TITLE:

More than Drought: Precipitation Variance, Excessive Wetness, Pathogens and the Future of the Western edge of the Eastern Deciduous Forest

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ABSTRACT:

For many regions of the Earth, anthropogenic climate change is expected to result in increasingly divergent climate extremes. However, little is known about how increasing climate variance may affect ecosystem productivity. Forest ecosystems may be particularly susceptible to this problem considering the complex organizational structure of specialized species niche adaptations. Forest decline is often attributable to multiple stressors including prolonged heat, wildfire and insect outbreaks. These disturbances, often categorized as megadisturbances, can push temperate forests beyond sustainability thresholds. Absent from much of the contemporary forest health literature, however, is the discussion of excessive precipitation that may affect other disturbances synergistically or that might represent a principal stressor. Here, specific points of evidence are provided including historic climatology, variance predictions from global change modeling, Midwestern paleo climate data, local climate influences on net ecosystem exchange and productivity, and pathogen influences on oak mortality. Data sources reveal potential trends, deserving of further investigation, indicating that the western edge of the Eastern Deciduous forest may be impacted by ongoing increased precipitation, precipitation variance and excessive wetness. Data presented, in conjunction with recent regional forest health concerns, suggest that climate variance including drought *and* excessive wetness should be equally considered for forest ecosystem resilience against increasingly dynamic climate. This communication serves as an alert to the need for studies on potential impacts of increasing climate variance and excessive wetness in forest ecosystem health and productivity in the Midwest US and similar forest ecosystems globally.

KEY TERMS:

Climate Variance; Precipitation Variance; Forest Ecosystems; Forest Pathogens; Drought; Excessive wetness

Introduction

Global forest health concerns have attained increased attention recently (e.g. Trumbore *et al.* 2015). Unlike the single causal relationships that have prevailed as explanations for impacts to forest sustainability and productivity in the past (despite warnings against such approaches) research is increasingly focused on multiple causal factors (i.e. stressors) and integrating forest health with climate change. This cultural shift is not unlike the theory of forest decline that considers predisposing, inciting and contributing factors (Manion, 1981). Recently, however, there is a renewed appreciation and acceptance of the prominent role of climate and that extreme weather events and disease causing agents (e.g. insects, pathogens) synergistically and somewhat unpredictably affect ecosystem function and resilience (McEwan *et al.* 2011, Millar and Stephenson 2015, Pautasso *et al.* 2014).

Despite the recognition that synergistic factors may be creating the potential for forest health crises, many combined effects have been omitted in research and literature. For example, the effects of year-to-year climate variance on forest productivity and dynamics have been greatly overlooked. This is important because climate variance includes drought (i.e. excessive dryness) *and* excessive wetness, and ecosystem responses to climate variables and variability are generally nonlinear and stochastic. While, it is indeed the variability (i.e. drought and wetness) of climate that creates the conditions for biological and ecological complexity (Burkett *et al.* 2005), the precipitation regime and often overlooked associated plant physiological stressors related to periods of excessive wetness are deserving of equivalent concern as drought in a dynamic and changing anthropogenic climate. It is arguable that increasing variability of climate conditions (both drought *and* wetness) is among a suite of characteristics requiring a changing perspective in terms of plant and ecosystem productivity, and forest health (Pautosso *et al.* 2014).

Ensemble global circulation models indicate future changes in precipitation throughout the central US ranging from -2.5 percent to 19.6 percent, with a mean increase of 12.4 percent under the A1B emissions scenario (Girvetz *et al.* 2009). These changes are supported by studies that show that since the 1950's larger precipitation events have a higher return interval in the central US (Groisman *et al.* 2012; Villarini *et al.* 2013). These observations, coupled with changing temperature regimes are likely to affect the timing of snow melt, evaporative demand, quantity and quality of water, and vegetation productivity. Obviously, considerations of such variance, and particularly excessive wetness in an increasingly wet environment, is of critical importance for forest management. Thus, understanding forest response to increasingly variable climates particularly the precipitation regime and identifying needed research to provide science-based management solutions are essential to manage legacy forests in new climates.

The effects of wetness and climate variance on forests of the western edge of the Eastern Deciduous Forest (EDF) of the United States at long and short time scales are the focus of this short communication. In particular, this urgent problem is exacerbated by recent increased mortality of a dominant forest species, white oak (*Quercus alba*), in the lower Midwest. This rapid mortality has occurred during periods of ample, if not excessive precipitation (NOAA 2015). The coincidence of tree mortality and excessive soil moisture might suggest a biotic factor that is aggravated by climate effects. On this basis, it is probable that increasingly extreme wet weather systems have contributed to the development of biotic agents, including pathogens and fungal-like oomycetes (water molds) such as *Phytophthora* and *Pythium* that often flourish with combined and prolonged soil and plant moisture (Sturrock *et al.* 2011). These organisms have been shown to develop in forest soils and cause root death and eventually tree death ultimately affecting plant species distribution and diversity (Augsburger and Wilkinson 2007,

Reinhart *et al.* 2005). In the following sections, specific points of supporting evidence are provided including climate data, geographic climatology, variance predictions from global change modeling, Midwestern paleo climate data, local climate influences on net ecosystem exchange and productivity, and pathogen influences on oak mortality and decline. Evidence indicates that the western edge of the Eastern Deciduous Forest (EDF) has the potential for increased year to year variance in climate, particularly excessive wetness, perhaps to the detriment of regional forest ecosystem productivity.

A Changing Climate and Precipitation Variance

There is currently a great deal of uncertainty in predictions of climate change impacts, and in particular precipitation regimes, and how ongoing human activities may continue to affect spatio-temporal precipitation variability. In general projections of global circulation models, under various emissions scenarios, indicate that a continuing warming atmosphere will result in more intense and also less frequent precipitation characterized by greater risk of droughts and floods (Trenberth *et al.* 2014; Meehl and Tebaldi 2004; Cook *et al.* 2015). In fact, recent and sudden (i.e. in the past 50 years or less) shifts in the precipitation regime may already be dramatically altering terrestrial vegetation communities that adapted to a more stable climate that exhibited less climate variance over the last millennia. These recent and dramatic shifts in drought *and* excessive wetness (the overabundance of precipitation) are likely to alter the dynamics of the terrestrial ecosystems and carbon and water cycles (Knapp *et al.* 2008).

Climatological variance is a key characteristic of the definition of a ‘continental climate’. In mid-continental North America (location of the western edge of the EDF) the climate has varied over the Holocene from Humid Continental, to Humid Sub-tropical continental, to Dry Steppe depending on climate era (Delcourt and Delcourt, 1987). Recent model predictions place

the western edge of the EDF in the center of a region of potential increased precipitation and temperature variance (Cook *et al.* 2015), thereby pointing to the importance of future investigations of forest productivity and excessive wetness in that region.

Precipitation data from St. Louis, Missouri (1873 to 2014) encompasses much of the period of accelerated global change (NOAA 2015, Mann *et al.* 1999). Annual precipitation data were analyzed with the a priori hypothesis that short periods of temporal variance in climate would promote stress and possible mortality of forest tree species. For ease of interpretation and graphical representation, a moving seven year standard deviation was used to quantify climate variance. Although somewhat arbitrary, the seven year period is arguably long enough for a climate variance estimate, and short enough to induce rapid biological consequences. A significant ($r = 0.42$, $p < 0.05$) correlation between time (i.e. the years of 1873 to 2013) and precipitation variance (a positive trend) indicates that climate variance exists and may therefore be a novel parameter to consider to quantify the influence of climate on forests on the western edge of the EDF (Figure 1). Of additional interest, recent periods from 1981 to 2011 exceeded the 95% prediction interval for the seven year variance indicating acceleration of change in recent decades. This finding is strengthened by an examination of drought and extreme wet years and forest productivity in the geographically associated Western edge of the EDF.

Figure 1. Increasing short-term variance (SD) in the annual precipitation record (St. Louis, Missouri, USA) that is hypothesized to be biologically relevant for forest trees and soils. The standard deviations of seven year periods of annual precipitation increased approximately 40 % in 130 years. The regression line is significant ($p < 0.05$). There are missing data in the 1930s (data: NOAA 2015).

Drought and Excessive Wetness

The Midwest United States represents an ideal region for investigating precipitation regime alterations and impacts on ecological processes. Droughts in the past 90 years (e.g. 1930s, 1950s, 1988-1989 and 2012) clearly showed ecosystem sensitivity to altered precipitation

regimes (Albertson and Weaver 1945; Jenkins and Pallardy 1995; Pedersen 1998; Voelker *et al.* 2008). A key long-term climate monitoring installation in the lower Midwest region is the Missouri AmeriFlux (MoFlux) site, in operation since 2004 and including a suite of meteorological and ecological instrumentation. MoFlux is located in the University of Missouri's Baskett Wildlife Research and Education Center Forest (BWREC, 38 4403900 N, 92 120 W) in the Ozark border region of central Missouri. Second growth upland oak-hickory forests constitute the major vegetation type (Pallardy *et al.*, 1988).

To investigate the scope of recent climate variability and ecosystem productivity, and thus support the suppositions presented here, the MoFlux climate record was examined for the recent period of 2005 (first full year of data) through 2013 ($n = 9$ years), the wet year of 2009, and the drought year of 2012 (Table 1). From 2005 through 2013, the annual average precipitation (PPT) was 880mm (minimum = 563, maximum = 1350 in 2008, $SD = 279$ mm). Precipitation was 1213 mm in 2009 as opposed to only 563 mm in 2012. Mean air temperature (T_a) was 13.5 °C ($SD = 10.6$ °C) over the period of 2005-2013, and was on average 1.3 °C lower ($SD = 9.9$ °C) and 2.0 °C higher during the excessive wetness and drought years of 2009 and 2012, respectively. Vapor pressure deficit (key ecosystem driver of photosynthesis, water vapor flux, and plant productivity) followed a similar pattern as T_a . Net ecosystem exchange (NEE) of carbon showed that in general the AmeriFlux (MoFlux) site is a net sequester of carbon, even during extreme drought years, (indicated by average negative values) with average NEE of $-0.7 \mu\text{mol}/\text{m}^2/\text{s}$ as a 2005-2013 average, $-1.1 \mu\text{mol}/\text{m}^2/\text{s}$ and $-0.5 \mu\text{mol}/\text{m}^2/\text{s}$ for 2009 and 2012, respectively. Air temperature, VPD, and NEE were all statistically different (One-Way ANOVA, $CI = 0.05$, $P < 0.001$) between 2009 and 2012.

The NEE results (a biological response to climate variability) stand out as one of the noteworthy observations from analysis in that total carbon flux for 2009 and 2012 was approximately $-403 \mu\text{mol}/\text{m}^2/\text{s}$ and $-187 \mu\text{mol}/\text{m}^2/\text{s}$, respectively (Figure 2). The nine-year average of NEE was $-248 \mu\text{mol}/\text{m}^2/\text{s}$. These differences are important to note for a number of reasons, not the least of which is that while SD's remained relatively similar between periods of study, 2009 had more than twice the average and maximum NEE relative to the 2012 drought year. Notably, average minimum NEE values over the nine-year period of study relative to excessive wetness vs. drought years were more than twice as high. These results indicate that at MoFlux, on average, minimum NEE, or greatest carbon sequestration, occurs under average conditions. Conversely, years of drought, or years with above average precipitation may both (i.e. extreme climate variance), in nearly equal proportion (i.e. -6.6 and $-6.7 \text{ mmol}/\text{m}^2/\text{s}$ during excessive wetness and drought years, respectively) be detrimental to forest productivity during those events. Further, due to prolonged excessive wetness forests may become more susceptible to disease causing agents including (but not limited to) pathogens during those times. These results, while admittedly a case study over an arguably short time-period, validate the presence of extreme climate at MoFlux in terms of both drought and excessive wetness in this central US forest region, and support the hypothesis that excessive wetness is of as great importance as drought for future forest productivity. Notably, the MoFlux site provides a basis to link long-term climate variability (Fig. 1) and forest net ecosystem productivity (i.e. biological impacts of climate) in the western edge of the EDF.

Table 1. Air temperature (Ta), Vapor Pressure Deficit (VPD) and Net Ecosystem Exchange (NEE) at the Missouri AmeriFlux (MoFlux) site, Ashland Missouri, USA., 2005-2013, and 2009 (extreme wet year) and 2012 (extreme drought year).

	Ta (°C)	VPD (kPa)	NEE (μmol/m²/s)
2005 - 2013 (MoFlux/AmeriFlux Climate)			
Mean	13.5	0.7	-0.7
Minimum	-16.0	0.0	-13.3
Maximum	33.7	3.4	6.8
Std. Dev.	10.6	0.5	2.4
2009 (Historic Wet Year)			
Mean	12.2	0.5	-1.1
Minimum	-16.3	0.0	-6.6
Maximum	29.6	1.8	5.1
Std. Dev.	9.9	0.4	2.5
2012 (Historic Drought Year)			
Mean	15.5	0.9	-0.5
Minimum	-7.8	0.0	-6.7
Maximum	33.8	3.3	3.1
Std. Dev.	10.0	0.7	2.0

Ta = Air Temperature, VPD = Vapor Pressure Deficit, NEE = Net Ecosystem Carbon Exchange, Std. Dev. = Standard Deviation

Figure 2. Cumulative air temperature (Ta), Vapor Pressure Deficit (VPD) and Net Ecosystem Exchange (NEE) at the Missouri AmeriFlux (MoFlux) site, Ashland Missouri, USA., 2005-2013, and 2009 (extreme wet year) and 2012 (extreme drought year).

Soil Moisture and Forest Pathogens

Among the forest pathogens most affected by climate conditions, *Phytophthora* (literal meaning: the plant destroyer), an oomycete (water mold), could increase in importance with warm and moist conditions (Bergot *et al.* 2004, Thompson *et al.* 2014). In warmer climates such as Australia, *Phytophthora* has long been a major agent of mortality. Recently, however, *Phytophthora cinnamomi*, (Pc) has become more frequently identified as having an important role in forest mortality in temperate forests. In the western edge of the EDF, specifically the Missouri Ozarks, mortality of *Q. alba* has reached a level not previously witnessed (Reed *et al.* 2016; Missouri Department of Conservation 2014). Since 2010, mortality of *Q. alba* has steadily increased in lower slope positions along waterways. Soil sampling has revealed that Pc is found in soils in the high mortality areas (Reed *et al.* 2016). The event has not be described as a decline, defined by a slow gradual mortality, but rather a distinct abrupt mortality event that targets dominant long-lived species. Similar mortality events of this species have been observed and studied in Ohio by Balci *et al.* (2010), who showed Pc associated with the same host tree species as in Missouri Ozarks (*Q. alba*).

Members of the genus *Phytophthora* include notorious pathogens such as *P. infestans* (late blight of potato), as well as *P. ramorum* (sudden oak death). The possibility of sudden oak death (currently restricted to the western US) occurring in the eastern US has generated interest in examining *Phytophthora* in forest soils in the eastern US. Balci *et al.* (2007) confirmed that *Phytophthora* appear to be common in soils in the US, but the occurrence was limited to areas south of 40° latitude. Investigation of soils in areas of Missouri associated with *Quercus* mortality confirm occurrence of *Pc*, among other possible *Phytophthora* species (Schwingle *et al.*, 2007). Although *Pc* is considered exotic in the US, it has been recognized as an important

pathogen of tree species since the 1930's (Crandall *et al.* 1945). Thompson *et al.* (2014) pointed out the importance of soil moisture and excessive wetness in predicting distribution of *P. cinnamomi*.

Recent work by Lehmann *et al.* (2015) reported a surge in record breaking rainfall events coincident with rising temperatures. *Phytophthora* can thrive in very moist soils and moderate to warm temperatures (Corcobado *et al.*, 2013; McConnell and Balci, 2014), but also may become rare in drought conditions (Brouwers *et al.* 2013). Increasing climate variance, including excessive soil moisture either followed or preceded by drought contributes to the deleterious effect and the further advancement of this group of pathogens (Desprez-Loustau *et al.*, 2006). Balci *et al.* (2010) directly implicated *P. cinnamomi* in white oak decline in Ohio and the presence of the root pathogen was associated with soils of higher moisture content. Experimentally, Corcobado (2014) simulated extreme weather events in seedlings and showed that drought may predispose seedlings to sensitivity to *Phytophthora* root infection. Seedlings that were inundated, and then subjected to drought conditions (i.e. high climate variance) resulted in 100% mortality.

Summary and Conclusions

It is increasingly accepted that multiple contributing factors (i.e. multiple stressors) affect forest health and productivity. Despite this, the relative impacts of an increasingly variable climate on forest ecosystem productivity remains underappreciated. This may be most evident in terms of potential detriments to forest ecosystem resilience against extreme events including drought but equally focused on excessive wetness. For example, recent research indicates a surge in record breaking rainfall coincident with rising temperatures. Concurrent rapid recent mortality

of white oak (*Quercus alba*) in the lower Midwest highlights this issue since mortality has been connected to periods of excessive precipitation in a warming climate.

This communication provides evidence from a variety of sources both historic and contemporary, and regional and local that support the supposition that certain regions, globally, may be sensitive and particularly susceptible to climate extremes, including both drought *and* excessive wetness. Given the evidence, this communication serves as an alert, and an appeal for research that equally considers the impacts of drought *and* excessive wetness both at the individual tree and the ecosystem level so that forests of the EDF and vegetated ecosystems elsewhere can be sustainably managed in an increasingly variable climate.

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