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Biogeosciences Discussions



# *Interactive comment on* "Does terrestrial drought explain global $CO_2$ flux anomalies induced by El Niño?" *by* C. R. Schwalm et al.

**C. R. Schwalm et al.**

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We respond to both interactive comments here as there is considerable overlap between them.

Response to A. Desai (Referee) Interactive comment on "Does terrestrial drought explain global CO2 flux anomalies induced by El Niño?" by C. R. Schwalm et al.

Response to opening comments

Re: Limits on the kinds of interactions between terrestrial carbon uptake and ENSO Analyzing drought in isolation as a causal factor is the key point of the work. This is motivated by the clear teleconnections between ENSO activity and precipitation. We agree that other factors (e.g., changes in growing season length) are worthy of exploration and leave these for future work.

Re: Hotspots and small area sizes We are careful to give the range of response. For example, for $\Delta$biotic < |2.5| g C m-2 month-1 is the rule with only 5 grid cells (out of 12371 vegetated pixels) across 5 El Niño events. While we agree that there are pixels that serve as hotspots for individual events, e.g., fire emissions in Indonesia, our point of reference is consistency across events. There is more consistency in sign but this is a weaker test (see Fig. 1 in original submission) and coincident with a range that spans orders of magnitude. Alternatively, the significant and non-trivial teleconnections do not translate into hotspots across events due to their small magnitude and scarcity. We also note that consistency does not improve with coarser spatial resolution (see below).

Re: A more thorough exposition of prior research We have incorporated additional material on previous research and have revised language in the Introduction.

Response to listed concerns

Re: Link between atmospheric CO2 anomalies and ENSO anomalies 1) We agree with the reviewer about motivating the study using known relationships between MEI and atmospheric CO2 growth rates –this was mentioned by R2 as well. We limit this to the 13-yr analysis period (best case overlap of MERRA, Jena, $\Delta$total, MEI, and Mauna Loa). Across the 13-yr window we did find a clear link between ENSO and the carbon cycle (Fig. 1). For this we related the Mauna Loa CO2 monthly time series to MEI. The Mauna Loa data was deseasonalized and detrended to focus on interannual variability and remove the secular trend associated with industrial loading and fossil fuel emissions. Variability in correlation was linked to lag which represented the time delay needed for changes in CO2 growth rate to reach the Mauna Loa observatory (cf. Patra et al., 2005b). As lag increased, correlation ($p < 0.1$) also generally increased: r = 0.12, 0.41, 0.55, and 0.62 for lags of 3, 6, 9, and 12 months respectively.

Re: The lack of representation in the tropics by FLUXNET 2) We agree with the reviewer that the tropics are underrepresented and added a figure showing global maps showing how well FLUXNET represents various biomes. Our discussion in the original submission was meant in a relative sense. We have followed the reviewer's suggestion to address representativeness and have mapped measurement sites for both networks (Fig. 2A) as well as the intersection of IGBP land cover classes (Loveland et al., 2001) and Köppen-Geiger climate (Peel et al., 2007) used in deriving the sensitivities. This intersection (Fig. 2B) allows the reader to visualize how well the underlying FLUXNET data sampled biome-climate space. Overall both networks clearly undersample the tropics. FLUXNET representativeness is highest in the northern mid-latitudes. Of the 938 available site-years used only ~5% were sourced from the tropics, mostly in evergreen broadleaf forests (EBF). NEE sensitivity in EBF peaked at ~12 g C m-2 month-1 with water deficit ranging from -2.85$\sigma$ to +3.28$\sigma$.

Re: Is FLUXNET representative of drought experienced during a strong positive ENSO? 3) The FLUXNET data used in upscaling are representative. The data was collected between 1991 and 2006, with a majority (~90%) collected between 1999 and 2006. This is comparable to the 1997 to 2009 time window analyzed here. Indeed, many FLUXNET site-years used to derive the sensitivities were spatially and temporally coincident with the examined El Niño events. Similarly, water deficit anomalies in the underlying FLUXNET dataset extended to $\sim\pm3\sigma$ and response magnitudes from nil (e.g., savannas in winter) to 80 g C m-2 month-1 for croplands during climatic summer (Schwalm et al., 2010).

Re: Spatiotemporal correlation and mapping MEI to MERRA to $\Delta$biotic 4) FLUXNET sites showed sensitivity to drought (see above). However, the mapping of MEI to MERRA water deficit anomaly would only carry over directly to the MERRA water deficit anomaly $\sim \Delta$biotic relationship if all three were perfectly correlated. As the correlations were not 1:1 the signal attenuates through successive mappings.

In terms of downscaling, the spatial scale of the MERRA product does not match a footprint. However, as noted by the reviewer, MERRA anomalies were downscaled by land cover type within each grid cell. We note that energy balance closure has no impact on the sensitivities as these are slopes and adjusting for energy balance closure (typically by scaling the fluxes) is a linear transformation of the data cloud that does not alter the slope after the data are normalized as used in sensitivity derivation. We also note that adjusting for energy balance closure is not standard in FLUXNET post-processing (e.g., flux partitioning) so we calculated sensitivities (Schwalm et al., 2010) using the "best estimates" from the La Thuile data compilation.

Re: Scale in the upscaled product 5) The amount of spatiotemporal consistency decreases as grid cell size increases. This occurs for the simple reason that, in the 1x1 case, adjacent pixels cannot act to cancel out the target pixel's response. This is visible using latitudinal bands (Fig. 3) where the overall lack of consistency across events is also evident. More specifically, the large excursion in the tropics for the 1998 event visible in the 1x1 grid attenuates once coarsened to the 3.75x5 grid used for the Jena results (Fig. 3A vs. 3B). Furthermore, consistency does not increase between the top-down and bottom-up approach when comparing both at the 3.75x5 resolution (Fig. 3B vs. 3C). We also test the scale-dependence of consistency by regenerating Fig. 1 from the original submission for $\Delta$biotic at resolutions of 1x1, 3.75x5, 10x10, and 15x15 (Fig. 4A-D). Consistency does not improve as the grid is coarsened. Results are similar for Jena and $\Delta$total (not shown). As such we keep the native resolution for both the upscaled and inversion results. The upscaled fluxes' native resolution is a combination of the land cover map (1x1) and MERRA (2/3 x 1/2 regridded to 1x1 to match the land cover map). Also, the assertion that "there must be some scale where the terrestrial anomalies become more consistent" does not hold because MEI and MERRA water deficit are not perfectly correlated. Recall that the global correlations are based on the native grid resolutions. Alternatively, (see response for #4 above) the signal attenuates from MEI to MERRA to $\Delta$biotic. However, we agree that reconciling the different native resolutions of the upscaled and inversion product has value as this dynamic is not obvious. For the revised manuscript we have coarsened the upscaled $\Delta$biotic product to match the inversion product and now display and discuss both.

Response to minor points

Re: P 4211 Lines 12-13 “I suggest bringing up these papers that DO show consistent responses into the discussion and argue why they are in contrast to your finding.” This concern has two aspects: the first is why top-down and bottom-up do not agree. We address this in the submission. Here we reiterate a key point, namely that the bottom-up approach does not consider any control on CO2 exchange outside of hydroclimate (from FLUXNET) and fire emissions (from GFED). For the Jena results the totality of response is present and the Jena result serves, conceptually, as a limit on the upscaled approach. The second aspect is why previous reports investigating the El Niño-CO2 flux links using inversion frameworks do not agree with the Jena results shown here.

Regarding discrepancy across inversion studies: (i) The well-sourced teleconnections between ENSO activity, the water cycle, and carbon flux anomalies, which we replicate, do not translate into a majority of variance explained in a least-squares sense. This is discussed in the original submission (text dealing with Figure 6 in the original submission) and is not unprecedented. Using the Patra et al. (2005a) study from 1994 to 2001 as a comparative baseline we note that only one of the 11 land regions evaluated there exhibited a correlation that translated into at least 50% variation explained (Tropical Africa at r = 0.71 with a 3-month lag → r2 = 0.5041 or 50.41% variation explained). (ii) There are studies that show both anomalous sources and sinks during El Niño years (e.g., Bosquet et al., 2000). The findings presented here are not unprecedented. We contend that the underlying mechanisms involved are not resolved, similar to the ongoing debate on whether the dry season (or drought) in the Amazon elicits an increase in CO2 uptake or not. This debate (mentioned in R2 as well) is also relevant for this study as the tropics dominate interannual variability of global CO2 flux.

Re: P4214 Line 12 on uncertainty in IGBP landcover There is no uncertainty product for the IGBP land cover product per se. Various investigators have published accuracy assessments. These range from 59% to 90%, but do not translate into $\sigma$land cover. See http://edc2.usgs.gov/glcc/globdoc2_0.php#valid for an overview. We agree that



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rigorous uncertainty estimates for such gridded data products are highly useful but note that such an effort is a study with a large field component in its own right and beyond the scope of this paper.

Re: Fig. 3 Inset This was removed prior to submission but the figure legend was not correspondingly updated. There is no inset and the legend has now been fixed.

Response to Anonymous Referee #2 Interactive comment on “Does terrestrial drought explain global CO2 flux anomalies induced by El Niño?” by C. R. Schwalm et al.

Response to major comments

Re: “a more appropriate biogeochemical modelling study” Our intent was to stay as close to data as possible and use the top-down Jena estimate as a counterpoint. We agree that biogeochemical model studies can help disambiguate controlling factors on CO2 exchange. But here we focus on extending the observed kernel of information encoded in FLUXNET. We focus on the link between hydroclimatic anomalies (drought), El Niño, and coincident carbon flux anomalies. We agree that light, temperature, and other factors are important and will assess such influences in future work.

Re: Jena inversion sites and scale The 3.75x5 boxes are a raw product and baseline output from the Jena inversion. We are, similar to R2, skeptical of fine scaled flux retrievals based on inversions. However, our results would have no credibility if we did not compare the bottom-up approach with top-down inversion estimates. We do this at multiple scales, from the native grid resolution to global aggregates. We agree that the inversion network would benefit from more continental sties. We have added a map of Jena inversion sites as suggested (see below).

Re: “fundamental limitations of the various data sources” ENSO exerts a strong influence on global precipitation patterns, so we wanted to focus on drought in isolation as a causal factor. We do not conclude from the $\Delta$biotic analysis that El Niño events do not induce terrestrial emissions but rather that El Niño events do not consistently



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induce terrestrial emissions due solely to hydroclimatic fluctuations as represented by water deficit, a robust drought metric (see Conclusion). Light, temperature, and other sources of flux anomalies could still have some influence that is not present in the water deficit metric and we plan to assess such influences in future work.

We agree that inversions are limited by the $CO_2$ sampling network. There are well known issues with inversions not being able to resolve sub-continental spatial patterns, e.g., Gurney et al. (2003). We only use 3.75x5 boxes as a standard output from the Jena inversion results. The ambiguity in response is however not scale-dependent (see above response to R1's comment #5).

We feel that basic statistical rigor is vital to our results and use the student t-test to determine statistical significance for the correlations reported. We agree that representativeness is also vital. To aid the reader in visualizing the representativeness of the FLUXNET and inversion networks we have included maps of both here (see above response to R1's comment #2) and in the revised submission.

We address a well-defined question, namely: Does terrestrial drought explain global $CO_2$ flux anomalies induced by El Niño? The purpose of the work is not to provide a new roadmap and set of insights about how to compare various data products. We contend that any such insights are context-driven, i.e., what works in one setting is likely not appropriate in a different one relative to the research question being addressed.

Re: $CO_2$ concentration anomaly We have included $CO_2$ concentration anomaly in our presentation. This was suggested by R1 as well and we refer the reader to our response above.

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Gurney, KR et al. (2003) TransCom 3 $CO_2$ inversion intercomparison: 1. Annual mean control results and sensitivity to transport and prior flux information. Tellus, Ser. B, 55, 555-579.



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Patra PK et al. (2005a) Role of biomass burning and climate anomalies for land-atmosphere carbon fluxes based on inverse modeling of atmospheric CO2. Global Biogeochem. Cycles, 19, GB3005, doi:10.1029/2004GB002258.

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Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci., 11, 1633-1644.

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Figure Legends [see also supplement]

Figure 1. Temporal profiles of CO2 atmospheric growth rate and MEI from 1997 – 2009. Monthly time series show MEI (red) and CO2 growth rate (green). Year label is centered on June-to-August. Grey background indicates El Niño event.

Figure 2. Inversion and FLUXNET measurement sites. Panel A: Location of FLUXNET (green circles) and inversion (red squares) sites used in this study. Panel B: Representativeness of FLUXNET. Values are from a mapped cross-tabulation of site-years by Köppen-Geiger climate (Peel et al., 2007) and IGBP land cover class (Loveland et al., 2001). Non-vegetated and non-sampled areas shown in white.

Figure 3. Latitudinal profiles of global flux anomaly. Panel A: Profile of $\Delta$total ($1^\circ$ x $1^\circ$) for 5 El Niño events from 1997 – 2009. Panel B: as Panel A but coarsened to $3.75^\circ$ x $5^\circ$ to match the Jena inversion grid. Panel C: Profile of Jena inversion NEE anomaly ($3.75^\circ$ x $5^\circ$) for 4 El Niño events from 1997 – 2008. Legend and color coding show starting year of El Niño events. Note change of scale for $\Delta$total vs. Jena results. A

positive sign indicates increased outgassing of $CO_2$ to the atmosphere.

Figure 4. Consistency of Δbiotic sign across 5 El Niño events from 1997 – 2009. Panels differ only in resolution. Panel A: 1° x 1°. Panel B: 3.75° x 5°, matches Jena inversion grid. Panel C: 10° x 10°. Panel D: 15° x 15°. Legend numbers indicate the number of events out of all 5 with the relevant sign. Non-vegetated grid cells and those with signs split 2 to 3 shown in white. A positive sign indicates increased outgassing of $CO_2$ to the atmosphere.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/8/C2166/2011/bgd-8-C2166-2011-supplement.pdf

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Interactive comment on Biogeosciences Discuss., 8, 4209, 2011.

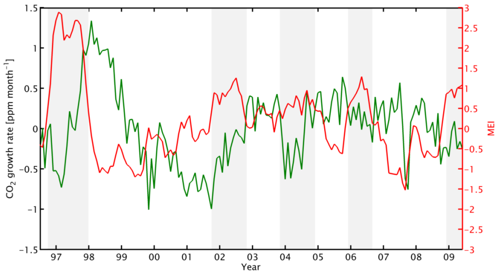


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**Fig. 1.** Temporal profiles of CO2 atmospheric growth rate and MEI from 1997 – 2009.



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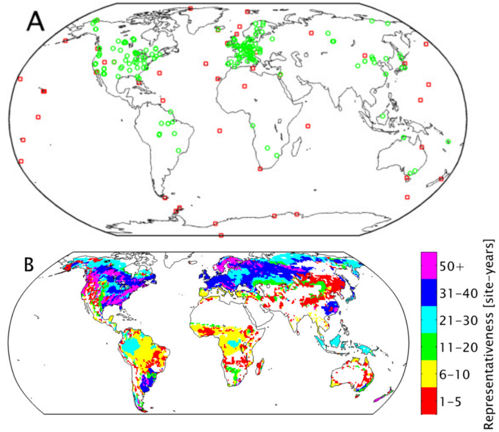


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**Fig. 2.** Inversion and FLUXNET measurement sites.



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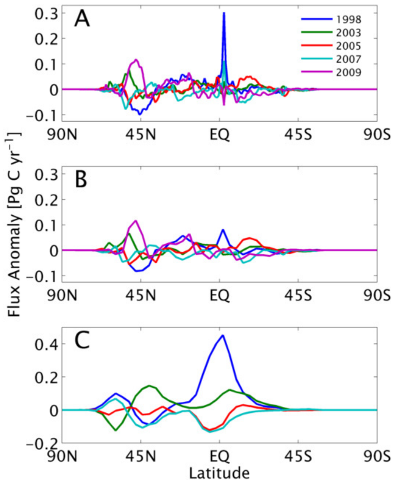


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**Fig. 3.** Latitudinal profiles of global flux anomaly.

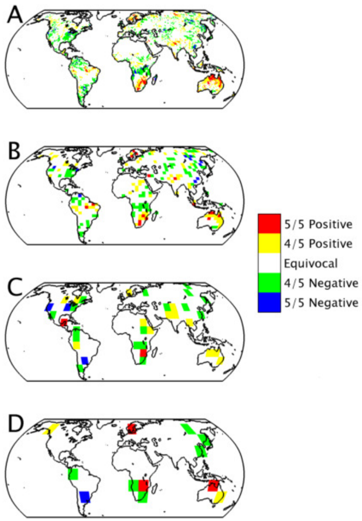


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**Fig. 4.** Consistency of Δbiotic sign across 5 El Niño events from 1997 – 2009.