Extreme late-summer drought causes neutral annual carbon balance in southwestern ponderosa pine forests and grasslands

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Abstract

We assessed the impacts of extreme late-summer drought on carbon balance in a semi-arid forest region in Arizona. To understand drought impacts over extremes of forest cover, we measured net ecosystem production (NEP), gross primary production (GPP), and total ecosystem respiration (TER) with eddy covariance over five years (2006–10) at an undisturbed ponderosa pine (*Pinus ponderosa*) forest and at a former forest converted to grassland by intense burning. Drought shifted annual NEP from a weak source of carbon to the atmosphere to a neutral carbon balance at the burned site and from a carbon sink to neutral at the undisturbed site. Carbon fluxes were particularly sensitive to drought in August. Drought shifted August NEP at the undisturbed site from sink to source because the reduction of GPP (70%) exceeded the reduction of TER (35%). At the burned site drought shifted August NEP from weak source to neutral because the reduction of TER (40%) exceeded the reduction of GPP (20%). These results show that the lack of forest recovery after burning and the exposure of undisturbed forests to late-summer drought reduce carbon sink strength and illustrate the high vulnerability of forest carbon sink strength in the southwest US to predicted increases in intense burning and precipitation variability.

S Online supplementary data available from stacks.iop.org/ERL/8/015015/mmedia

1. Introduction

Climate in the southwest US is expected to become warmer and drier and include more frequent and severe droughts in the future (Seager *et al* 2007, Overpeck and Udall 2010). Projected future changes for this region include less winter precipitation, greater variability of summer precipitation, and a northward shift in distribution of monsoon rains that may reduce late-summer precipitation (Kim 2002, Cook *et al* 2004, Hamlet *et al* 2005). This potential reduction in late-summer monsoon precipitation could alter ecosystem carbon fluxes because late-summer rains typically supply about 30% of annual precipitation in the region (Sheppard *et al* 2002) and net carbon balance of forests in the region has been estimated to be highly sensitive to drought (Yi *et al* 2010, Schwalm *et al* 2012).

Impacts of late-summer drought on forest carbon fluxes are poorly understood for the southwest US. Dendrochronology studies of dominant trees in southwestern forests suggest stronger control over annual tree production by winter precipitation than summer precipitation (Fritts 1966, Adams and Kolb 2005, Stahle *et al* 2009) perhaps because winter precipitation is more effective at recharging deep soil layers where trees acquire most of their water (Kerhoulas *et al* 2013). Yet, the often-reported positive relationship between tree latewood ring width and late-summer precipitation (Meko and Baisan 2001, Stahle *et al* 2009) suggest an influence of summer precipitation on productivity. Moreover, ecosystem respiration fluxes are well-known to be controlled by environmental and biotic changes during drought (Luo and Zhou 2006). For example, soil respiration, a major component of total ecosystem respiration (Goulden *et al* 1996, Law *et al* 1999), is positively related to soil water content, soil temperature (Sullivan *et al* 2008, 2011) and plant production (Janssens *et al* 2001, Irvine *et al* 2007).

Here, we use five years (2006–10) of data on net ecosystem production (NEP), gross primary production (GPP) and total ecosystem respiration (TER) produced via eddy covariance measurements to understand impacts of extreme late-summer drought that occurred in 2009 on carbon balance of ponderosa pine forests in the southwestern US These forests are increasingly being exposed to intense burning that kills many trees and can covert forest to grass/shrubland (Savage and Mast 2005, Roccaforte *et al* 2012) that has low carbon sink strength for decades (Dore *et al* 2008, Ross *et al* 2012). Thus, the analysis includes an undisturbed densely forested site and a fire-disturbed former forest that was converted to grass/shrubland after burning in order to facilitate understanding of drought impacts over extremes of forest cover that occur in the region.

2. Methods

Our analysis focused on late-summer drought in 2009, which was an extreme climatic event in the southwestern US. In 2009, annual precipitation measured at a regional weather station near our study sites (29.6 cm) was 53% of the long-term average (55.5 cm) because of unusually low late-summer rain (supplementary figure S1 available at stacks.iop.org/ERL/8/015015/mmedia). In addition 2009 was unusual in having greater precipitation in May (5 cm) than normal (2 cm). Cumulative July–August precipitation in 2009 was 4.5 cm, which was 31% of the long-term average, and was the lowest cumulative precipitation for these months in the last 30 years (supplementary table S2 available at stacks.iop.org/ERL/8/015015/mmedia). Low late-summer precipitation in 2009 was mostly caused by lack of rain in August, which in 2009 was the lowest precipitation for this month in the last 30 years. Extreme late-summer drought in 2009 is well documented by the Palmer Moisture Anomaly Index (PMAI), which is a measure of departure from normal of the moisture climate for a month that is more sensitive to short-term drought than the standard Palmer Drought Severity Index (Karl 1986, Heim 2000). The PMAI for the study site region in

2009 was the most severe in the last 30 years in August and the second-most severe in July (supplementary table S2 available at stacks.iop.org/ERL/8/015015/mmedia). Air temperature in 2009 was higher than normal. Annual temperature in 2009 was 1.2 °C above the 30-year average, and 2009 was the second warmest year in the last 30 years. Temperatures in July and August 2009 were warmer than average by 1.1 and 0.4 °C, respectively, which ranked as the 6th (July) and 12th (August) warmest in the last 30 years.

We used five years of carbon flux and environmental data collected from 2006 to 2010 at an undisturbed densely forested site (UND) and at a similar formally forested site that burned in an intense fire over a decade before our measurements (BUR). The sites were located about 35 km apart near Flagstaff, Arizona, USA on similar basalt-derived clay-loam soils. The UND site was a ponderosa pine stand (35°5′20.5″N, 111°45′43.33″W, elevation 2180 m a.s.l.) that was excluded from silvicultural treatments and fire over the last century. During the five years of our measurements at the UND site projected leaf area index ranged between 2.3 and 2.4 m^2 m^{-2}, tree basal area ranged between 29 and 32 m^2 ha^{-1}, and tree density at the start of the study averaged 853 trees ha^{-1} (Dore *et al* 2010). The BUR site was part of a 10 500 ha area (35°26′43.43″N, 111°46′18.64″W, elevation 2270 m a.s.l.) burned by intense fire in 1996. The fire killed all trees in the stand that, prior to the fire, had similar tree density and basal area as the UND site (Dore *et al* 2010). More than a decade after the fire, vegetation of the BUR site lacked trees and consisted of grasses, forbs and shrubs, with average ground cover of 40% vegetation, 50% bare soil and 10% snags and logs (Montes-Helu *et al* 2009). Seasonal maximum leaf area index at the BUR site occurred in September and ranged between 0.6 and 1.1 m^2 m^{-2} over the five years of the study. More details about the sites and measurements have been reported by Dore *et al* (2010, 2012).

We measured carbon fluxes simultaneously at both sites with the eddy covariance technique (Aubinet *et al* 1999) using identical systems, data acquisition, processing, analysis and quality assessment described by Dore *et al* (2008, 2010). For the measurements, we used a 3D sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) and a closed path CO_2 and water analyzer (Li-7000, Li-Cor, Lincoln, NE, USA), with additional air and soil meteorological measurements, all recorded at 30 min intervals. To quantify annual fluxes, we applied different combinations of gap-filling and data filtering described in Dore *et al* (2008). Quality-filtered, quality- and u^*-filtered, and only u^*-filtered data were gap-filled using look-up tables and non-linear regressions (Moffat *et al* 2007). We used variation among estimates from different gap-filling procedures to estimate total uncertainty in annual ecosystem fluxes as standard deviations because gap-filling approaches contributed the most to total uncertainty (Dore *et al* 2010). We used a negative sign to indicate carbon uptake by the ecosystem (atmospheric perspective), and NEP to indicate monthly or annual sums of instantaneous net ecosystem exchange (Chapin *et al* 2006). GPP was calculated as daytime NEP + TER; TER was measured during the night and was calculated during the day from the night time relationship of

good quality data with soil temperature, and using look-up tables (Falge *et al* 2001).

We examined relationships between annual and monthly sums of carbon fluxes (NEP, GPP, TER) and drought indices for each site using scatter plots and regressions. We used four drought indices to examine the robustness of these relationships because drought indices often differ in underlying biophysical drivers and temporal scale (Heim 2000). The first drought index was monthly PMAI obtained from the National Climatic Data Center for Arizona Climatic Division 2, which includes both study sites. The second index was late-summer (July–August) precipitation measured directly at both sites with automatic sensors; we did not use all directly measured precipitation data in our analyses due to sensor failure during several cold periods at the sites. The third index was average monthly vapor pressure deficit (VPD), which was calculated for each site based on site-specific measurements of air humidity and temperature. Because of the difference in spatial scale between eddy covariance measurements and our measurements of soil water content with a small number of sensors, we calculated a fourth index, $\alpha = \lambda E / \lambda E_{\mathrm{eq}}$. This index expresses water availability at the ecosystem scale as the ratio of measured latent heat (λE) to a theoretical, equilibrium, non-water-limited latent heat (λE_{eq}) estimated using the Priestly–Taylor Model (Baldocchi and Xu 2007). We calculated alpha at each site on a daily basis as $(S+\gamma)/S \cdot (1+\beta)$, where S as the slope of the saturation vapor pressure versus temperature, γ the psychometric constant, and β the daily Bowen ratio. Alpha was based on β instead of net radiation to avoid the inclusion of any energy closure imbalance into the calculation (Krishnan *et al* 2006). We summed alpha for each warm-season (April–October) month in each year and site as an index of ecosystem-level water availability. We present linear regression lines, slopes, and R^2 values for all relationships to show trends in the response of carbon fluxes to temporal variation in drought indices, and also present p values for regressions that had large sample sizes (>5), such as monthly data pooled over all warm months. We used SigmaPlot and JMP software to perform the regressions.

3. Results

Annual NEP varied over the five years of data collection at both sites. The unmanaged site (UND) was a carbon sink in all years (negative NEP with our sign convention). NEP at the UND site ranged between high values of -174 g C m^{-2} yr^{-1} in 2006 (figure 1(A)) and -170 g C m^{-2} yr^{-1} in 2010 (figure 1(E)) to a low value of -19 g C m^{-2} yr^{-1} in 2009 (figure 1(D)). In contrast, the burned site (BUR) was a carbon source to the atmosphere in all years. NEP at the BUR site ranged between a high value of 108 g C m^{-2} yr^{-1} in 2006 (figure 1(A)) to a low value of 27 g C m^{-2} yr^{-1} in 2009 (figure 1(D)).

The time series of cumulative carbon fluxes (figure 1) provides insight into the impact of the late-summer 2009 drought on NEP. At the UND site cumulative NEP increased (became more negative) between July and October in all years

except 2009 when cumulative NEP decreased (became less negative) (figure 1(D)). The decrease in NEP at the UND site between July and October in 2009 was caused mostly by decreased GPP. Cumulative GPP at the UND site in 2009 (figure 1(D)) slowed substantially by the middle of summer whereas TER continued to increase during this period. Annual GPP at the UND site was lowest in 2009 (-841 g C m^{-2} yr^{-1}; 90% of 5-year mean) among all years, whereas annual TER in 2009 was the second lowest (839 g C m^{-2} yr^{-1}; 99% of 5-year mean). At the BUR site, cumulative NEP became more positive after late-summer rains in all years except 2009 (figure 1(D)) when cumulative NEP remained near zero. Both GPP and TER at the BUR site were lowest in 2009 among all years (GPP: -350 g C m^{-2} yr^{-1}, 91% of 5-year mean; TER 383 g C m^{-2} yr^{-1}; 86% of 5-year mean).

Plots of annual carbon fluxes versus mean July–August PMAI for the study site region show that extreme late-summer drought in 2009 forced site carbon balance towards neutrality at both sites (figure 2). Specifically, carbon sink strength of the UND site decreased in response to extreme PMAI; carbon source strength of the BUR decreased in response to extreme PMAI. This decrease in carbon sink strength at the UND site was driven more by a decrease in GPP (figure 2(B)) than a change in TER (figure 2(C)) based on the regression slopes. In contrast, decrease in carbon source strength at the BUR site in 2009 was driven more by a decrease in TER (figure 2(C)) than by a change in GPP (figure 2(B)).

Carbon fluxes in August, which had a large influence on annual carbon flux at both sites (figure 3), were particularly sensitive to late-summer drought. Plots and regressions of August NEP versus August regional PMAI show that extreme late-summer drought in 2009 shifted NEP at the UND site from sink to source, whereas August NEP at the BUR site shifted from a weak source to almost neutral (figure 4(A)). Responses of August GPP and TER to August PMAI show that the late-summer shift from sink to source at the UND site (figure 4(A)) was caused by a larger reduction in GPP (figure 4(E)) than TER (figure 4(I)). The shift from source to neutral NEP in August at the BUR site (figure 4(A)) was caused by a larger decrease in TER (figure 4(I)) than GPP (figure 4(E)). Results from using one regional PMAI for both sites are consistent with results based on summer precipitation measured directly at each site (figures 4(B), (F), (J)).

Vapor pressure deficit (VPD) also was extreme in late summer 2009. Mean August VPD for the non-drought years of 2006–8 and 2010 ranged between 0.78 and 0.95 kPa at the UND site and between 0.82 and 0.95 kPa at the BUR site. In contrast, in the drought year of 2009 mean August VPD was 1.67 kPa at the UND site and 1.40 kPa at the BUR site. Response of August NEP to August VPD differed between sites. At the UND site NEP switched from sink to source in response to high VPD (figure 4(C)). In contrast, this response at the BUR site was muted and opposite in direction to the UND site. At the UND site the switch in August NEP from sink to source was due to a larger decrease in GPP (figure 4(G)) than TER (figure 4(K)). The muted response of August NEP to high VPD at the BUR site was caused by approximately equal reductions in GPP (figure 4(G)) and TER (figure 4(K)).
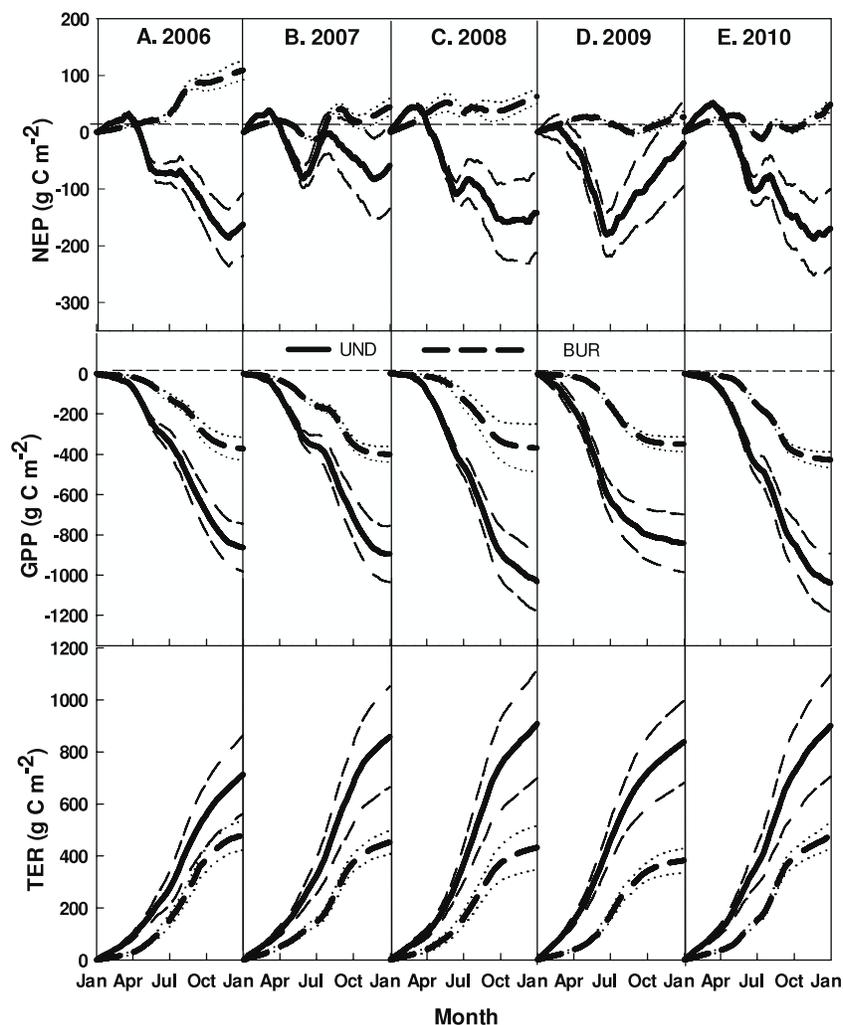
Figure 1. Cumulative ecosystem carbon fluxes (± standard deviation) for years 2006 (A), 2007 (B), 2008 (C), 2009 (D), and 2010 (E) at the undisturbed (UND, solid line) and burned (BUR, heavy dashed line) sites. Carbon fluxes are net ecosystem production (NEP), gross primary production (GPP), and total ecosystem respiration (TER). Positive values indicate ecosystem carbon loss and negative values indicate carbon uptake.

The index of ecosystem water availability based on eddy covariance measurements of water and energy balance at each site, cumulative alpha, showed unusually low water availability in late summer of 2009 at both sites (supplementary figure S3 available at stacks.iop.org/ERL/8/015015/mmedia). Relationships between August carbon fluxes and August cumulative alpha (figures 4(D), (H), (L)) were similar to relationships for August PMAI (figures 4(A), (E), (I)) and precipitation (figures 4(B), (F), (J)). In response to low cumulative alpha in August 2009, August NEP shifted from sink to source at the UND site and from weak source to neutral NEP at the BUR site.

Relationships between carbon fluxes and cumulative alpha in August (figures 4(D), (H), (L)) were consistent with relationships between cumulative monthly carbon fluxes and alpha for the warm months of April through October over the five measurement years (figure 5). NEP at the UND site shifted from sink to about neutral in response to a decrease in cumulative alpha ($p = 0.005$; figure 5(A)) whereas NEP at

the BUR site was not strongly affected by cumulative alpha ($p = 0.35$). The decrease in NEP at the UND site in response to decreased cumulative alpha was due to a larger decrease in GPP ($p < 0.0001$, figure 5(B)) than TER ($p = 0.02$, figure 5(C)). The muted effect of cumulative alpha on NEP at the BUR site was due to roughly offsetting reductions in GPP ($p = 0.01$, figure 5(B)) and TER ($p = 0.0004$, figure 5(C)).

4. Discussion

The drought caused by lack of late-summer rains in year 2009 was an extreme climatic event in the southwestern US. Long-term climate data show that rains in July and August typically supply about one third of annual precipitation in the region of our study sites, whereas in 2009 they supplied only 15% of annual precipitation. The extreme late-summer drought in 2009 occurred following below-average precipitation the preceding winter and above-average precipitation in May,
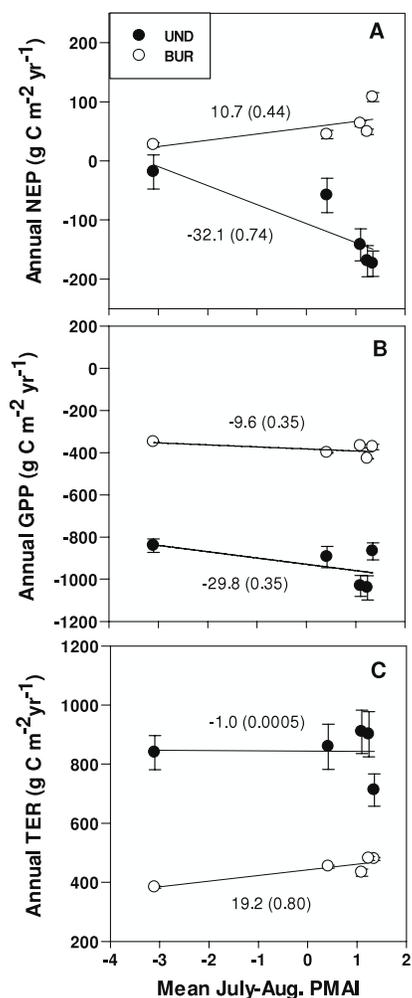
Figure 2. Annual net ecosystem production (NEP; (A)), gross primary production (GPP; (B)), and total ecosystem respiration (TER; (C)) for five years (2006–10) in the undisturbed (UND, filled symbols) and burned (BUR, open symbols) sites versus average July–August Palmer moisture anomaly index (PMAI) for Arizona Region 2. The mean anomaly index value for 2009 was extreme at −3.1. The slope (R^2) is shown for each regression line.
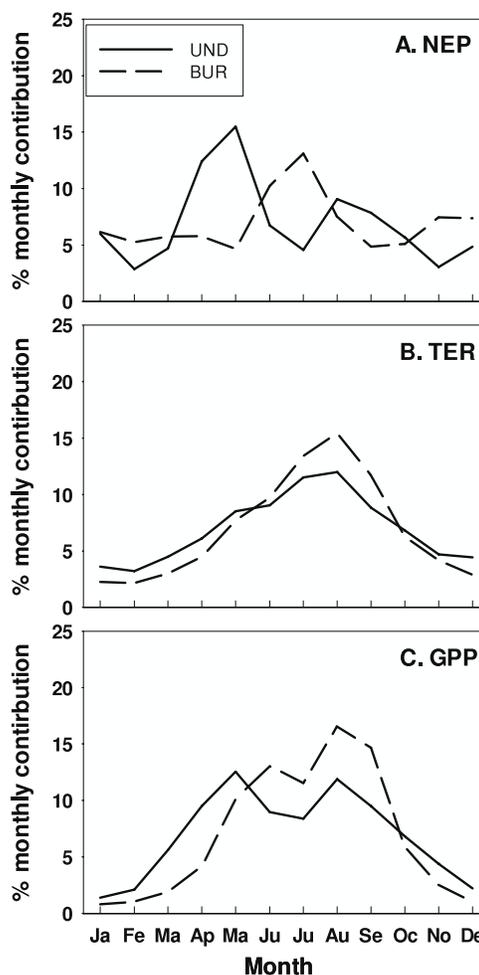

Figure 3. Average per cent monthly contribution to net ecosystem production (NEP; (A)), gross primary production (GPP; (B)), and total ecosystem respiration (TER; (C)) at the undisturbed (UND, solid line) and burned (BUR, dashed line) sites over all years of the study (2006–10).

which also likely affected carbon fluxes in 2009. Overall, the late-summer drought of 2009 is an example of unusual weather and intense drought that are predicted to increase in the study region with continued climate warming (Kim 2002, Cook *et al* 2004, Seager *et al* 2007, Overpeck and Udall 2010).

Impacts of extreme late-summer drought on carbon fluxes varied with forest disturbance in our study. The impact of late-summer drought on annual NEP was larger at the densely forested UND site than at the BUR site, where intense burning killed all trees and converted dense forest to sparse grassland a decade before the start of our measurements (Dore *et al* 2008). The UND site was an annual carbon sink (NEP −80 to −174 g C m^{-2} yr^{-1}) in the three wetter years prior to 2009, but shifted to an almost neutral carbon balance in 2009 (NEP −19 g C m^{-2} yr^{-1}). This shift from annual carbon

sink to neutral balance at the UND site was driven by a decrease in GPP and not a change in annual TER, which was similar for all years. Loss of carbon sink strength during severe drought at the UND site in our study is consistent with reports for severe droughts in other temperate regions (Ciais *et al* 2005, Zeng *et al* 2005). In contrast, temporal variation in annual NEP at the BUR site was smaller than at the UND site. Annual NEP at the BUR site shifted from being a weak carbon source in the wetter years prior to 2009 (NEP 40–100 g C m^{-2} yr^{-1}) to an almost neutral balance in 2009 (NEP 29 g C m^{-2} yr^{-1}). This small shift at the BUR site was driven largely by a reduction in annual TER rather than a change in GPP. These results suggest that extreme late-summer drought produced near-neutral carbon balance at each site via water-stress limitations on the dominant carbon flux at each site, which was photosynthesis at the UND site and respiration (TER), especially heterotrophic respiration, at the BUR site.
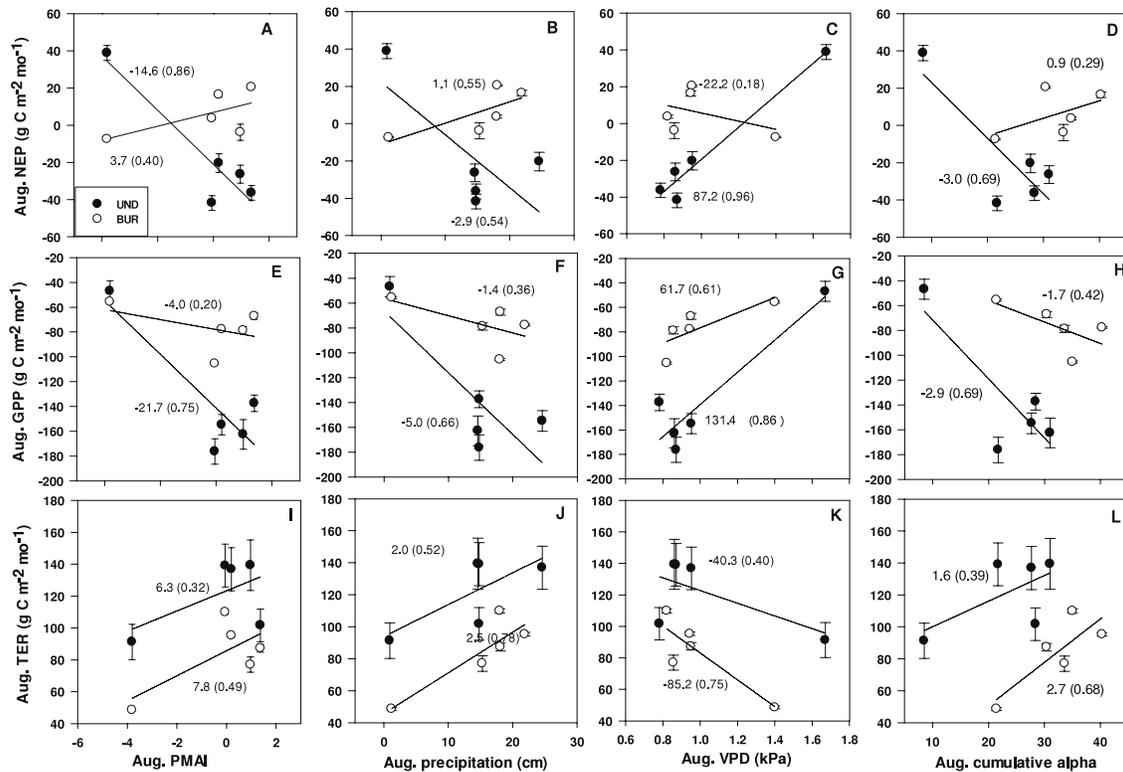
Figure 4. August net ecosystem production (NEP; (A)–(D)), gross primary production (GPP; (E)–(H)), and total ecosystem respiration (TER; (I)–(L)) for five years (2006–10) in the undisturbed (UND, filled symbols) and burned (BUR, open symbols) sites versus August Palmer moisture anomaly index (PMAI) for Arizona Region 2 and, for each study site, August precipitation, August mean vapor pressure deficit (VPD) and August cumulative alpha. The most negative PMAI, highest VPD, lowest precipitation and lowest cumulative alpha occurred in 2009 at both sites. The slope (R^2) is shown for each regression line.

Extreme drought had large impacts on carbon fluxes in August, which is one of the most important months for carbon sequestration at both sites. August NEP was especially sensitive to extreme drought at the UND site, which switched from a strong carbon sink in non-drought years (~ -160 g C mo^{-1}) to a carbon source in the drought year of 2009 (~ 50 g C mo^{-1}). This switch from carbon sink to source in August at the UND site was largely driven by a $\sim 70\%$ decrease in GPP because TER concurrently declined by $\sim 35\%$. The direction of impact of drought on August GPP at the BUR site was consistent with the UND site, but the change was smaller (-20%). In contrast to the UND site, drought at the BUR site reduced TER (40%) more than GPP (20%). These carbon flux responses to late-summer drought in 2009 are mirrored in the overall response of warm-season monthly fluxes to water availability; low water availability shifted NEP at the UND site from sink to source due to reductions in GPP that exceed reductions in TER, whereas at the BUR site low water availability had less impact on NEP because GPP and TER decreased similarly.

Recovery of carbon sink strength after intense burning at the BUR site in our study was unusually slow compared with recovery in other forest types. A synthesis of recovery after fire and harvesting of forest annual carbon balance measured by eddy covariance over many North American chronosequence sites (Amiro *et al* 2010) showed that GPP

recovered to equal TER within 10 years after disturbance for most regions. In contrast to this trend of quick recovery, the BUR site in our study was a weak carbon source to the atmosphere in all measurement years, which were the tenth through fourteenth years after burning. The difference between our study and other studies of forests can likely be attributed to the lack of tree regeneration following intense burning at the BUR study site. Lower evapotranspiration at the BUR site than the UND site (Montes-Helu *et al* 2009, Dore *et al* 2012) increased ecosystem-level water availability during drought at the BUR site, but GPP at the BUR site was constrained by low leaf area index and short leaf area duration of the dominant herbaceous plants. Our results are consistent with reports from other regions of much lower annual carbon sink strength in grasslands than forests (Pereira *et al* 2007). Our finding of slow regeneration of ponderosa pine at the BUR site after intense burning is consistent with other studies that have included many sites in the southwestern US (Savage and Mast 2005, Roccaforte *et al* 2012, Ross *et al* 2012) and thus suggests that our results for the BUR site apply widely to intensely burned forests in the region. Collectively these results indicate that disturbance status of ponderosa pine stands within a region must be considered when assessing regional carbon balance, and that recent increase in intense forest burning in the southwestern US (Westerling *et al* 2006, Williams *et al* 2010) is reducing carbon sink strength.
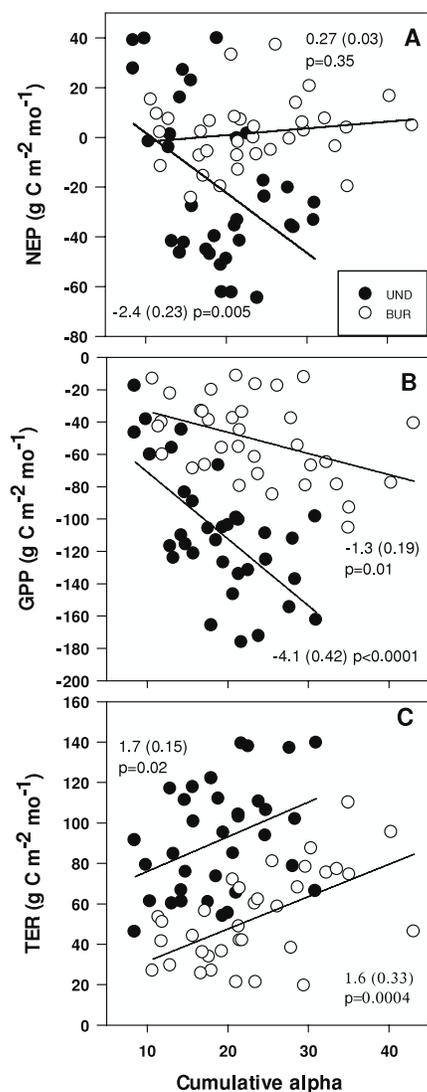
Figure 5. Monthly net ecosystem production (NEP; (A)), gross primary production (GPP; (B)), and total ecosystem respiration (TER; (C)) for April through October of five years (2006–10) in the undisturbed (UND, filled symbols) and burned (BUR, open symbols) sites versus monthly cumulative alpha measured at each site. The slope (R^2) and p value are shown for each regression line.

Extreme late-summer drought reduced NEP at the densely forested UND site via reduction in GPP rather than an increase in TER. Our finding of a greater importance of GPP than TER in reducing carbon sink strength during severe drought is consistent with previous reports of recent drought impacts in Europe (Ciais *et al* 2005, Pereira *et al* 2007), China (Xiao *et al* 2009), the western US (Schwalm *et al* 2012), and midlatitudes of the northern hemisphere (Zeng *et al* 2005). Consistent with Reichstein *et al* (2007) and Schwalm *et al* (2012), we found that the climate constraint of drought reduced both GPP and TER at the forested UND site, but the reduction was greater for GPP and consequently NEP decreased.

We speculate that low GPP at the UND site during late-summer drought was due more to stomatal closure and consequent reduced photosynthesis in response to high VPD rather than a direct effect of low late-summer rain on tree water uptake. Kerhoulas *et al* (2013) recently showed that mature ponderosa pines near our study site used deep soil water supplied from winter precipitation for the entire growing season in both wet and dry years, including the focal drought year (2009) of our study. Water in surface soil supplied by late-summer rain was not used by mature trees in wet or dry years. The negative association between TER and VPD likely occurred because the autotrophic component of TER is coupled with GPP. Williams *et al* (2012) recently concluded that high warm-season VPD is an important component of drought stress to forests in the region of our study sites. These collective findings suggest that decrease in ponderosa pine photosynthesis in response to high VPD at the leaf (Kolb and Stone 2000), whole-tree (Fischer *et al* 2002) and stand (Dore *et al* 2012) levels reduces ecosystem GPP during late-summer drought. Consistent with Williams *et al* (2012), our results portend a future weakening of forest carbon sink strength in the southwest US as increasing atmospheric temperature increases VPD.

In summary, we show that extreme late-summer drought in the southwest US caused neutral annual carbon balance at two sites that differ substantially in vegetation via different directional responses. Drought shifted annual carbon balance of the undisturbed forest from sink to neutral due largely to reduced GPP and shifted the carbon balance of the burned site from weak source to neutral due largely to reduced TER. Our results strongly suggest that predicted increases in temperature, drought and precipitation variability in the southwestern US will weaken forest carbon fluxes.

Acknowledgments

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