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Interactive comment on "Water availability limits tree productivity, carbon stocks, and carbon residence time in mature forests across the western United States" *by* Logan T. Berner et al.

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Anonymous Referee #3

General comments

In my view, this paper makes an important contribution in quantifying the relationship between forest characteristics (net primary productivity, NPP; live biomass, BIO; mean carbon residence time, CRT) and climatic moisture regimes in the western United States. The analysis is strengthened by the inclusion of two fundamentally different data sources and methods, including forest inventory measurements from 3 states (WA, OR and CA) and satellite-based estimates across an even larger area (11 west-

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ern states). The results are striking as both methods show that forest characteristics in this region are governed primarily by spatial gradients in climatic moisture regimes (as represented by a simple climate moisture index, CMI_wy). Although this general conclusion is not new, the work provides valuable quantitative estimates of forest-climate relationships that are likely to be useful in improving models of forest responses to the climatic drying that is already evident in this region. Overall, the paper is clearly presented and the methods seem appropriate, given the major challenges of spatial scaling in this mountainous and climatically diverse region.

My main questions relate to a) the justification for including only mature stands > 100 years, and b) unstated assumptions and potential sources of error in estimating CRT (see specific points, below).

RESPONSE: Thank you for providing valuable comments on our manuscript. In the revised manuscript we provide (1) better justification for focusing on mature stands and (2) a more thorough discussion of the assumptions and limitations associated with computing CRT as BIO/NPP. We describe these revisions in greater detail below.

Specific comments:

L110 What is the justification for restricting the analysis to mature stands older than 100 years? Is this age considered to be a threshold, beyond which the variables BIO, NPP and/or CRT remain constant over time?

RESPONSE: We focused on mature stands (>100 years) because inventory plots in this region showed that tree BIO and NPP tended to increase rapidly with stand age during the first century and then change more gradually during subsequent years (Hudiburg et al., 2009). In essence, we assume that BIO and NPP have hit much of their 'climatic potential' after 100 years. Several prior studies similarly focused on mature stands that were at least 100 years old (Whittaker and Niering, 1975; Gholz, 1982; Webb et al., 1983). Furthermore, computing CRT as BIO/NPP assumes (as discussed below) that BIO is stable through time, which is an assumption met more closely by examining older stands. We did perform the analysis using all forestland, regardless of stand age, and found very similar results (albeit with lower BIO and CRT). We added the following text to the introduction (starting on line 76):

"Prior studies drew on small networks of field sites (n < 20) to investigate how tree net primary productivity (NPP) and BIO varied among mature stands spread along hydrologic gradients in parts of this region (Whittaker and Niering, 1975; Gholz, 1982; Webb et al., 1983; Berner and Law, 2015). Tree BIO and NPP can vary widely with stand age (Hudiburg et al., 2009) and thus these studies focused on mature stands (stand age generally > 100 years) where BIO and NPP had somewhat stabilized after reaching their 'climatic potential.'"

We also added the following text to the introduction directly before stating our hypotheses (starting on line 112):

"We focused on forest stands that were at least 100 years old because field surveys from the region indicated that BIO and NPP reached much of their 'climatic potential' after a century, though we acknowledge that BIO tends to gradually increase and NPP remains stable or gradually declines during subsequent centuries (Hudiburg et al., 2009)."

L127-128: Do these inventory sites represent forests across the full range of elevations in this region? If they exclude sampling of unproductive forests in climatically cold, wet sites near the upper timberline then I'm wondering if this could explain the observed differences in response to CMI for inventory sites versus satellite-derived estimates (Fig. 2).

RESPONSE: An astute question. The Forest Service inventory sites are spread among areas > 1 acre (0.40 ha) that have at least 10% tree cover (Bechtold and Patterson, 2005). The sites do occur in cold, wet, high-elevation areas so long as those requirements are met. We compared the average (SD) elevation of inventory sites and MODIS forest pixels (stands > 100 years) at each step along the CMIwy gradient and found that inventory sites and MODIS forest had very similar elevational distribution across WAORCA. A paired t-test found no significant difference in average elevation between inventory sites and MODIS forest along the CMIwy gradient in WAORCA (P=0.43). The differences between inventory and satellite-derived estimates of BIO and NPP were most apparent in the wettest areas (e.g, CMIwy > 100 cm/yr) that overwhelming occurred in WAORCA (e.g., 98% of MODIS forest with CMIwy > 100 cm/yr was in WAORCA). Consequently, it does not appear that differences between inventory and satellite-derived estimates of BIO and NPP in wet areas can be attributed to the satellite data systematically including cold, high-elevation areas that are were not represented by the inventory sites. We added text in several places to help clarify. We edited part of the methods to read (starting on line 134):

"These 1-ha sites were surveyed by the US Forest Service Forest Inventory and Analysis (FIA) program between 2001 to 2006 and comprise a representative sample of forest lands (tree cover > 10%) in the region (Bechtold and Patterson, 2005). The inventory sites occurred at elevations ranging from 5 m to 3,504 m, with an average (±1SD) elevation of 1429±677 m."

Additionally, we added modified part of the discussion to read (starting on line 336):

"The NPP-CMIwy relationship was similar when NPP was assessed using field measurements from across WAORCA or using MODIS covering the western US, though MODIS did show NPP leveling off in the wettest parts of WAORCA (CMIwy ≈ 100-200 cm yr-1), whereas this was less evident in the field measurements. The inventory sites and MODIS forestland occurred at similar elevations along the CMIwy gradient in WAORCA, suggesting that this discrepancy in NPP was not due to MODIS systematically including cold, high-elevation areas not sampled by the inventory sites. One possibility is that MODIS NPP did not increase in the wettest areas because MODIS becomes less sensitive to increases in the fraction of photosynthetically-active radiation (FPAR) absorbed by plant canopies in densely vegetated areas (Yan et al., 2016)."

L138-140: I believe that the equation used for carbon residence time (CRT = BIO / NPP) is based on the assumption that BIO is constant over time (e.g., see equation 1 of Friend et al 2014, reference cited in the MS). If so, then this assumption (and any others) should be stated explicitly. Overall, I'm wondering how much of the variation in the reported estimates of CRT is driven simply by variation in stand age, given that in my experience, older stands tend to exhibit increasing (or stable) values of BIO along with age-related declines in NPP. On a related point, using the above equation, I would expect estimates of CRT to be inflated in forests with anomalously low NPP over the 10-year period of calculation (e.g., during droughts or insect defoliation episodes that are not sufficiently severe to cause a proportional decline in BIO). Again, it would be helpful to at least acknowledge the potential sources of bias in the reported CRT estimates.

RESPONSE: You are correct that calculating mean carbon residence time (CRT) as CRT = BIO/NPP assumes that BIO is constant over time and we agree that this assumption should be explicitly stated and more thoroughly discussed in our manuscript. We added the following text to the introduction to note this assumption (starting on line 91):

"Several of these earlier field studies also indicated that plant communities accumulated more BIO per unit of NPP in progressively wetter areas, suggesting slower turnover of plant BIO as climate became wetter (Whittaker and Niering, 1975; Webb et al., 1983). Mean carbon residence time (CRT) describes the average duration that a carbon molecule will remain in a specific pool (Waring and Running, 2007) and for CRT in live biomass can be computed as BIO/NPP assuming that BIO remains constant over time (Whittaker, 1961; Friend et al., 2014). CRT in live biomass is also known as the biomass accumulation ratio (Whittaker, 1961) and ranged, for instance, from ∼2 years in a hot desert shrubland to ∼75 years in an wet, old-growth Douglas-fir forest (Webb et al., 1983)."

Older stands did have higher CRT and average stand age did increase moving into wetter areas. Together, these indicate that the CRT-CMIwy relationships we observed did incorporate an age-related effect; however, the age-relate effect appears to be rather small. For instance, let's compare the median CRT between mature (100-200 years) and old (>200 years) stands occupying very dry (CMIwy < -100 cm yr-1) and very wet (CMIwy > 100 cm yr-1) areas. Median CRT differed by 6% (16 vs. 17 years) between mature and old stands in very dry areas and by 10% (47 vs. 52 years) in very wet areas. Conversely, median CRT of mature stands differed 98% (16 vs. 47 years) between very dry and very wet areas, while the median CRT of old stands differed 101% (52 vs. 17 years) between very dry and very wet areas. In very dry areas 80% of stands were mature and 20% were old, whereas in very wet areas 67% of stands were mature and 33% were old. Furthermore, CRT-CMIwy relationships constructed using mature and old were quite similar, diverging slightly in the wettest areas. These comparisons illustrate CRT is affected by stand age, but that the age effect is quite small relative to the climate effect. We edited the CRT discussion section so that it now begins by addressing uncertainty in our estimates of CRT (starting on line 430):

"One limitation of our study is that computing CRT in this manner assumes that BIO is constant over time (Friend et al., 2014). We focused on mature stands (>100 years) to minimize the change in BIO over time, though acknowledge that BIO can gradually increase during subsequent centuries (Hudiburg et al., 2009), which would lead us to underestimated CRT. Conversely, drought and insect-induced defoliation in the early 2000s could have suppressed NPP (Schwalm et al., 2012; Berner and Law, 2015) without a proportional reduction in BIO, which could have inflated our estimates of CRT in some areas."

We then revised the text to include a discussion of the age-related effect (starting on line 457):

"We also found that mature stands tended to be older in wetter areas and that older stands tended to have longer CRT, likely as a result of these stands having higher BIO and similar NPP (Hudiburg et al., 2009). Consequently, the CRT-CMIwy relationships that we observed incorporate an age-related effect; however, the effect was quite small relative to the climate-effect. This can be illustrated by comparing median CRT between mature (100-200 years) and old (>200 years) stands occupying very dry (CMIwy< -100 cm yr-1) and very wet (CMIwy > 100 cm yr-1) areas. Median CRT differed by 6% (16 vs. 17 years) between mature and old stands in very dry areas and by 10% (47 vs. 52 years) in very wet areas. Conversely, median CRT of mature stands differed 98% (16 vs. 47 years) between very dry and very wet areas, while the median CRT of old stands differed 101% (52 vs. 17 years) between very dry and very wet areas. In other words, the difference in CRT between stands in contrasting climates is much greater than difference in CRT between mature and old stands within a climate zone. Our study demonstrates that CRT in live tree biomass was strongly influenced by water availability, yet additional efforts are needed to determine the underlying mechanism by which changes in water availability affect CRT, particularly given that CRT is a primary source of uncertainty in global vegetation model projections of future terrestrial carbon cycling (Friend et al., 2014)."

L396-400: The discussion includes reporting of the large percentage difference in BIO across the climatic moisture gradient (CMI_wy) using the two methods (from Fig. 2) but I expect that the percentage difference would be even greater than this if dry, naturally unforested areas (with zero forest BIO and NPP) were included in the analysis. In this respect, it would be interesting to see how %forest cover varies as a function of the binned values of CMI_wy across this region. I recognize that such an analysis would go beyond the scope of this paper, but it could provide an interesting additional indicator of how forest NPP and carbon stocks may respond over the long term under the projected (and ongoing) climatic drying, i.e., drought-related loss of forest cover in addition to drought-related decreases in BIO, NPP and CRT in those sites that continue to remain forested.

RESPONSE: We appreciate the suggestion and believe that it would be interesting to investigate how forest cover changes with CMIwy over this region; however, we believe

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this addition is beyond the scope of our current study.

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