Short communication

Observed compression of in situ tree stems during freezing

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ABSTRACT

Freezing temperatures can influence the material properties of trees. Understanding how forest biometeorological interactions respond to freezing temperatures is important for forest science and management, as its effects can cascade through coupled hydrological and ecological processes including limitations on tree growth, changes to canopy interception, and influences on atmospheric turbulence. This short communication details the effect of sub-freezing temperatures on the mechanical displacement of three in situ *Pinus contorta* Douglas (lodgepole pine) stems during a winter season (2013–2014) at Niwot Ridge Mountain Research Station (CO, USA). Although previous research on harvested trees suggests longitudinal stem expansion should occur as temperatures decrease below freezing, we observed longitudinal compression in live stems below −3 °C that linearl y correlated with sub-zero air temperatures ranging down to −22 °C. Freeze-related compression of stems frequently achieved displacement magnitudes comparable to applying 55 kN of compressive force (800 μm). Hypotheses are proposed to explain the significant mechanical displacement observed due to freezing: (1) internal gas release as freezing fronts propagate through stems; (2) short-term relocation of water via sap exudation or preferential ice crystal growth. As the observed stem compression response to freezing is substantial, future work on underlying processes and consequences is merited. The measurement technique used here may prove useful to others interested in the dynamics of stem freezing.

1. Introduction

Many forest ecosystems are exposed to freezing temperatures that can influence the material properties of trees and, thereby, interactions with meteorological conditions (Schmidt and Pomeroy, 1990; Granucci et al., 2013). These freezing related changes in forest biometeorological interactions can affect hydrological processes (Schmidt and Pomeroy, 1990), competitive interactions (Hemp, 2006; Morin et al., 2007; Doležal et al., 2013), physiological functioning (Neuner, 2014; Wisniewski et al., 2014), aerodynamic interactions (Granucci et al., 2013), and even result in economic consequences (Gardiner et al., 2000; Moore and Maguire, 2004; Aubrey et al., 2007). Thus, a thorough understanding of how freezing alters the mechanical properties of trees is useful to a wide range of forest science and management topics.

The majority of past research examining processes controlling the mechanical response of trees to freezing used dried lumber or recently cut stems and focused on stiffness, specifically Young's modulus of elasticity (*E*) (Gerhards, 1982; Schmidt and Pomeroy, 1990; Green

et al., 1999; Silins et al., 2000; Green and Evans, 2008; Umbanhowar et al., 2008; Granucci et al., 2013). A common view of changes in morphology in wood science needs to be distinguished from the present work. For example, Wiedenbeck et al. (1990) looked at changes in stemwood shrinkage as the wood dried, but work was limited to changes due to moisture loss in cut stems. It is important to draw a distinction between processes that affect cut stems, and those that affect live trees. For this reason, we do not use the term "shrinkage" in this work to refer to changes in live stem length, as that term has been applied primarily to drying of cut stems. In contrast, the present work looks at live stems, which remain subject to a compressive force due to the weight of the live tree above. Even studies concerned with freeze avoidance strategies, like deep supercooling and ice propagation barriers—see recent review on these topics by Wisniewski et al. (2014)—were typically based on recently cut stems. Results from these studies show increased complexity in a stem's internal response to freezing when wood anatomy interacts with water (e.g., Green and Evans, 2008; Wisniewski et al., 2014). Green and Evans (2008), for

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example, show E in dried lumber decreases in a consistently linear fashion across the freezing line down to temperatures of $-26\,°C$. However, the behaviour of E in moist wood at sub-zero temperatures differed significantly from non-freezing temperatures, likely as a result of ice propagation through cell lumens where there was insufficient air available to compensate for ice expansion (Mishiro and Asano, 1984; Green et al., 1999). This process would increase internal pressure and, thereby, E along with a modest increase in wood dimensions. This modest expansion at sub-zero temperatures was particularly apparent in the longitudinal direction in the results of Mishiro and Asano (1984). In freshly harvested (near-live) tree stems, infrared differential thermal analysis (IDTA) identified nonlethal freezing events in intercellular water beginning below $-3\,°C$ that resulted in linearly accelerating longitudinal ice propagation rates (Neuner et al., 2010). The Neuner et al. (2010) results indicate that ice expansion-related pressurization of stems characterized in lumber also occurs in live stems. To the knowledge of the authors, the Neuner et al. (2010) study represents the only research to date with this level of detail on freezing in fresh cut tree stems, and no studies have provided information on freezing in live, intact tree stems.

Previous research on dried and fresh cut stems agrees that initiation and primarily longitudinal propagation of ice within trees should cause longitudinal stem expansion as temperatures decrease below freezing. In this short communication, however, we report and discuss the first in situ measurements of mechanical displacement in individual live stems (*Pinus contorta*, lodgepole pine). The discussion touches on testable hypotheses aimed at explaining this phenomenon: (i) freezing-related internal gas release and (ii) short-term water relocation in response to preferential ice crystal growth or cryopreventive measures. As these data were collected for the purpose of measuring snow and rain water storage dynamics (q.e.d., Friesen et al., 2008; Martin et al., 2013; Van Stan et al., 2013) internal mechanical and physiological variables for the study trees were not measured. Thus, this short note is also meant to spur discussion of potential processes that could result in the striking freeze-related alteration to stem mechanical properties described below.

2. Materials and methods

2.1. Study site and meteorological monitoring

The instruments were located 33 m West of the Niwot Ridge ameriflux tower (40.032931, -105.547202). This site is located at 3050 m above sea level, approximately 8.5 km East of the continental divide (Fig. 1), and the surrounding terrain slopes down gently to the East (5° slope). This site has a mean annual air temperature of 1.3 °C and mean annual precipitation of 700–800 mm (Knowles et al., 2015; Diamond et al., 2013). See Greenland (1989) for additional background on the site climatology. The ground at the site is covered with a seasonal snowpack from early November through late May or early June (Burns et al., 2014), and precipitation is almost entirely in the form of snow during this period, with typical maximum snow depths of around 1.5 m.

Forest cover at the site is predominantly Lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*), with a mean LAI of 4.2, a mean canopy height of 11.5 m, and a canopy gap fraction of 17% (Turnipseed et al., 2002, 2003). Three *P. contorta* trees were selected for stem mechanical displacement monitoring. All trees were similar in size (Trees 1, 2, and 3 were 15.7, 20.7, and 18.8 cm in diameter at breast height, respectively) and their heights were approximately 12 m $\pm$ 2 m. Compressive E for the selected trees, as determined from lateral pull tests (i.e., Van Stan et al., 2013) and published relationships between bending:compressive E for *P. contorta* (Forest Products Laboratory, 2010), ranged from 2.14 to 3.39 GPa. Temperature measurements were made next to a tree stem inside the insulated covering around one of the trees (Fig. 2). The
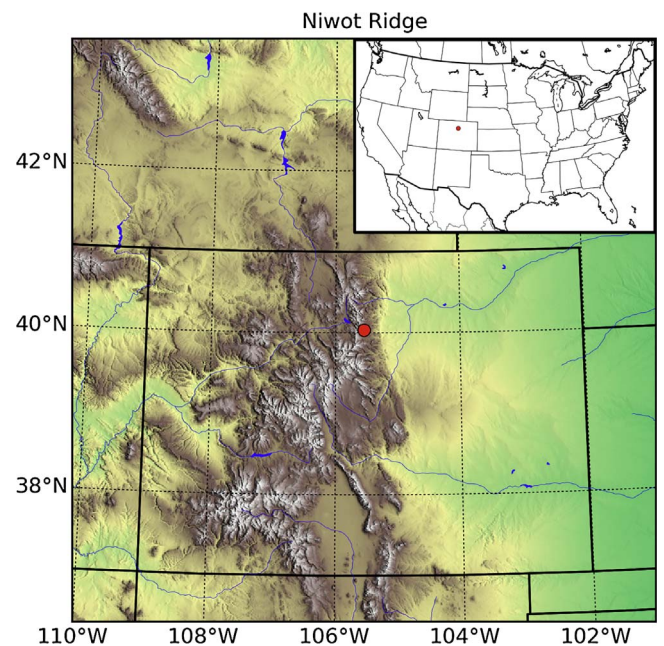

Fig. 1. Location where stem compression monitors were installed, near the Niwot Ridge Niwot Ridge Ameriflux tower site (red dot) just east of the continental divide.

temperature sensor within the insulation was a 10 K thermistor with an accuracy of $\pm$ 1% at 25 °C, and a valid range from $-55\,°C$ to $+125\,°C$. This tree stem temperature sensor was located on tree #3 approximately 2 m above the ground.

2.2. Measurement of stem mechanical displacement

Mechanical displacement monitoring was installed on the stems of three *Pinus contorta* (lodgepole pine) trees. Before installation, each tree stem was scanned with the LaserBark automated tree measurement system (Van Stan et al., 2010) to determine the placement of four sensors per methods described in detail by Van Stan et al. (2011). Mechanical displacement monitoring was done using the (Friesen et al., 2008) sensor design, consisting of a linear motion potentiometer (Bourns 3046L-2-103) extended to 1 m length by a quartz rod clamped to the stem as shown in Fig. 2. Each end of the sensor (the potentiometer and quartz rod) were epoxied to bolts (Fig. 2c), screwed into brackets that were hammered into the stem to several mm depth, and secured with steel banding (Fig. 2d). Prior to epoxying potentiometers to the bolts, each was moved to the center of the allowable electrical travel range using live computer output. Quartz rods were epoxied to magnets, then hung from the upper bolt (Fig. 2c) to ensure they hung within 0.5° of vertical, reducing likelihood of potentiometer pinching due to shear stress. To minimize epoxy expansion and contraction with temperature fluctuations, a high-strength epoxy with the lowest coefficient of thermal expansion (reported to $-40\,°C$) available was used: Scotch-Weld 1838 (3M, St. Paul, MN, USA). After installation, all four sensors around each stem were covered by protective PVC pipes, and the entire stem was wrapped with insulation. The insulation extended nearly 0.5 m above and below the instruments. Data were collected using a 16-bit analog-to-digital converter (Texas Instruments ADS1115) controlled by an ATmega328 microcontroller running Arduino firmware. Data were logged to an SD card at 10 Hz.

2.3. Data processing

Raw data from the three instrumented trees were processed to stem compression by averaging data from opposite sensors. For example, data from the North and South aligned sensors were averaged for each tree. The compression data were then averaged to 5-minute time