Observed Changes in West Virginia’s Climate, Land Use, and Forest Species Composition

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Abstract

Relatively few studies have simultaneously addressed observed changes in climatic averages and variability, land use, and forest species composition that jointly influence coupled land-atmosphere interactions (e.g. water and carbon cycles). West Virginia (WV), USA represents a quintessential region to do this since old growth hardwood forests were cleared for timber extraction, agricultural development, and settlement near the turn of the 20th century. It was estimated that agriculture and pasture lands comprised 72% of WV’s land area in 1909, but farm abandonment resulted in rapid afforestation with forest cover estimated at 64% and 79% in 1949 and 1979, respectively. Forest cover remained steady (~79%) through the 2016 forest inventory analysis, but the forest species composition shifted from oak (Quercus spp.) to maple (Acer spp.) species in response to a positive-feedback loop more commonly referred to as mesophication. For example, in 2013, oaks and maples represented approximately 46% and 5% of larger trees (>50.8 cm in diameter) and 5% and 27% of smaller trees (5.1 to 10.2 cm in diameter), respectively suggesting mesophication will continue. Oaks and maples have different hydraulic architectures that may reflect an evolutionary trade-off between hydraulic conductivity (i.e. water use) and drought vulnerability suggesting that climatic changes in WV increased water availability and reduced drought severity. Seven year moving averages and standard deviations of observed maximum temperatures, minimum temperatures, precipitation, and modeled vapor pressure deficits (VPD) were quantified and averaged across WV (n = 18) over a 111 year period of record (1906-2016). Results showed that maximum temperatures decreased significantly over the period of record (-5.3%; $p = 0.000$), minimum temperatures increased significantly (7.7%; $p = 0.000$), and precipitation increased (2.2%; $p = 0.107$). Additionally, maximum temperature variance decreased (-17.4%; $p = 0.109$), minimum temperature variance decreased significantly (-22.6%; $p = 0.042$), and precipitation variance increased significantly (26.6%; $p = 0.004$). Results indicate a reduced diurnal temperature range with less temperature variance that is further supported by significant reductions in modeled VPD (-10.3%; $p = 0.000$), which is a key ecosystem driver of photosynthesis, water vapor flux, and plant productivity. Therefore, feedback mechanisms associated with simultaneous changes in climatic averages and variability, and use (e.g. afforestation), and forest species composition may have reduced drought severity in WV with regional implications for water, energy, and carbon transfer.

Evolutionary Trade Off

- **Isohydric species** (e.g. maple) maintain relatively constant leaf water potential by regulating stomatal conductance and are generally diffuse porous.
- **Anisohydric species** (e.g. oak) maintain relatively constant stomatal conductance allowing variable leaf water potentials and are generally ring porous (Yi et al. 2017).

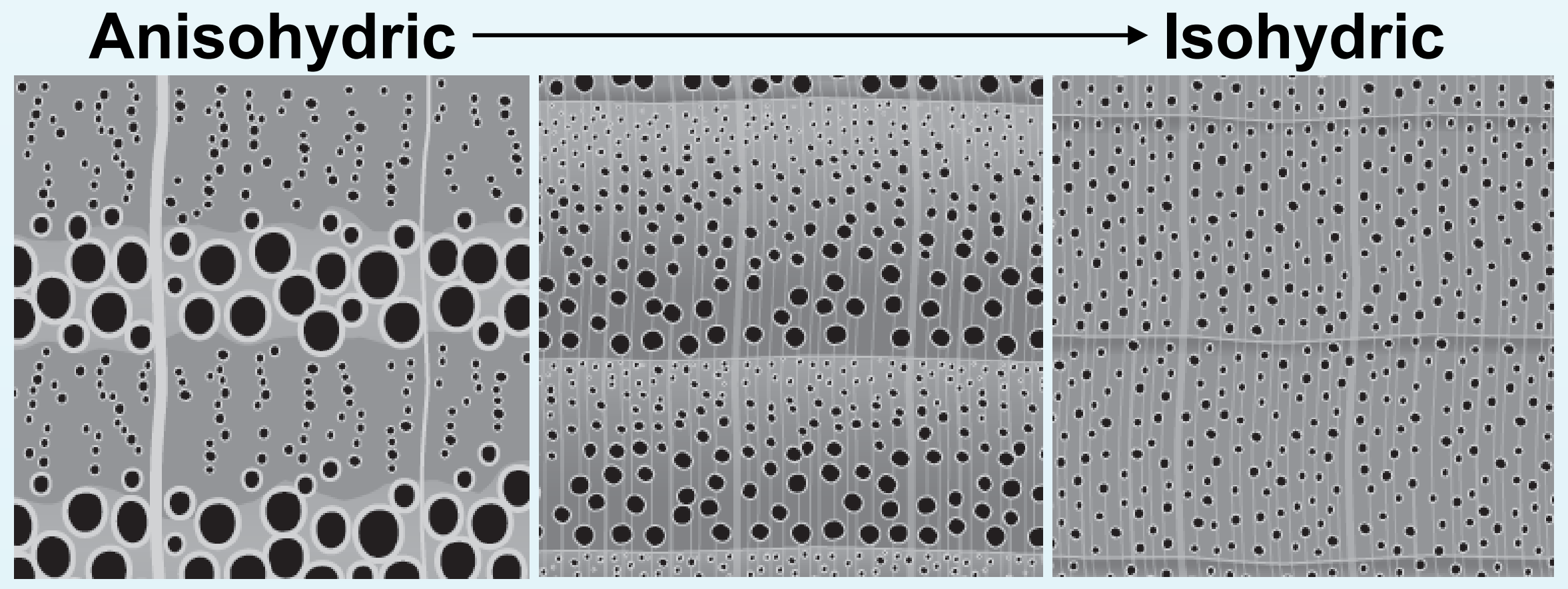

Figure 1. Magnified cross sectional depiction of three xylem porosity types: ring porous (R; left), semi-ring porous (SR; middle), diffuse porous (D; right; Hoadley 2000).

Ring Porous (R):	**Diffuse Porous (D):**
Most common in northern temperate habitats	Common across a broad range of latitudes
- Less shade tolerant, more fire tolerant	- More shade tolerant, less fire tolerant
Less vulnerable to drought-induced cavitation	More vulnerable to drought-induced cavitation
- Maintains C assimilation during drought	- Reduces C assimilation during drought
More vulnerable to freeze-induced embolism	Less vulnerable to freeze-induced embolism
- Up to 95% vessels embolized first freeze	- Gradual embolism losses during winter
- Larger vessels, rarely survive one year	- Smaller vessels, can be active for years
Xylem vessels form during leaf expansion	Xylem vessels form after leaf expansion
- Later leaf out → shorter growing season	- Earlier leaf out → longer growing season

Table 1. West Virginia’s 2015 Forest Inventory Analysis data of trees ≥12.7cm (Morin et al. 2017) and xylem porosity of each species from the InsideWood Database (Wheeler 2011).

Species	Trees (millions)	Net volume (hm³)	Net Growth (hm³/yr)	Mortality (hm³/yr)	Growth / Mortality	Porosity
Yellow-poplar	147 ± 24	120.3 ± 1.3	2.85 ± 0.12	0.67 ± 0.03	**4.29**	**D**
Red maple	237 ± 38	76 ± 0.8	1.72 ± 0.07	0.50 ± 0.02	**3.42**	**D**
Sugar maple	164 ± 26	57.1 ± 0.6	1.43 ± 0.06	0.44 ± 0.02	**3.24**	**D**
Chestnut oak	152 ± 24	77.1 ± 0.8	1.28 ± 0.05	0.41 ± 0.02	3.15	R
Hickory spp.	128 ± 20	53.5 ± 0.6	1.05 ± 0.04	0.35 ± 0.02	2.99	R
Black cherry	59 ± 9	35 ± 0.4	0.70 ± 0.03	0.27 ± 0.01	**2.54**	**SR**
Northern red oak	70 ± 11	65.2 ± 0.7	1.40 ± 0.06	0.57 ± 0.03	2.47	R
White oak	117 ± 19	67.4 ± 0.7	1.00 ± 0.04	0.61 ± 0.03	1.63	R
Black birch	51 ± 8	14.4 ± 0.2	0.21 ± 0.01	0.15 ± 0.01	**1.36**	**D**
Ash spp.	42 ± 7	21.1 ± 0.2	0.15 ± 0.01	0.45 ± 0.02	0.34	R
American beech	76 ± 12	30.3 ± 0.3	0.00 ± 0.00	0.50 ± 0.02	**0.01**	**D**

D = diffuse, **SR** = semi-ring, R = ring

Climatic Trend Methodology

Daily precipitation, maximum temperature, and minimum temperature data were acquired from the National Center for Environmental Information (NCEI) for eighteen sites spatially distributed across West Virginia (Kutta and Hubbart 2018). Stations were selected with a start date prior to 1930 ensuring analyses included the unprecedented summer heat associated with droughts during the 1930’s (i.e. Dust Bowl) and 1950’s (Cook et al. 2007; Vose et al. 2017). Vapor pressure deficit (VPD) was calculated as the difference between saturation (maximum temperature) and actual (minimum temperature) vapor pressures (Buck 1981; Kimball et al. 1997). Seven year moving averages were used to smooth inter-annual modes of climate variability, namely the El Nino-Southern Oscillation (Detto et al. 2018), and seven-year moving standard deviations were used to quantify changing climate variance. Mann-Kendall’s trend test and Sen’s slope estimator were used to determine significance (α = 0.05) of estimated rates of change. Mann-Kendall’s trend test and Sen’s slope estimator are non-parametric approaches that don’t assume normally distributed data and are less sensitive to outliers (e.g. Tabari et al. 2011; Gocic and Trajkovic 2013).

Temperature Trends

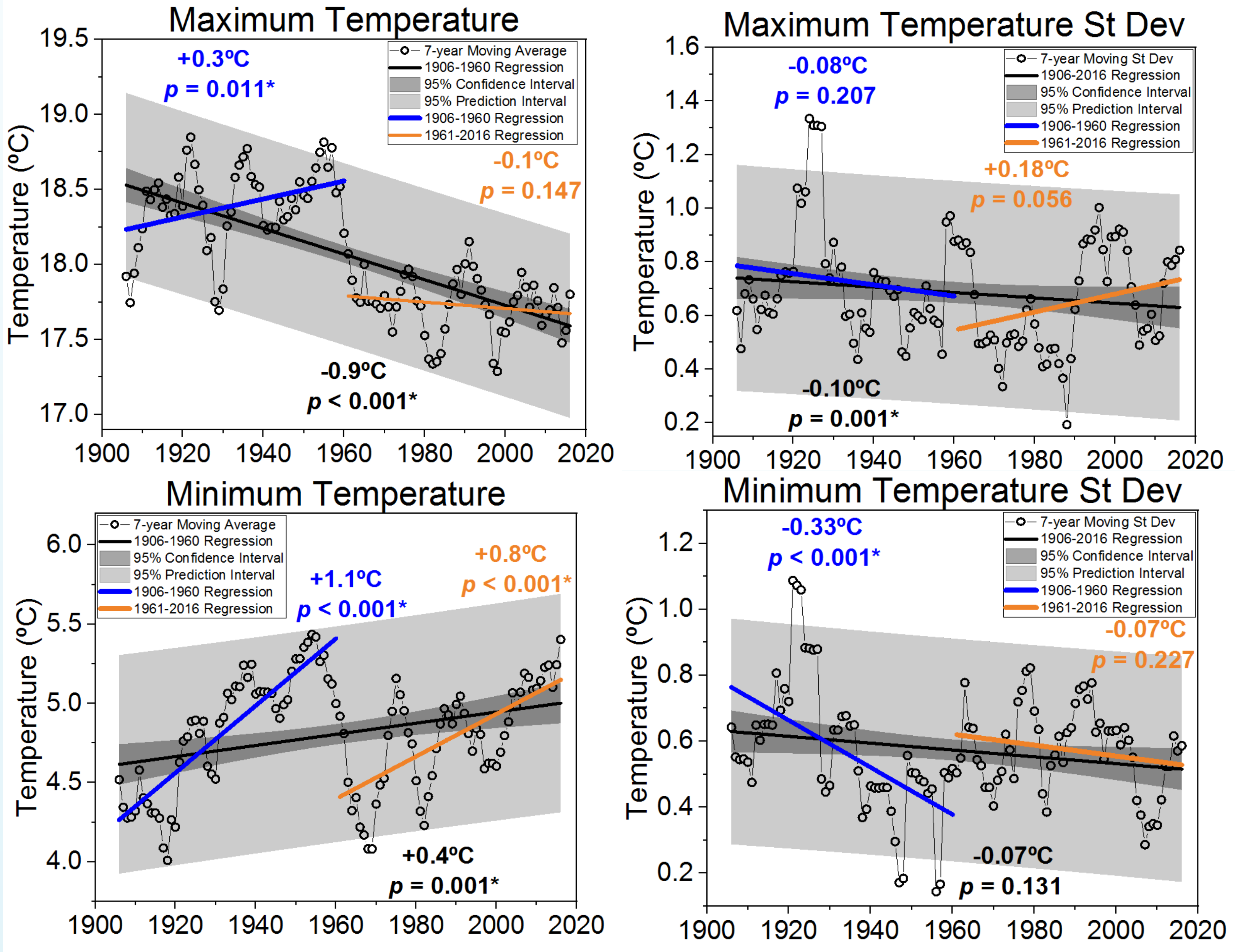

Figure 2. Seven year moving averages (left) and standard deviation (St Dev; right) of observed maximum (top) and minimum (bottom) temperatures in West Virginia, USA. Black, blue, and gold lines and text correspond with linear regressions and estimated magnitudes of change during the whole (1906-2016) time series and the first (1906-1960) and second (1961-2016) halves, respectively. * = significance ($p < 0.05$)

Results and Discussion

1906-1960:

- West Virginia’s estimated forest cover increased from ~28% to >64% (Brooks 1911; Bones 1978)
- Warming temperatures and decreasing precipitation suggests long-distance impacts associated with the 1930s (Vose et al. 2017) and 1950s droughts (Cook et al. 2007) that may have favored R xylem structures.
- Temperature variability decreased indicating persistently warmer temperatures and year-to-year precipitation variability increased indicating greater difference between wet and dry years, especially during the 1930’s Dust Bowl (Figure 3).

1961-2016:

- Stem counts (Morin et al. 2015) and growth to mortality ratios (Morin et al. 2017; Table 1) suggest D species are outcompeting R species; simultaneously increasing carbon assimilation and drought vulnerability (Yi et al. 2017).
- Diurnal temperature range (DTR) and VPDs decreased implying increased cloudiness and soil moisture (Easterling et al. 1997; Dai et al. 1999) and decreasing evapotranspiration rates (Kutta et al. 2018), despite warming temperatures.
- Precipitation and precipitation variability increased implying more frequent and more extreme wet years (Easterling et al. 2017) consistent with wetter summers characterized by more frequent rainfall (Bishop and Pederson 2015).

1906-2016:

- Gradually warming annual average temperatures mask converging trends in maximum and minimum temperatures
- Temperature variability decreased implying an increasingly temperate climate with fewer extreme hot or cold years.
- Precipitation increased and trends may be accelerating consistent with global climate trends (Easterling et al. 2017).
- Precipiation variability increased significantly implying more frequent precipitation extremes (Fischer and Knutti 2015).
- VPD and VPD variability decreased indicating increased landscape wetness that may exacerbate pest and pathogen vulnerabilities including emerald ash borer and beech bark disease (Herms and McCullough 2014; Cale et al. 2015).

Moisture Trends

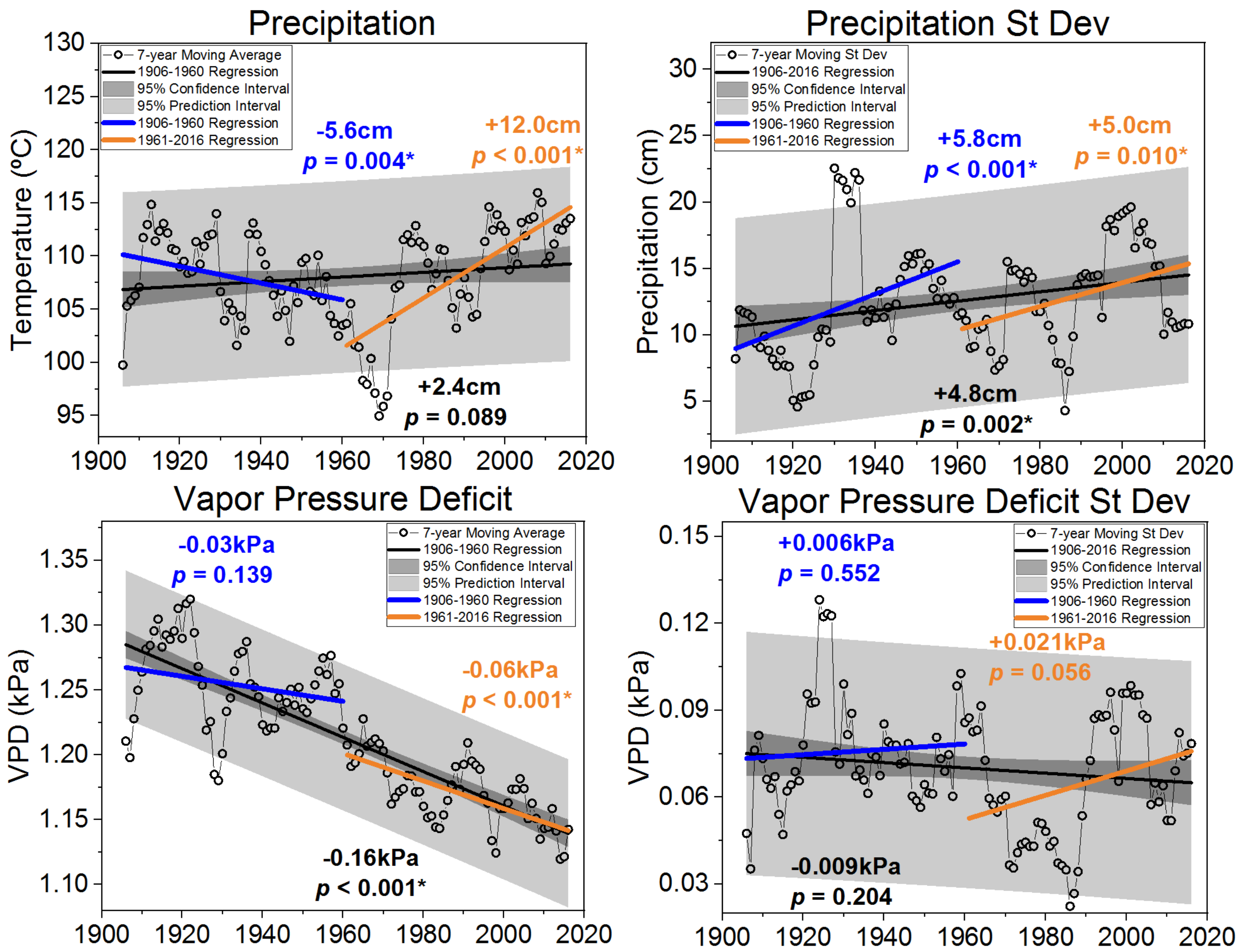

Figure 3. Seven year moving averages (left) and standard deviation (St Dev; right) of observed annual precipitation (top) and vapor pressure deficit (VPD; bottom) in West Virginia, USA. Black, blue, and gold lines and text correspond with linear regressions and estimated magnitudes of change during the whole (1906-2016) time series and the first (1906-1960) and second (1961-2016) halves, respectively.
* = significance ($p < 0.05$)

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Conclusions

- Between 1906 and 2016, West Virginia’s climate became increasingly humid, wet, and temperate associated with reforestation: ~28% (1909) to 79% (1979 to present)
- Trends in maximum and minimum temperatures converged indicating decreasing VPD and DTR consistent with increased precipitation and associated cloudiness
- Decreasing VPD and temperature variability indicates increasingly common small DTRs that may prolong wet conditions and increase vulnerability to pests and pathogens
- Increasing precipitation and precipitation variability indicates more frequent and extreme wet years in West Virginia that may increase frequency or magnitude of flooding.
- Changes in West Virginia’s forest species composition are consistent with reduced drought duration or severity, which implies accelerating water and carbon cycles.

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