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Key Points:

- Forest productivity was influenced by snow aridity, which was calculated from the ratio of evaporative demand and snow water supply
- An inverse relationship between early and late season productivity resulted from the joint effects of snow aridity and summer precipitation
- Forecasted climate changes could lead to decreased forest carbon sequestration from semiarid mountain regions

Correspondence to:
J. F. Knowles,
johnknowles@email.arizona.edu

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Snowmelt-Driven Trade-Offs Between Early and Late Season Productivity Negatively Impact Forest Carbon Uptake During Drought

John F. Knowles[1,2], Noah P. Molotch[1,3,4], Ernesto Trujillo[5], and Marcy E. Litvak[6]

[1]Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO, USA, [2]School of Geography and Development, University of Arizona, Tucson, AZ, USA, [3]Department of Geography, University of Colorado Boulder, Boulder, CO, USA, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [5]School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, [6]Department of Biology, University of New Mexico, Albuquerque, NM, USA

Abstract Future projections of declining snowpack and increasing potential evaporation are predicted to advance the timing of snowmelt in mountain ecosystems globally with unknown implications for snowmelt-driven forest productivity. Accordingly, this study combined satellite- and tower-based observations to investigate the forest productivity response to snowpack and potential evaporation variability between 1989 and 2012 throughout the Southern Rocky Mountain ecoregion, United States. Our results show that early and late season productivity were significantly and inversely related and that future shifts toward earlier and/or reduced snowmelt could decrease snowmelt water use efficiency and thus restrict productivity despite a longer growing season. This was explained by increasing snow aridity, which incorporated evaporative demand and snow water supply, and was modified by summer precipitation to determine total annual productivity. The combination of low snow accumulation and record high potential evaporation in 2012 resulted in the 34 year minimum ecosystem productivity that could be indicative of future conditions.

Plain Language Summary Snow is melting earlier, and there is potential for greater evaporation as a result of warmer, drier conditions in semiarid mountain regions around the world. These changes combine to affect seasonal moisture availability on the landscape, which is essential to proper ecosystem function. This research used 34 years of satellite- and field-based data that included three distinct droughts to show that forest activity, measured as the amount of carbon dioxide removed from the atmosphere, may decrease as a result of this scenario. This work has broad implications for global climate change since forests in seasonally snow-covered areas currently contribute to mitigating carbon dioxide emissions.

1. Introduction

Climate forecasts for snow-dominated regions including the western United States consistently indicate that increased air temperature will increase summer potential evaporation (PE) and reduce winter snow accumulation in regions and elevations near the freezing point, resulting in earlier growing seasons as well as more frequent and more severe droughts (Barnett et al., 2005; Dai, 2012; Schwartz et al., 2006; Sheffield et al., 2012). Previous work has also shown that increases in air temperature can be linked to longer, less productive growing seasons in the western United States mainly due to drought stress resultant from the combination of earlier snowmelt, reduced snow accumulation, and increased drying/atmospheric demand for moisture (Angert et al., 2005; Hu et al., 2010; Piao et al., 2007; Trujillo et al., 2012). Notwithstanding, seasonal changes in forest productivity associated with the combination of these perturbations have not been characterized. Snow aridity takes into account both snow water equivalent (SWE) and PE and is therefore a useful composite index for understanding drought (Knowles et al., 2017). In particular, the 2012 growing season in the Southern Rocky Mountains provides an ideal analog with which to evaluate the sensitivity of forest productivity to the combined effects of reduced SWE and increased PE (i.e., snow aridity) as it included the third lowest snowpack and warmest spring on record (Wolf et al., 2016).

The overarching goal of this work was to quantify how semiarid mountain forests respond to the low snowpack and high PE conditions associated with future climate projections for snow-covered forests globally. To explore this question, we evaluated satellite-based estimates of SWE, normalized difference vegetation index

(NDVI), PE, and gross primary productivity (GPP) throughout the U.S. Environmental Protection Agency (EPA) Level III Southern Rocky Mountain ecoregion for 34 years (1989 to 2012) that included three distinct drought years. These results were then compared against eddy covariance-derived GPP measurements at two locations within the study domain. Insofar as climate change may be compounding the effects of reduced SWE and higher PE toward earlier snowmelt, we propose that the established relationships between winter snow accumulation and intra-annual GPP in the western United States (Schimel et al., 2002; Trujillo et al., 2012; Winchell et al., 2016) may be subject to modification as a result of progressively decreased water availability throughout the growing season. We specifically hypothesized that directional changes in seasonal moisture availability may be fundamentally changing the ratio between early and late season forest GPP such that increased early season GPP occurs at the direct expense of both late season and total annual GPP. Any perturbation to the carbon cycle at this scale represents a potential feedback to climate change since snow-covered forests represent an important global carbon sink (e.g., Luyssaert et al., 2007).

2. Methods

2.1. Study Area

The Southern Rocky Mountain ecoregion study area (144,462 km^2) was extracted from a North American ecoregions level 3 layer developed by the Commission for Environmental Cooperation (CEC) and updated and distributed by the U.S. EPA (http://www.epa.gov/wed/pages/ecoregions.htm) (Commission for Environmental Cooperation (CEC) 1997; U.S. EPA, 2010). Further, the 2001 National Land Cover Database (NLCD) evergreen forest class was used to restrict our analysis to evergreen forested areas, which covered 43% of the total land area (http://www.mrlc.gov/nlcd2001.php) (Homer et al., 2004). The mean maximum 1979–2012 SWE was calculated from 132 United States Department of Agriculture National Water and Climate Center Natural Resources Conservation Service SNOTEL (SNOwpack TELemetry) stations located throughout the Southern Rocky Mountain ecoregion (http://ftp.wcc.nrcs.usda.gov/data/snow/snotel/cards). The date of snowmelt was determined as the average date that the snow water equivalent remained at 0 for three or more days across all 132 stations for each year.

2.2. Normalized Difference Vegetation Index

The 1 km NDVI biweekly composites were downloaded from the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center (https://lta.cr.usgs.gov/NDVI) for the conterminous United States. The NDVI was computed from the red and near-infrared (NIR) spectral bands ((NIR − red)/(NIR + red)) as observed by the advanced very high resolution radiometer sensor (Tucker et al., 2005). Composites that contained clouds or other errors were not used in this study. The maximum NDVI was calculated for each pixel for each year between 1989 and 2012, and this layer was then masked by the NLCD evergreen forest class. A single mean maximum NDVI value was calculated for evergreen forested areas within the Southern Rocky Mountain ecoregion between 1989 and 2012. We extended the USGS NDVI time series back to 1981 by calculating a regression equation between the USGS NDVI and an 8 km advanced very high resolution radiometer-derived NDVI data set produced by the Global Inventory Modeling and Mapping Studies (GIMMS) group at the Global Land Cover Facility at the University of Maryland (http://glcf.umd.edu/data/) (Pinzon et al., 2005; Tucker et al., 2005, 2006). Mean maximum evergreen-masked 1981–2008 GIMMS NDVI was calculated using GIMMS biweekly composites that matched with the USGS biweekly composites; the regression equation was evaluated for the overlap years between the GIMMS and the USGS NDVI products (1989 to 2008), and this equation was used to extend the USGS NDVI product back to 1981.

2.3. Potential Evaporation, Precipitation, and Snow Aridity

Ecoregion-scale PE and precipitation were derived from monthly, 1/8 degree, North America Land Data Assimilation System Phase 2 data (http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings) (Mitchell et al., 2004; Xia et al., 2012). The North America Land Data Assimilation System Phase 2 PE uses a modified Penman equation (Mahrt & Ek, 1984) and is spatially interpolated from the National Centers for Environmental Prediction North American Regional Reanalysis modeled output. Monthly total PE and precipitation were summed from April (PE) or June (precipitation) to August, masked, and then used to determine mean growing season PE and mean summer precipitation using the ArcGIS zonal statistics function. Percent PE anomaly spatial layers were created for each year using the Raster Calculator in ArcPy as $((GS_{year} - PE_{mean})/PE_{mean}) \times 100$ where GS_{year} is the monthly total PE during the growing season and

PE_{mean} is the 1979–2012 mean PE during the same time period. Record high polygons for each year between 1979 and 2012 were located using the maximum statistical function in ArcGIS.

At the Niwot Ridge, CO (US-NR1; Blanken et al., 1998), and Valles Caldera, NM (US-VCM; Litvak, 2007), AmeriFlux sites within the study domain, potential evapotranspiration (PET) was calculated from meteorological forcing data using the Penman approach (Shuttleworth, 1993). A snow aridity index (Knowles et al., 2017) was subsequently evaluated as PET/SWE where annual maximum SWE was measured at the Niwot SNOTEL site (US-NR1) or averaged from measurements at the Quemazon and Vacas Locas SNOTEL sites (US-VCM). An analogous calculation was performed at the ecoregion scale where snow aridity index was equal to PE/SWE. Representative summer (June-July-August) precipitation for the US-VCM site was averaged from measurements at the Quemazon and Vacas Locas SNOTEL stations, whereas US-NR1 precipitation was determined as the average of the Niwot SNOTEL and the Niwot Ridge Long Term Ecological Research Program C-1 sites.

2.4. Gross Primary Productivity

An improved, cloud-corrected, and meteorologically consistent version of NASA's 1 km resolution Moderate Resolution Imaging Spectroradiometer (MODIS) gross/net primary production (GPP/NPP) data set was downloaded for 2000–2012 from the Numerical Terradynamic Simulation Group at the University of Montana (http://www.ntsg.umt.edu/project/mod17) (Zhao et al., 2005). The monthly GPP/NPP files were masked by the 2001 NLCD evergreen forest class and clipped to the CEC Southern Rocky Mountain ecoregion, and then mean GPP/NPP was calculated using the ArcGIS zonal statistics function. Net ecosystem exchange of carbon dioxide data was obtained from the AmeriFlux network (http://ameriflux.ornl.gov) for the US-NR1 and US-VCM AmeriFlux sites, and the GPP was separated from net ecosystem exchange of carbon dioxide following Reichstein et al. (2005). The AmeriFlux GPP fluxes were summed by month for each year and converted to grams of carbon per square meter. In order to minimize the confounding effects of winter snowmelt and summer precipitation, relationships between early and late season GPP were evaluated using ordinary least squares linear regression analysis for the month of April versus June (US-VCM) or July (all other sites), in recognition of the earlier snowmelt season at the US-VCM site.

3. Results and Discussion

3.1. Variability of SWE, NDVI, and PE

The water required by forests for growth and survival during the growing season is mainly provided by snowmelt in semiarid mountain ecosystems (e.g., Nemani & Running, 1989). Although springtime conditions including precipitation, climatic water deficit (PE-precipitation), and air temperature (growing degree days) can influence growing season productivity (Bergeron et al., 2007; Stephenson, 1998), the objective of this work was to quantify the effect of forecasted snow aridification on GPP. As is typical in snow-dominated regions (e.g., Trujillo & Molotch, 2014), snowmelt date was highly correlated with mean maximum SWE ($R^2 = 0.89$; $p \ll 0.001$), and both snowmelt date ($R^2 = 0.58$; $p = 0.002$) and mean maximum SWE ($R^2 = 0.29$; $p = 0.002$) were significant predictors of mean maximum NDVI throughout the Southern Rocky Mountain ecoregion. Accordingly, years with above-normal snow accumulation correspond to above-normal forest productivity (e.g., 2009; Figure 1a), while years with below-normal snow accumulation correspond to below-normal productivity (e.g., 2012; Figure 1b). Notably, however, the summer of 2012 exhibited record low forest greenness over the 34 year record, but this was not associated with a record low snowpack as SWE accumulation was lower in the previous drought years of 2002 and 1981 (Figure 1c).

The leaf area index and the resulting photosynthetic capacity and GPP of vegetation are also governed by PE, which increasingly exceeds available water during the growing season in a variety of high-altitude and high-latitude ecosystems (Peng et al., 2011; Sun et al., 2010). Overall, monthly total PE explained 20% ($p = 0.01$) of the variance in mean maximum NDVI, but this increased to 36% ($p \ll 0.001$) when normalized by the mean maximum SWE (i.e., the snow aridity index; Figure 2a). Insofar as it generally captured the NDVI response to record low SWE (in 2002) and record high PE (in 2012), snow aridity was an effective predictor of NDVI irrespective of drought type (Figure 2b). Estimates of PE based on the NASA Land Information System provide additional insight into the record low NDVI during 2012. Even during the drought years of 1981 (Figure 2c) and 2002 (Figure 2d), growing season PE remained below average for 25% and 28% of the study domain,

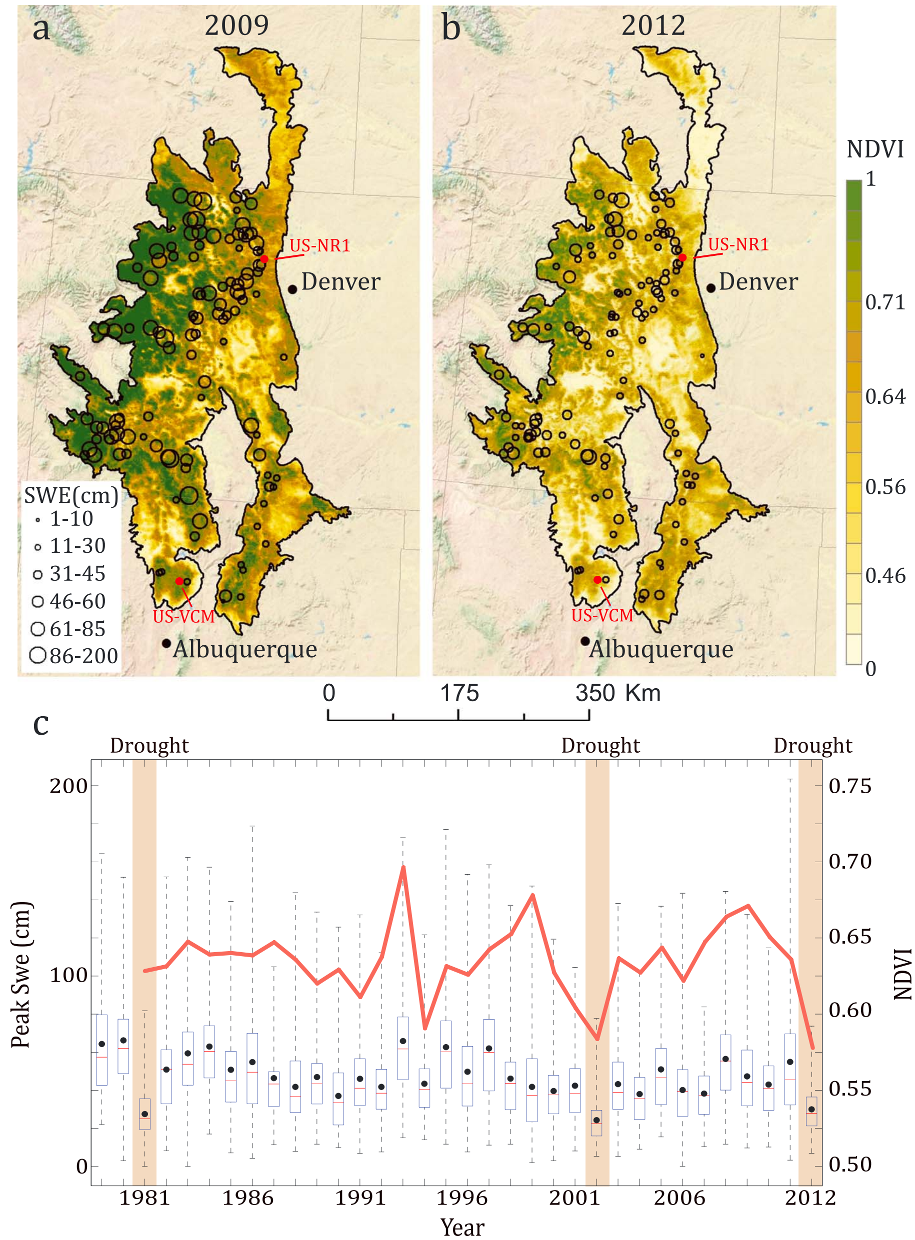

Figure 1. The spatial variability of snow water equivalent (SWE) and normalized difference vegetation index (NDVI) in (a) a wet year and (b) a drought year throughout the Southern Rocky Mountain ecoregion. (c) The 34 year time series shows minimum NDVI (red line), but not minimum SWE (box plots), in 2012. US-VCM = Valles Caldera, NM; US-NR1 = Niwot Ridge, CO.

respectively, decreasing the overall moisture demand on vegetation at this spatial scale. In contrast, record high PE values were observed for 65% of the study area in 2012 (Figure 2e); hence, the spatially integrated atmospheric demand for moisture was a record high in 2012, which offset greater SWE inputs to result in lower NDVI than that in 1981 or 2002. Multiple linear regression of monthly total PE (p = 0.005), mean maximum SWE (p = 0.02), and their interaction (p = 0.01) on NDVI (model R^2 = 0.33, p = 0.003) further supports that increasing summer PE may be capable of compounding the moisture deficit caused by reduced SWE to amplify the productivity response to drought in forests subject to seasonal moisture limitation.

3.2. Seasonal Forest Carbon Uptake Dynamics

To specifically quantify the effect of an earlier growing season on forest GPP, intra-annual satellite GPP observations from the MODIS instrument were analyzed over time with a particular focus on the relationship

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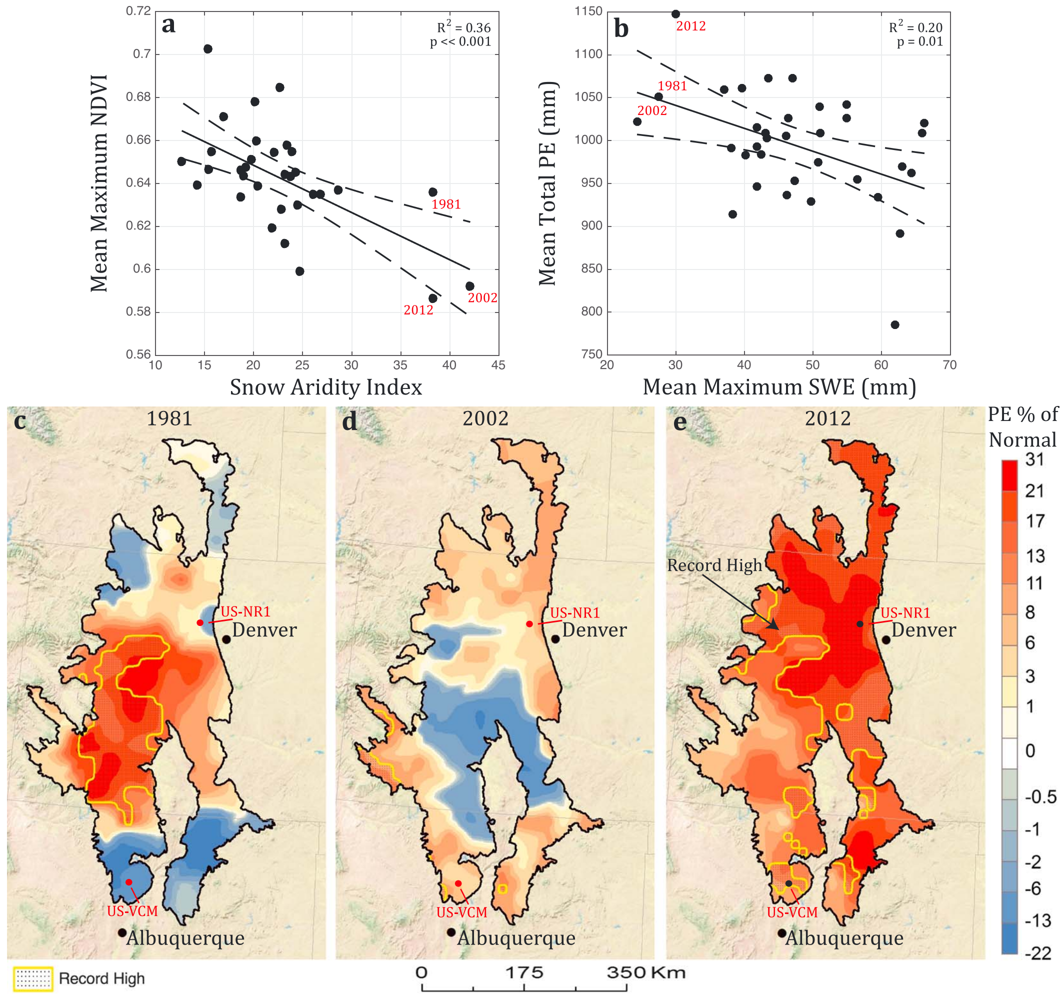

Figure 2. (a) Snow aridity predicted normalized difference vegetation index (NDVI) during (b) droughts characterized by both record low snow water equivalent (SWE) (2002) and record high potential evaporation (PE) (2012). The spatial variability of PE throughout the Southern Rocky Mountain ecoregion during three drought years: (c) 1981, (d) 2002, and (e) 2012. Solid and dashed lines in (a) and (b) are the best fit trendline and the 95% confidence interval, respectively. US-VCM = Valles Caldera, NM; US-NR1 = Niwot Ridge, CO.

between early and late season GPP during both wet and dry years (Figure 3). This analysis demonstrates the seasonal phenology of forest vegetation in the Southern Rocky Mountains and other seasonally snow-covered forests in semiarid regions; carbon uptake is greatest early in the growing season during and immediately after snowmelt and typically declines thereafter (Monson et al., 2002; Sacks et al., 2007) (Figure 3a). In the record low NDVI year of 2012, the ecoregion (10^5 km^2) scale April + May GPP was the highest of any year since observations began in 2000, which likely resulted from reduced temperature limitations on productivity associated with the record warm spring in 2012 (Winchell et al., 2016; Wolf et al., 2016). Conversely, the 2012 July GPP was the lowest of any year during the MODIS data record. Statistically, early season GPP was a positive function of both snowmelt date (R^2 = 0.81; $p \ll 0.001$) and mean maximum SWE (R^2 = 0.80; $p \ll 0.001$), whereas late season GPP was a positive function of summer precipitation (R^2 = 0.28; p = 0.06) but a negative function of the snow aridity index (R^2 = 0.41; p = 0.02). At the ecosystem (~1 km^2) scale, GPP observations from two eddy covariance towers within the study domain at the US-NR1 and US-VCM AmeriFlux sites corroborated this phenological pattern, and the tower data showed good agreement with the four nearest MODIS pixels (Figures 3b and 3c). The southern portion of the study domain is increasingly affected by the North American monsoon (e.g., Adams & Comrie, 1997), which accounts for the secondary productivity maximum during July and August that is periodically observed at the US-VCM site.

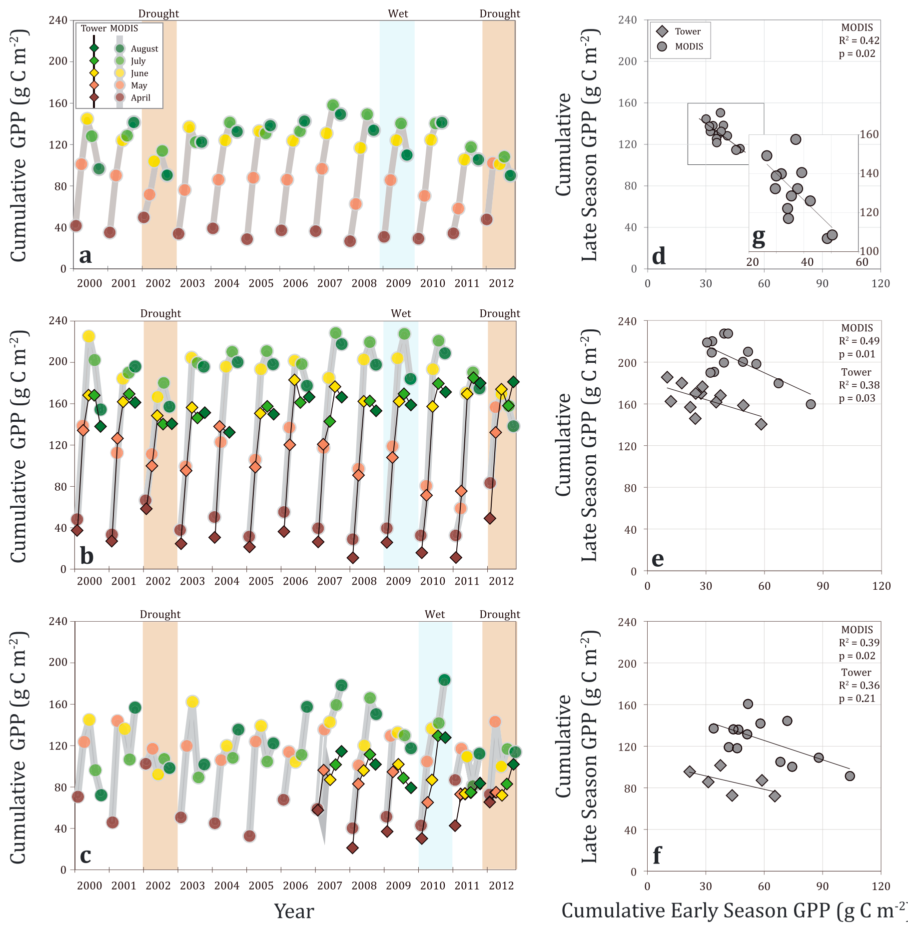

Figure 3. Monthly (April–August) cumulative (a) Moderate Resolution Imaging Spectroradiometer (MODIS)-derived gross primary productivity (GPP) for the Southern Rocky Mountain ecoregion, (b) eddy covariance- and MODIS-derived GPP from the Niwot Ridge, CO (US-NR1) AmeriFlux tower and the four MODIS pixels nearest to the US-NR1 tower, and (c) eddy covariance- and MODIS-derived GPP from the Valles Caldera, NM (US-VCM) AmeriFlux tower and four closest MODIS pixels from 2000 to 2012. A representative wet year for each site and the drought years of 2002 and 2012 are highlighted for emphasis. Also shown are the corresponding statistical relationships between early and late season GPP for the (d) Southern Rocky Mountain ecoregion, (e) the US-NR1 tower and four closest MODIS pixels, and (f) the US-VCM tower and four closest MODIS pixels; note that "late season" is defined as July in (d) and (e) versus June in (f). (g) Enlarged view to show the interannual variability in (d).

To more precisely quantify intra-annual patterns of carbon cycling during wet and dry years, we analyzed the statistical relationship between early and late season carbon assimilation during the length of the MODIS and eddy covariance instrumental records over the entire study domain and at both AmeriFlux sites. At the ecoregion scale, early and late season GPP were significantly and inversely correlated (R^2 = 0.42; p = 0.02) (Figure 3d), and similar site-specific relationships were observed using the US-NR1 eddy covariance data (R^2 = 0.38; p = 0.03) and the four MODIS pixels surrounding the US-NR1 (R^2 = 0.49; p = 0.01) and US-VCM towers (R^2 = 0.39; p = 0.02) (Figures 3e and 3f). We attribute the lack of a significant relationship (p = 0.21) at the US-VCM eddy covariance tower to a combination of the shorter (6 years) instrumental record and the relatively greater influence of monsoon precipitation in the southern portion of the study domain. From this analysis, we conclude that the effects of forecasted regional warming, including increased snow aridification and an earlier onset of snowmelt and the growing season, may compound to change the seasonality of forest productivity.

3.3. Controls on the Early/Late Season Productivity Ratio

Although SWE represents the dominant moisture source in seasonally snow-covered semiarid forests (e.g., Clow, 2010), recent work has also highlighted the importance of summer precipitation to GPP in the Rocky Mountains (Berkelhammer et al., 2017). The steeper negative slopes of the ecoregion scale and the US-NR1 regression analyses relative to the more southern US-VCM site (Figures 3d–3f) reinforce that the combined

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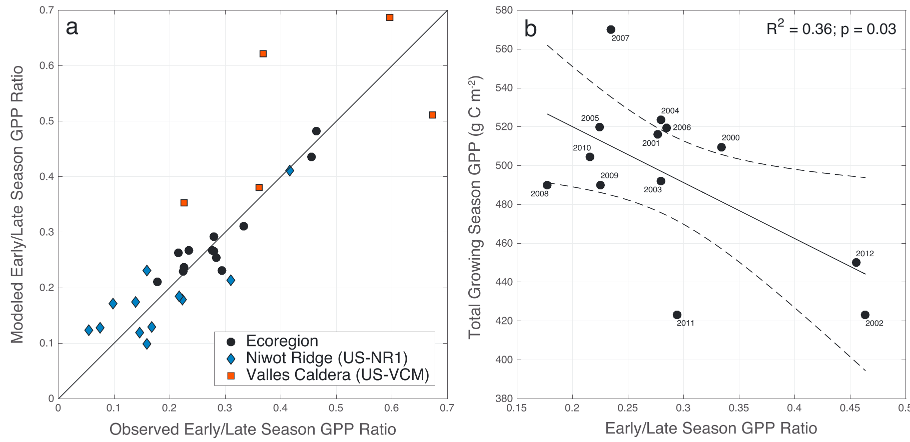

Figure 4. (a) Multiple linear regression of the snow aridity index and summer (June-July-August) precipitation was a significant ($p < 0.05$) predictor of the ratio between early and late season gross primary productivity (GPP) throughout the Southern Rocky Mountain ecoregion and at the Niwot Ridge, CO (US-NR1) but not the Valles Caldera, NM (US-VCM) AmeriFlux site. As a result, earlier snowmelt is projected to increase the ratio between early and late season GPP, which, although subject to modification by summer precipitation, can be linked to (b) decreased annual GPP at the ecoregion scale. The black line in (a) is the 1:1 line; solid and dashed lines in (b) are the best fit trendline and the 95% confidence interval, respectively.

effect of increasing PE and earlier snowmelt can be tempered in ecosystems, or years, that are more affected by summer precipitation, for example, the bimodal snowmelt/monsoon precipitation maximum that is particularly relevant at the US-VCM site. As a result, we conceptualize a framework in which the supply of snowpack moisture (i.e., SWE) interacts with atmospheric moisture demand (i.e., PE) during the spring and early summer to establish antecedent moisture conditions for the rain-influenced portion of the growing season. From that point, the final early/late season GPP ratio for a given year is determined as a function of both total winter *and* summer precipitation. This is illustrated by Figure 4a, where a multiple linear regression model incorporating the snow aridity index and summer (June-July-August) precipitation is shown to accurately predict the observed early/late season GPP ratio at the ecoregion scale (R^2 = 0.88; $p \ll 0.001$) and at the US-NR1 site (R^2 = 0.67; p = 0.007). The snow aridity index term was significant at both the ecoregion ($p \ll 0.001$) and ecosystem (p = 0.003) scales, but the summer precipitation term was not; therefore, neither model included an interaction term. Although incorporation of summer precipitation increased model R^2 at both scales, the corresponding sample size-corrected Akaike information criteria suggested that the snow aridity-only models were more parsimonious. Poor performance of the corresponding model at the US-VCM site (R^2 = 0.29; p = 0.60) could have resulted from the shorter observational data record and/or the location of the US-VCM site on the southern fringe of the ecoregion where the early/late season GPP ratio may be governed by actual evapotranspiration or slow-changing factors to a greater degree (Biederman et al., 2016).

This work further identified a significant inverse relationship (R^2 = 0.36; p = 0.03) between the early/late season GPP ratio and total annual GPP at the ecoregion scale that was primarily driven by very low GPP during the drought years of 2002 and 2012 (Figure 4b). This behavior suggests the potential for an ecohydrological threshold where total annual GPP can be curtailed by a shift toward earlier forest productivity given sufficient accumulated late season moisture stress. Although this phenomenon was only observed during extreme drought conditions, more severe and widespread droughts are forecasted during the 21st century (e.g., Dai, 2012). Consequently, drought events during the study period may represent an analog for more prevalent conditions in the future. Although an inverse relationship between the early/late season GPP ratio and total annual GPP was also observed at both the US-NR1 and US-VCM sites using the longer-term MODIS data, the early/late season GPP ratio was not a significant predictor of total annual GPP at the representative ecosystem-scale sites in this study. The significant early/late season effect on total GPP (Figure 4b) may thus result from spatial integration of heterogeneous meteorological and/or ecosystem conditions; that is, some areas within the ecoregion may not have experienced sufficient drought severity to activate the cumulative GPP response during the widespread drought years of 2002 and 2012. Longer distances from the best fit linear trendline in 2007 and 2011 may have been due to interannual lags in snow water storage or spatial variability within the ecoregion (Knowles et al., 2017).

While future projections of snowmelt timing and PE throughout the Southern Rocky Mountain ecoregion are relatively robust as they are based largely on future temperature estimates, projections of future precipitation at the regional scale are uncertain (e.g., Luce et al., 2016). Under the more certain scenario of earlier snowmelt and increased aridification, this study identifies the potential for a net negative effect on cumulative GPP as late season moisture stress increases along with the early/late season GPP ratio. Moreover, earlier snowmelt resulted in a higher early/late season ratio per unit SWE (i.e., holding SWE constant) both at the US-NR1 site and at the ecoregion scale ($0.001 < p < 0.02$), indicating that snow water use efficiency could also decrease in a commensurate way. Together with the superior performance of snowmelt date relative to SWE as a predictor of NDVI, this suggests that snowmelt timing and subsequent growing season length may represent the principal controls on the forest productivity response to forecasted snow aridification. This behavior is inherent to water-limited, snow-dominated ecosystems such as those at midlatitudes, but recent evidence suggests that high-latitude systems, which have been historically energy-limited, are also beginning to show evidence of water limitation (Girardin et al., 2016; Peng et al., 2011; Zhu et al., 2016). Nevertheless, there are mechanisms by which increasing early season GPP could partially offset the negative effects of decreasing snow water use efficiency and warming temperatures on forest carbon storage. For example, the GPP/respiration ratio was higher in the wet (2010) than in the dry (2011) year at the US-VCM site (data not shown), which could result from an increasing temporal phase shift between peak GPP (early season temperature and moisture limitations relaxed) and peak respiration (remains low in the presence of snow cover) (e.g., Anderson-Teixeira et al., 2011; Monson et al., 2002). Previous work has also shown that the biological impact of increasing aridification is subject to modification by the positive response of vegetation productivity to rising atmospheric carbon dioxide (Roderick et al., 2015; Swann et al., 2016).

4. Conclusion

This study is the first to quantify how increasing PE, which is linked to future climate warming, can amplify decreases in forest productivity associated with earlier snowmelt, lower annual peak SWE, and earlier and longer growing seasons. Since this scenario represents some of the most well-constrained effects of climate change, this study supports a primary influence of snow aridification and subsequent moisture limitation on both seasonal and cumulative forest productivity with implications for the carbon sink of western North America and other snow-dominated forests globally. Although the exact magnitude of the early/late season effect will be subject to modification by changes in precipitation amount that are highly uncertain, our results highlight the potential for decreased productivity per unit SWE under the influence of increasing snow aridity. As a result, the early/late season productivity metric characterized by this work can be used to inform future studies seeking to model the forest ecosystem response to climate change in this region and across seasonally snow-covered forested regions worldwide.

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