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Research Paper

Phenology and growth responses of Fraser fir (*Abies fraseri*) Christmas trees along an elevational gradient, southern Appalachian Mountains, USA

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ABSTRACT

Fraser fir (*Abies fraseri*) trees are endemic to locations above 1500 m in the southern Appalachian Mountains, and are also grown commercially for Christmas trees well below their native range (down to 600 m). To evaluate how phenology and growth of this species will respond to climate drivers associated with warming, we assessed the timing of bud-burst, shoot growth, trunk growth, as well as shoot- and leaf-level architecture, of Fraser fir Christmas trees along an elevational gradient from 664 to 1228 m. Daytime maximum temperatures and evaporative demand were highest at low elevation and cloud events and higher wind speeds occurred more often at high elevations. Bud-burst occurred 6 days sooner, new shoots ceased elongation 10 days sooner, and radial trunk growth ended 8 days later at low elevations than at high elevations, indicating a shift and lengthening of the growing season. Final shoot length did not vary among elevations, but the percent increase in trunk diameter was greatest at middle elevations. Architectural characteristics such as specific needle mass, needle packing density, and silhouette-to-projected area ratios generally did not vary with elevation. As climate change progresses, higher cloud ceilings, increased evaporative demand, and higher temperatures may further shift the timing of the growing season and reduce growth at low elevation Christmas tree farms, but farms at higher elevations may benefit from a longer growing season.

1. Introduction

Fraser fir (*Abies fraseri* [Pursh] Poir.) is a southern tree species endemic to only seven high-elevation peaks above 1500 m, where it occupies an area of ~18,000 ha in the southern Appalachian Mountains. Trees in these sites experience frequent cloud immersion and it has been estimated that they are immersed in clouds for part of the day on ~70% of all days (Reinhardt and Smith, 2008a,b; Berry and Smith, 2012). They are also subject to cool temperatures during the growing season (Johnson and Smith, 2006; Potter et al., 2008; Berry and Smith, 2013; Berry et al., 2013), with daytime temperatures rarely exceeding 22 °C. These cloud conditions and cool temperatures improve plant water status by reducing the leaf-to-air water vapor pressure deficit (VPD), maintaining high soil moisture content, and contributing to direct and indirect foliar uptake from cloudwater (Berry et al., 2013, 2014; Berry and Smith, 2014).

Although Fraser firs in their native range are adapted to those unique microclimatic conditions, this species is also grown commercially for Christmas trees at much lower elevations (as low as 600 m) and is overwhelmingly the most popular species of Christmas tree in the southern Appalachians, accounting for over 90% of all commercial production. In North Carolina alone, ~50 million trees are grown on > 30,000 ha, and the industry is valued at > $100 million/year (North Carolina Cooperative Extension Service, 2015). Christmas trees at these lower elevation farms are genetically derived from the seeds of trees growing at their natural, high-elevation locations (Arnold et al., 1994; Emerson et al., 2006, 2008). But to survive at these lower elevations, they require both weeding to eliminate competition from other vegetation and a variety of fungicides and pesticides to reduce fungal pathogens and insect pests that are predominant at these locations and which they do not encounter in their natural ranges, e.g. Phytophthora root rot. In addition, Fraser firs grown for Christmas trees must be sprayed to avoid the lethal effects of the exotic, invasive balsam woolly adelgid (Newton et al., 2011) that has decimated more than 95% of this species in its original habitat (McManamay et al., 2011).

Fraser firs in the commercial tree farms experience very different microclimatic and environmental stressors than trees in their native range, including higher temperatures in both summer and winter, lower relative humidity and hence a higher VPD, leading to an increased evaporative demand, lower soil moisture (most farms are not irrigated), and less frequent cloud immersion, resulting in much less direct foliar

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uptake of water than trees in their native habitat. The elevational gradient over which commercial Fraser firs are grown (600 m to 1250 m) provides a unique opportunity to study phenology and growth of Fraser fir in response to climate change. Such a study may yield valuable information on the ability of this species to tolerate a wide range of microclimatic conditions and provide information on the future of this industry should the region experience significant warming. The latest predictions suggest that the southern Appalachians may experience a 2.2–4.4 °C increase in temperature by the turn of the century, but only a moderate change in precipitation ranging from −20% to +10% depending on which global circulation model (GCM) is used (MacCracken et al., 2001; IPCC, 2013; Carter et al., 2014). In either case, warming will raise the cloud base and reduce the duration of cloud immersion, especially at the higher elevation farms (Richardson et al., 2003). The estimated temperature increase of 2.2–4.4 °C due to future climate change is nearly equivalent to the expected temperature difference from the highest elevation farms to the lowest based on an adiabatic lapse rate of 7 °C/1000 m elevation.

In this study, which was part of a larger one that also involved gas exchange and water relations responses along an elevational gradient (Cory, 2015; Wood, 2016), we monitored the timing of bud-burst and trunk diameter growth, the magnitude of shoot and trunk growth, as well as plasticity and adjustments of leaf and shoot architecture, along an elevational gradient from 664 m to 1228 m. We addressed the following three hypotheses: (H1) Fraser fir Christmas trees growing at low elevations (warmer and drier habitats) may shift their growing season to earlier in the season, resulting in earlier bud-break, and foliar and cambial growth, (H2) mid-summer high temperatures and increased water stress at lower elevations will decrease shoot and trunk growth during this part of the year, and (H3) architecture (*e.g.*, arrangement of needles and shoots) will adjust to maximize self-shading at the hottest and driest times of day to cope with higher temperatures and water stress at lower elevations. The results obtained may shed light on the ecophysiological plasticity of Fraser firs and how climate change might affect future Christmas tree production in the western NC mountains, as well as understanding how native populations of this species will respond to warming.

2. Methods

2.1. Study sites

Prior to the 2014 growing season, six Christmas tree farms ranging in elevation from 664 to 1228 m were chosen for study in collaboration with the North Carolina Cooperative Extension Service (Table 1), under the premise that elevation could be used as a surrogate for warming. In order to minimize factors that could be confounded with elevation, we only used study farms that had similarly aged trees (~11–14 years old, 2.5 ± 0.2 m tall) that originated from common seed sources, were planted at near equivalent densities (3906 ± 152 trees/ha; mean ± se; 5 of 6 farms in 95% confidence interval), were located on north-facing slopes, and were within 48 km of each other. Farmers at each site practiced similar agriculture techniques in terms of fertilization and shearing, although our sample trees were not trimmed during our study. All farmers removed naturally recruited plants once per growing season, but did not mow or plant cover crops, such that the understory communities were similar among farms. At each farm, 10 trees were selected for study and each was located at least 3 m from another, but all were within a 15 m radius, in order to preserve independence among replicates while minimizing within-farm variation.

To further verify that differences in agricultural practices minimally affected plant physiology and growth, we measured foliar C and N content, as well as photosynthesis and respiration under identical conditions (Cory, 2015). Foliar C differed by < 0.2% and N content differed by < 0.6% of dry needle mass (N content > 1.15% at all sites). Neither photosynthesis ($p = 0.567$) nor respiration ($p = 0.399$) under standardized conditions were affected by elevation. This evidence further supports the notion that phenology and growth responses were driven by microclimatic variation along the elevational gradient and less so by differences in agricultural practices or nutrient status among farms.

2.2. Environmental measurements

Microclimatic conditions along the elevational gradient were monitored with Davis VantagePro2 weather stations (Davis Instruments, Hayward, California) installed in May 2014 at one farm at each of the three main elevation categories (for which locations, see Table 1; images in Fig. 1). Weather stations were centrally located among the study trees at a height of ~2 m. At each farm, air temperature, relative humidity, precipitation, wind speed, and solar radiation were measured every 2 s and averages recorded every 10 min. Expected temperature increases due to adiabatic lapse follow Bolstad et al. (1998), who reported an increase of 7 °C per 1000 m decrease in elevation for the daily maximum, and 3 °C per 1000 m decrease for the daily minimum temperatures in the southern Appalachian Mountains.

Air vapor pressure deficit (VPD), the difference between saturation vapor pressure and the actual vapor pressure in the atmosphere, was used for microclimate calculations because needle temperatures were not directly measured in this study. Hernandez-Moreno et al. (2017) have shown that leaf temperatures of Fraser fir in direct sun are much higher than ambient air temperatures, so air VPD reported here is a minimal estimate of the true leaf-to-air VPD.

Throughout each day, solar radiation and VPD were integrated, yielding daily total insolation and daily evaporative demand. Soil moisture was measured weekly at a depth of 0–20 cm from April to

Table 1
Location and characteristics of the study farms. Bold represents the farm at each elevation category where weather stations were installed and gas exchange measurements took place. Tree heights are means ± s.e.

Elevation (m)	Elevation Category	Geographical Coordinates	County, State	Tree Height (m)	Planting Density (# trees per ha)
664	Low	36°22′0.95″N 82° 0′54.47″W	Johnson, TN	2.38 ± 0.07	4499
710	Low	36°23′3.37″N 81°51′19.69″W	Johnson, TN	2.62 ± 0.06	3660
1021	Middle	36°10′42.10″N 81°45′37.76″W	Watauga, NC	2.28 ± 0.04	4026
1048	Middle	36°10′47.10″N 81°45′44.17″W	Watauga, NC	2.49 ± 0.06	3681
1224	High	36°17′23.86″N 81°40′55.92″W	Watauga, NC	2.36 ± 0.04	4090
1228	High	36°16′13.51″N 81°44′3.41″W	Watauga, NC	2.59 ± 0.07	3477

Footnote: The 1228 m site was outside of the 95% C.I. for planting density.