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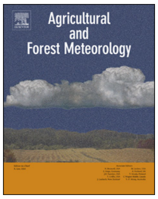

Estimating tree phenology from high frequency tree movement data

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ABSTRACT

Shifts in forest tree phenology are one of the most important and conspicuous plant responses to climate variability. However, systematically documenting changes in phenology of individual trees across large areas at high temporal frequency is often prohibitively labor- and resource-intensive. Here we present a new method that uses accelerometers to overcome challenges of measuring high-frequency tree phenology in the field. Accelerometers are small, portable devices that can be attached to trees to record movement due to forcing by wind. Time series analyses of tree movement data recorded by accelerometers can yield an approximation of tree mass. Because leaf emergence and leaf drop alter aboveground tree mass, these phenological events are expected to be detectable from accelerometer data. To test how well accelerometers can be used to measure phenological dates, we deployed 20 accelerometers on balsam poplar (*Populus balsamifera*) trees across a variety of sites during the 2016 growing season and assessed how well phenology derived from accelerometers matched visual observation of phenology recorded by citizen scientists. We found that accelerometer measurements fit the theoretical expectation for the seasonal change in tree mass associated with leaf phenology; specifically, an increase in tree mass in the spring, and a decline in the autumn. Furthermore, we found that accelerometer-derived phenology matched visual observations for leaf emergence, with a strong correlation between the dates of first observed full leaves and accelerometer-derived phenology ($r = 0.82$, $p < 0.01$). Estimates of leaf drop from accelerometers and visual observations, however, were not significantly correlated ($r = 0.16$, $p = 0.69$). Our work shows that accelerometers can reliably be used to detect spring phenology of forest trees, and have the potential to overcome some of the challenges related to documenting spring tree phenology at high spatial and temporal resolution in the field.

1. Introduction

Changes in plant phenology, the timing of periodic life-cycle events, are among the most prominent biological signals of climate change (Parmesan and Yohe, 2003). Temperate forests in particular have exhibited extreme sensitivity to climate variability, with the timing of spring onset fluctuating from days to weeks on an inter-annual basis in response to recent warming (Schwartz et al., 2006). Because forest phenology mediates interactions between climate and the biosphere (Fitzjarrald et al., 2001; Peñuelas et al., 2009), it plays an important role in ecosystem processes such as carbon and nutrient cycling (Elmore et al., 2016a; Richardson et al., 2009), and can be diagnostic of ecosystem responses to climate change. Phenology is also known to be genetically variable, with many species showing strong heritability and quantitative genetic differentiation for vegetative phenology among locally adapted populations (Keller et al., 2011; Savolainen et al., 2007). At the scale of individual plants, phenology has been shown to influence fitness and reproductive success (Ehrlén and Münzbergová, 2009; Inouye, 2008), thereby playing a role in limiting species distributions (Chuine, 2010). Ultimately, changes in phenology can have far-reaching consequences, from exposing individuals to detrimental abiotic conditions and disrupting species interactions (Visser et al., 2006) to altering the carbon cycle and even global climate itself.

While forest phenology undisputedly responds to climate variability, our understanding of phenology has been limited by the ability to document phenological processes that operate across spatial and temporal scales that span orders of magnitude—from individuals to biomes and from days to seasons. Repeated visits to individual plants by observers recording phenophases through direct visual observations are one means of monitoring phenology (e.g., Jeffree, 1960; Sparks and

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Carey, 1995). While direct observations have improved our understanding of how organisms in particular locations have responded to climate over time, high frequency monitoring is often too labor- and resource-intensive to be implemented systematically across geographically widespread field sites. While other approaches have been developed to monitor forest phenology over larger spatial areas, including via satellites, near-surface web cameras (Richardson et al., 2007), and publicly available traffic cameras (Graham et al., 2010), there is often a trade-off between spatial-temporal coverage and resolution among these systems. Satellite-derived phenology, for instance, can provide broad spatial coverage, but has limited utility in discerning the phenology of individual plants. In short, methods that overcome the challenge of spatial coverage are often too coarse-grained to quantify phenology of individual plants (Polgar and Primack, 2011), except when phenology of individual plants correlates with surface phenology of forests (Elmore et al., 2016b).

Another approach to monitoring phenology of individual trees is with on-tree sensors. Recent work has shown the utility of a variety of on-tree sensors to estimate phenology, including light emitting/detecting sensors focused on individual leaf buds (Kleinknecht et al., 2015) and sensors that measure changes in light transmitted through the tree canopy during the growing season (Schwartz et al., 2013). Other studies have explored the idea that phenological events, such as leaf emergence and leaf drop, will affect aboveground tree mass, which in turn will alter patterns of acceleration when the tree is subjected to forcing (e.g., by wind) (Selker et al., 2011; H. Lintz, unpublished). These studies show that accelerometers – a sensor that detects changes in tree acceleration related to changes in mass – can be used to detect changes in tree mass before and after leaf emergence and may offer a way to detect phenological dates without relying on intensive ground observations. However, it remains uncertain if accelerometers can be used to detect the actual dates of phenological events, and how well accelerometer-derived phenology compares to direct human observations.

Here we present and validate the use of on-tree accelerometers to derive high temporal resolution measurements of individual tree phenology. With the help of citizen scientists, we deployed accelerometers over an entire growing season, in order to: (i) determine if accelerometers can be used to derive a season-length phenological signal and (ii) compare accelerometer-derived phenology with visual observations made by citizen scientists. We demonstrate that accelerometers represent a promising way of measuring the dates of phenological events, and possibly other biological processes, of individual trees.

2. Materials and methods

2.1. Study species

We focused on the phenology of balsam poplar (*Populus balsamifera* L.), a northern broad-leaf tree species, distributed throughout much of Canada and the northern United States (Zasada and Phipps, 1990). Poplars are a model system for understanding the genetic and physiological basis of climate adaptation in trees (Soolanayakanahally et al., 2009), and previous studies have shown that both spring and autumn vegetative phenology in *Populus* has a genetic basis and is adapted to local climate conditions (Keller et al., 2012, 2011; Soolanayakanahally et al., 2013). High resolution field phenology data may be particularly useful to research in model systems such as *Populus*, and other well-studied tree species, seeking to understand the relationship between phenology, climate, and genetics.

2.2. Principles of accelerometer operation

Accelerometers detect movement by measuring acceleration in three dimensions and, when attached to a tree, detect movement caused by wind or other forces (Selker et al., 2011). When forced by wind, a tree will vibrate at a particular frequency, similar to how a bell vibrates at its resonant frequency when struck. The resonant frequency of a tree, when treated simply as a mass spring with damping, is inversely related to its mass:

$$f_0 \propto \sqrt{\frac{k}{mb}} \Rightarrow T_0 \propto \sqrt{\frac{mb}{k}} \tag{1}$$

where f_0 is the dominant resonant frequency, T_0 is the corresponding period, k is stiffness, m is mass, and b models the effect of damping. As Eq. (1) shows, changes in mass will have a direct effect on tree resonant period (T_0). In the context of phenology, when leaves emerge, the aboveground mass of the tree will increase, causing the resonant period to increase, while the opposite will occur during leaf drop (i.e., a decrease in mass, and a decrease in the resonant period). Because the dominant resonant period/frequency can be estimated from an acceleration signal, it is possible to derive a phenology signal from accelerometer data. It is worth emphasizing that there is no need to estimate the actual mass of the tree over the growing season to document phenology, as only the relative percent change in mass, approximated by a changing dominant period, is needed. Hence, our use of dominant period should be interpreted as a proxy measure, proportional to the percent change in tree mass, and this change in dominant period should be associated with phenological shifts such as leaf out, leaf drop, and other large-scale influences on tree mass.

It is important to note that the change in dominant period is affected by additional factors, such as changes in stiffness (e.g., by the growth and hardening of xylem, or hydraulic conductance of stem water) and damping (e.g., altering air resistance by growing or losing leaves). We consider these changes to be of secondary importance relative to the change in mass associated with leaf emergence, though potentially interesting topics for follow-up study. Furthermore, we note that a portion of the mass in newly expanding leaves is already present in trees before leaf emergence (before leaves become autonomous from stored carbon) in the form of non-structural carbohydrates (Hoch et al., 2003). Hence, a change in tree mass during leaf emergence and expansion is likely due to a combination of new leaf material and new water mass in the leaves and woody tissue. Partitioning the sources of mass increase would be an interesting topic for future study.

In this study, we used Oregon Research Electronics (Tangent, OR, USA) AL100 Acceleration Loggers (Fig. 1). The AL100 devices use STMicro LIS3DSH MEMS accelerometers with supporting electronics. AL100 loggers operate on one or two C cell batteries and record daily (24-h) data files to a microSD card inside the unit, which can be uploaded to a computer for processing. The AL100 devices incorporate a real-time, temperature-compensated clock that provides time-stamps for the recorded data. The electronics are enclosed in a robust weather-resistant plastic case that can be attached to trees around the primary trunk using rope or zip ties. These devices are the same as those used in van Emmerik et al. (2017).

2.3. Citizen scientists & accelerometer deployment

To validate accelerometer-derived phenology with direct estimates of tree leaf out and leaf drop, we partnered with citizen scientists to monitor phenology of individual poplar trees across our study region. Observational data (including phenology) from trained volunteers is particularly useful when sampling is required across a broad geographic area and established and reliable protocols are employed to yield high-quality data (e.g., Bonney et al., 2014). Such an approach has recently been shown in *Populus* to correlate well with phenological estimates at larger spatial scales estimated from satellite remote sensing data (Elmore et al., 2016b; Vanbeveren et al., 2016). In the present study, we trained eight citizen scientists to deploy accelerometers and record phenological observations during the 2016 growing season. This diverse group consisted of adults with various experiences monitoring