP taken on various years from one region, the Amazon, and questioned the credibility of our results. However, the authors ignore a number of methodological differences between NPP measured on the ground

and NPP measured by satellite. First, the satellite is radiometrically integrating each entire square kilometer of landscape, whereas their field data directly measures only a few fully forested ha at each study site. The field measures quantified only growth of trees [more than 10-cm diameter

in many cases; see SOM text in (2)], whereas the satellite measurement quantifies growth of all vegetation leaf areas. The field measurements were taken sporadically for various single years, as shown in Table 1 of Samanta *et al.* (2), not annually for the whole period, so

they document no interannual variability [see SOM text in (2)]. Even the field methodologies offered by Samanta *et al.* are very different from plot to plot, because these were not an organized project, yet the authors present no discussion of measurement uncertainty or error.

Beginning in 1996, an exhaustive international effort was made to synthesize and scale published ground-measured NPP data to a data set for validating global carbon models called the Global Primary Production Data Initiative (GPPDI). We evaluated our MODIS NPP using the GPPDI NPP data set (13) (Fig. 2). For all 2335 half-degree cells, MODIS NPP generally agrees well with the GPPDI NPP ($r^2 = 0.8$, $P = 0.00$). Nevertheless, the GPPDI data set represents a single NPP value for each cell with no interannual variability, whereas NPP measures year-to-year variability of $\pm 20\%$ (16). Time series of NPP are best estimated from eddy covariance flux tower data, of which >400 towers exist worldwide, some with 10 to 15 years of continuous data. However, flux towers directly measure net ecosystem CO_2 exchange (NEE), which then must be disaggregated to NPP from carbon cycle principles (14).

As to the remaining critiques by Samanta *et al.*, Phillips *et al.* (6) stated that “These (biomass) losses were driven by occasionally large mortality increases and by widespread but small declines in growth,” a signal more likely quantified by the satellite data than by isolated plot data. Based on table S4 of ZR10 (1), the reduction of NPP in the 2005 drought of the Amazon is 5.56% of the mean NPP from 2000 to 2004. Our spatio-temporally complete satellite-based MODIS NPP data set provides more consistent information on spatial heterogeneity and interannual variability in global NPP than 1 year of field measurements, such as those 14 small plot samples supposedly representing the entire Amazon Basin. Relatively higher VPD and temperatures, as evidenced in our meteorological data, were the likely causes of lower Amazonian NPP in 2006 and 2007 [figure S14 in (1)].

We found previously that as the global land air temperature increased from 1982 to 1999, there was a 6% increase in global NPP, and 80% of that increase came from energy-limited ecosystems (17). In the past decade, water limitations appear to have overtaken energy limitations as the strongest global constraint on NPP. Jung *et al.* (18) found that global evapotranspiration has declined since 1998, with drought impacts con-

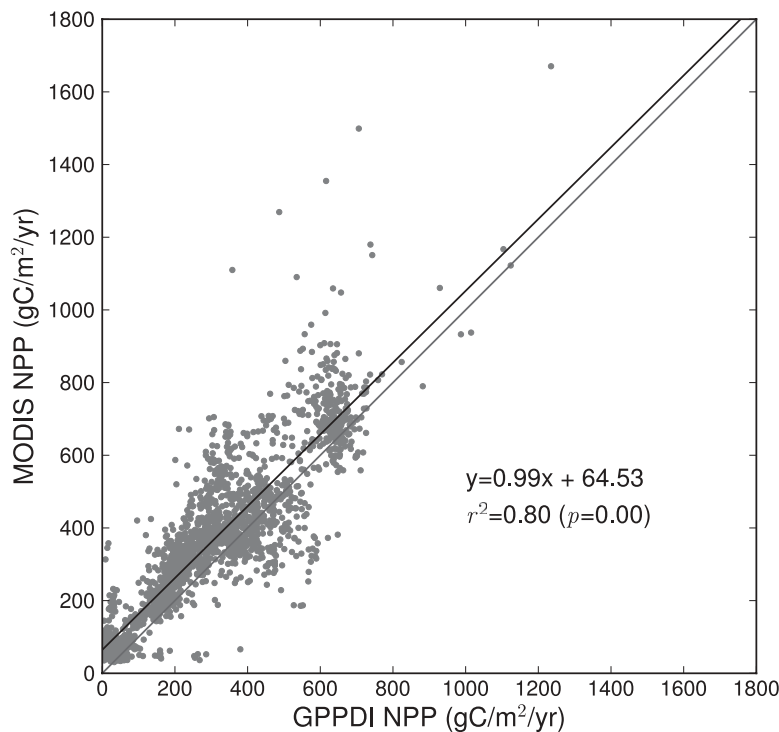


Fig. 2. Comparison of average MODIS NPP from 2000 through 2009 at half-degree scale with 2335 NPP cells from the Global Primary Production Data Initiative (13). The gray line is a slope of 1.0, and the black line is the regression line.

Table 1. Percentage (%) of vegetated land areas with consistent or opposite changes in the Collection 5 MODIS annual NPP and growing season average vegetation indices, FPAR, NDVI, and EVI from 2000 through 2009 (SOM text S1). The plus sign refers to an upward trend, whereas the minus sign denotes a downward trend. Sum shows the total percentage of vegetated land areas with either decreased or increased trends. The consistency in directions refers to the percentage of total land areas with the same direction in changes between NPP and the three different vegetation indices. The corresponding spatial results are shown in Fig. 1.

	FPAR –	FPAR +	NDVI –	NDVI +	EVI –	EVI +
NPP –	29.98	17.24	35.32	11.95	34.11	13.16
NPP +	19.48	33.30	24.92	27.81	24.43	28.30
Sum	49.46	50.54	60.24	39.76	58.54	41.46
Consistency in the directions	63.28		63.13		62.41	

Table 2. Global terrestrial MODIS NPP and its changes (the slope of linear trends) calculated with the control and four sensitivity tests for the period from 2000 through 2009 (SOM text S2). Anomalies are shown in Fig. 3. The percentage

of samples with a negative slope for each calculation is also listed base on 10,000 times of bootstrap resample, each time drawing a sample of equal size to the original dataset and calculating the regression slope from each bootstrap sample.

	Control	Sensitivity 1 ($Q_{10} = 2.0$)	Sensitivity 2 ($Q_{10} = 1.4$)	Sensitivity 3 ($VPD_{\max} = 5000 \text{ Pa}$, $Q_{10} = 1.4$)	Sensitivity 4 ($VPD_{\max} = 10,000 \text{ Pa}$, $Q_{10} = 1.4$)
Average NPP (Pg C/year)	53.39	53.02	55.10	61.07	67.63
NPP trend (Pg C/year)	-0.0552	-0.0548	-0.0061	-0.0141	-0.0187
% bootstraps with negative slopes	76.5	75.5	54.9	67.7	65.9

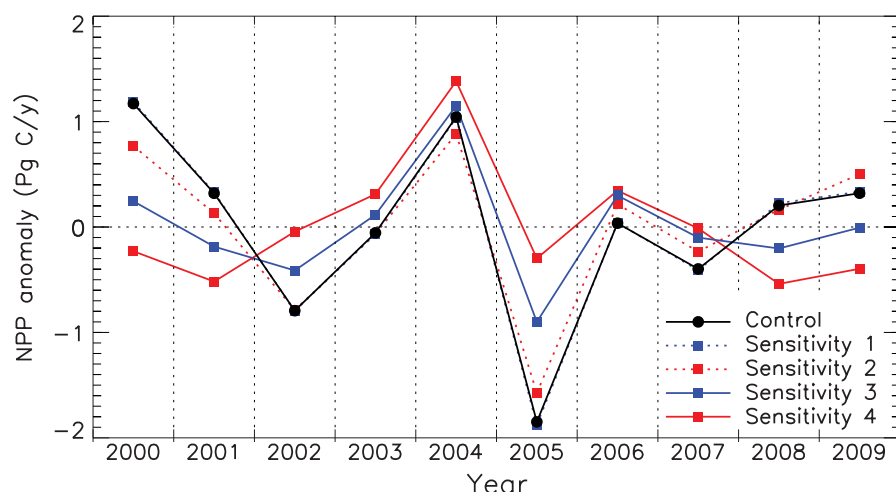


Fig. 3. Interannual variations from 2000 through 2009 in anomalies of annual total global terrestrial NPP calculated with control and four sensitivity tests (SOM text S2): Sensitivity 1 ($Q_{10} = 2.0$), Sensitivity 2 ($Q_{10} = 1.4$), Sensitivity 3 ($VPD_{\max} = 5000$ Pa, $Q_{10} = 1.4$), and Sensitivity 4 ($VPD_{\max} = 10,000$ Pa, $Q_{10} = 1.4$). Control NPP is NPP estimated without these modifications of parameters.

centrated in the Southern Hemisphere, consistent with our PDSI results. Beer *et al.* (14) found that variation in measured global gross primary production was best correlated with precipitation. Recent studies have revealed a persistent drying trend in the Amazon from 2000 to 2005 [Fig. 3 in (19)], and a severe drought occurred again in 2010 (20). Gobron *et al.* (21) evaluated a 1998 to 2009 time series of FPAR from the Sea-Viewing Wide Field-of-View Sensor (SeaWiifs) and Medium Resolution Imaging Spectrometer (MERIS) satellite sensors and confirm independently the recent negative trend in global vegetation activity that we report using the MODIS sensor.

The significant positive correlation between land surface temperature and global CO_2 annual growth rates shown by Samanta *et al.* in fact suggests the negative role of warming temperature in land carbon sink strength. That is, warming

induces drought and high ecosystem respiration that weaken the terrestrial carbon sink, consistent with the conclusion in ZR10 (1). In 2010, severe droughts occurred again in the Amazon and Europe (20, 22), leading to concerns of a possible weakening of terrestrial carbon sinks (20, 1).

In summary, changes in NDVI and EVI and sensitivity tests of our model, as well as other studies, all suggest reduced vegetation activity and NPP from 2000 through 2009. Our continuous monitoring shows that global NPP in 2010 (53.19 Pg C) was lower than that in 2009 (53.84 Pg C), largely due to the two large-scale droughts in the Amazon and Europe. We expect that the strongest impacts of changing climate on terrestrial ecosystem productivity will continue to be manifested through the hydrologic cycle, but whether these current trends continue can only be answered by global monitoring.

References and Notes

1. M. Zhao, S. W. Running, *Science* **329**, 940 (2010).
 2. A. Samanta *et al.*, *Science* **333**, 1093 (2011); www.sciencemag.org/cgi/content/333/6046/1093-c.
 3. B. E. Medlyn, *Science* **333**, 1093 (2011); www.sciencemag.org/cgi/content/333/6046/1093-d.
 4. M. Zhao, S. W. Running, R. R. Nemani, *J. Geophys. Res.* **111**, (G1), G01002 (2006).
 5. A. Samanta *et al.*, *Geophys. Res. Lett.* **33**, L06405 (2010).
 6. O. L. Phillips *et al.*, *Science* **323**, 1344 (2009).
 7. P. Jönsson, L. Eklundh, *Comput. Geosci.* **30**, 833 (2004).
 8. D. A. Clark, S. C. Piper, C. D. Keeling, D. B. Clark, *Proc. Natl. Acad. Sci. U.S.A.* **100**, 5852 (2003).
 9. S. B. Peng *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **101**, 9971 (2004).
 10. M. J. Tjoelker, J. Oleksyn, P. B. Reich, *Glob. Change Biol.* **7**, 223 (2001).
 11. S. Piao *et al.*, *Ecology* **91**, 652 (2010).
 12. M. D. Mahecha *et al.*, *Science* **329**, 838 (2010).
 13. D. Zheng, S. Prince, R. Wright, *Glob. Change Biol.* **9**, 46 (2003).
 14. C. Beer *et al.*, *Science* **329**, 834 (2010).
 15. O. Atkin, H. Millar, M. Turnbull, *New Phytol.* **187**, 268 (2010).
 16. A. K. Knapp, M. D. Smith, *Science* **291**, 481 (2001).
 17. R. R. Nemani *et al.*, *Science* **300**, 1560 (2003).
 18. M. Jung *et al.*, *Nature* **467**, 951 (2010).
 19. P. M. Brando *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 14685 (2010).
 20. S. L. Lewis, P. M. Brando, O. L. Phillips, G. M. F. van der Heijden, D. Nepstad, *Science* **331**, 554 (2011).
 21. N. Gobron, A. Belward, B. Pinty, W. Knorr, *Geophys. Res. Lett.* **37**, L15402 (2010).
 22. D. Barriopedro, E. M. Fischer, J. Luterbacher, R. M. Trigo, R. García-Herrera, *Science* **332**, 220 (2011).
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Supporting Online Material

www.sciencemag.org/cgi/content/full/333/6046/1093-e/DC1
SOM Text

Figs. S1 to S4

Table S1

References and Notes

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