Forest Systems
24(3), eSC04, 4 pages (2015)
eISSN: 2171-9845
http://dx.doi.org/10.5424/fs/2015243-08292
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)

SHORT COMMUNICATION

OPEN ACCESS

Bending of *Pinus jeffreyi* in response to wind

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Abstract

Aim of study: To evaluate the degree of trunk sway in relation to wind velocity, with varying temporal integration and to compare this relation among seasons.

Area of study: Sierra de Juárez, Baja California, México

Materials and Methods: Displacements of a 19 m tall Jeffrey pine tree were recorded at 6 m from a three dimensional digital compass during one year, at c. 4 Hz. Adjacent wind speed at 6 m was recorded at 1 Hz.

Main results: Sway was essentially unaffected by wind in the same second but increasing dependence of cumulative displacement on average sustained wind speed was found for intervals of 1 to 60 minutes (r^2 up to 0.89). The relation is generally log-linear but apparently differs in parameters between seasons.

Research highlights: Wind-sway relations are clear from integration of several-to-many minutes. However, to estimate cumulative stress, sub-second data on sway are essential. Sub-second, precision measurements of sway can be registered from small, inexpensive sensors.

Keywords: biomechanics; *Pinus jeffreyi*; seasonality; stress accumulation; time series; tree bending.

Citation: Bullock, S.H., Martínez-Osuna, J.F., López-Reyes, E., Rodríguez-Navarro, J.L. (2015). Bending of *Pinus jeffreyi* in response to wind. Forest Systems, Volume 24, Issue 3, eSC04, 4 pages. http://dx.doi.org/10.5424/fs/2015243-08292.

Received: 11 Jul 2015. **Accepted:** 11 Sep 2015

Funding: Fondo Mixto of the Secretaría de Medio Ambiente y Recursos Naturales - Consejo Nacional de Ciencia y Tecnología (Grant 2006-C01-23807) and Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California.

Competing interests: The authors have declared that no competing interests exist.

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Introduction

The movement of air is considered one of the environmental factors that stresses trees by strikes and strains. It might be thought that the adverse effects of wind would increase with the age of a plant, inasmuch as the plant grows in height and width, but at the same time the trunk and persistent branches continue to be reinforced (Ezquerra & Gil, 2001; Telewski, 1995). Moreover, it is recognized that mechanical stress provokes greater thickening, and that in the case of wind and conifers, the thickening is on the downwind side of the tree (Telewski & Jaffe, 1986; Gardiner, 1997). If repeated and/or sustained, such response to mechanical stress becomes translated into variations in quantitative characters of the wood across and along the trunk, which can be seen as industrial problems (Weinkamer & Fraztl, 2011; Zipse *et al.*, 1998) or also as opportunities to read the history of stress and learn about past environments (Hamilton, 2005; Sheppard *et al.*, 2005).

It is difficult to conceptualize the relation among tree trunk movements and the wind over short intervals, given the flexibility and elasticity of wood and the trunk's inertia, as well as the variability of wind speed and direction, which is affected by forest canopy structure. Thus, despite the wind being the driver of trunk movements, these latter are complex and not simple to record. Thus, we suggest a different perspective than analysis of instantaneous forcing (Schindler *et al.*, 2010), which is to relate the integration of both the force and the reaction over periods of several seconds to many minutes, although the recording interval that permits such analysis is necessarily small. At the same time, it is relevant to recall both that the acclimation of living structures to stress is a much slower process, and that it may respond to past events, even months past (Lundqvist & Valinger, 1996; Telewski & Pruyn, 1998).

While our long-term goal is to evaluate the potential of conifer growth rings to represent variations in the strength and direction of sustained winds, our goal for this study was to evaluate the movement of trees in relation to wind velocity, given the scarcity of such basic information.

Materials and Methods

The study focused on a single tree of *Pinus jeffreyi* Grev. & Balf. in an open, young stand in the Sierra de Juárez, Baja California, México (32.113°N 115.914°W, 1664 m elevation). The tree was 19 m tall with a diameter of 0.33 m at 1.3 m. The tree was instrumented at 6 m height with a three dimensional digital compass (OS5000-S, Ocean Server Technology Inc.), which reported at a frequency of approximately 4Hz. This technology simplifies the resolution of technical difficulties (Hassinen *et al.*, 1998; James *et al.* 2006; James & Kane 2008). At 11 m from the tree, we installed a tower with anemometers and wind vanes at 6 and 10 m height, which reported at 1 Hz. The study period was 10 November 2009 to 15 November 2010. The data analyzed here were 7 to 11 day blocks in the months of January, March, August and October of 2010. The number of 1 second records was 907678 (January), 643019 (March), 977520 (August), 950400 (October). Air temperatures varied as follows: January, 4.0 C ± 6.3 C (mean ± standard deviation; full range -9.9 to 28.2 C); March, 9.1 ± 8.5 C (-4.1 to 34.8); August, 24.7 ± 8.7 C (3.9 to 43.2); October, 11.5 ± 6.4 C (1.7 to 30.5).

Trunk movements were calculated with the positions determined by angular rotation in two axes ("pitch" and "roll"), with reference to a point arbitrarily designated at one meter below the sensor. For the present analysis, the direction of movement was ignored. Displacement was calculated second by second using the average of the data registered in the second for lack of sub-second resolution of the records.

The anemometer (Vortex; Inspeed.com LLC) was calibrated by comparison of field data with an ultrasonic anemometer (81000V; R.M. Young Co.). The anemometer reported complete revolutions, resulting in a jump from zero to 2.3 m sec^{-1}, given the frequency of 1 Hz.

Results and Discussion

The month of January presented the strongest winds and the highest frequency of moderate and strong winds. The greatest trunk displacements during one second approached one meter in January. We emphasize that the distances calculated are the differences between successive seconds and not the length of the entire trajectory of movement in that interval.

The data showed little relation between the velocity of the wind in a second and the displacement in the same second ($r^2 = 0.06$), although with 15000 data this relation was significant (Figure 1; Table 1). We found increasingly close relationships by summing the displacements and averaging the wind velocities for longer intervals, of 1, 10 or 60 minutes (Figure 1, Table 1). It is possible that the relations were not linear on normal. Also, the form of the relationship apparently was not constant though the year (Figure 2).

The relation between bending of the trunk and wind is not instantaneously evident but appears clearly with the integration of short-interval data over periods of several to many minutes. Given the size of the system that integrates the reactions to wind stress and the complexity of the wind itself inside a forest environ-

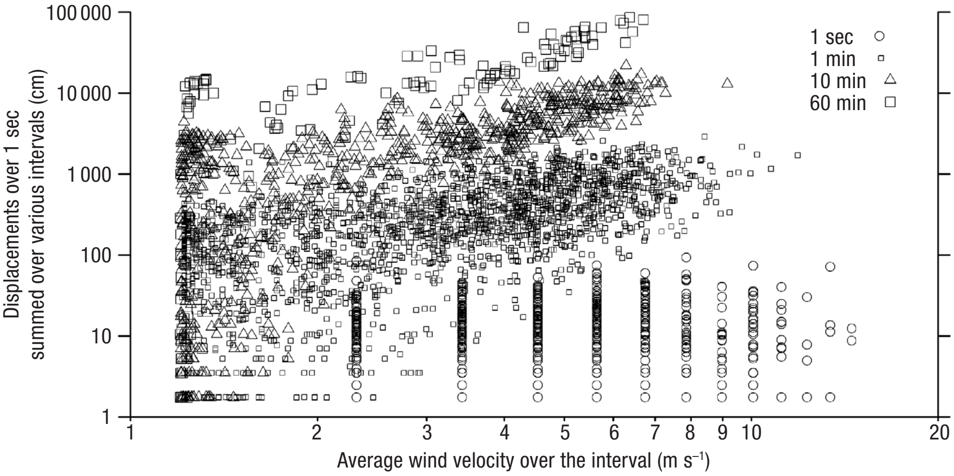

Figure 1. Data on trunk displacement and wind velocity for January.

Table 1. Results of linear regression of trunk displacement (sum of 1 Hz measurements) on wind velocity (mean of 1 Hz measurements).

Month	Interval	N	r^2_{adj}	Standard error of the estimate / mean displacement	Slope
January	1 second	15000	0.06	1.33	
January	1 minute	15000	0.55	1.32	
January	10 minutes	1513	0.75	0.89	
January	60 minutes	252	0.84	0.50	0.90
March	60 minutes	178	0.84	0.60	4.91
August	60 minutes	270	0.89	0.40	0.89
October	60 minutes	264	0.88	0.42	1.24

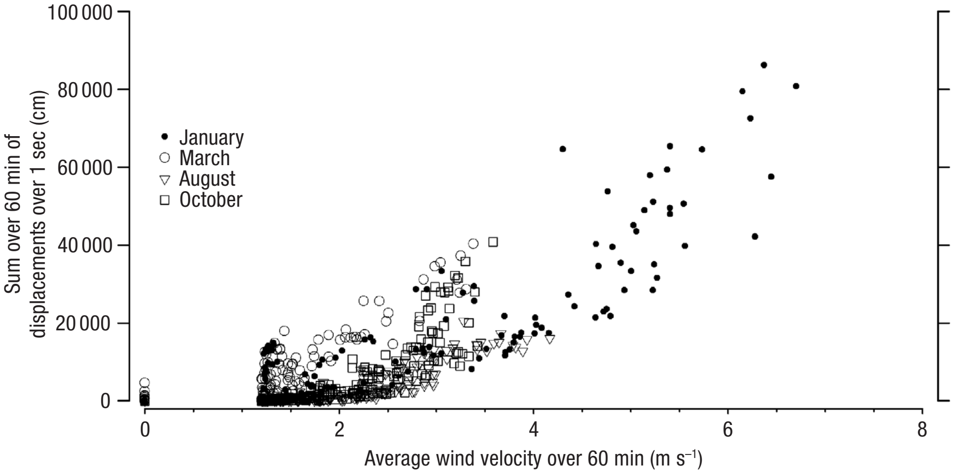

Figure 2. Seasonal patterns of 1 second trunk displacements, summed by hour, in relation to 1 second wind velocity averaged by hour.

ment, modeling the instantaneous wind-movement relation would be any extremely difficult task and not easily generalized. It is statistically, physically and biologically reasonable to take a longer-term perspective of stress and reaction as presented here. Indeed an even broader level of generalization may have useful results, e.g. climatic normal for wind can contribute at a gross level to the understanding of dimensional relations in certain trees (Meng *et al.*, 2008). We started with simple observations and analyses at 1 Hz but the effect of wind is more clearly shown in cumulative stress and reaction. However, full diel summations would introduce systematic biases due to strong diurnal fluctuations in conditions of temperature, winds and physiology.

The calculated extent of movement is dependent on the reference point, which we assume is closer to the sensor than to ground level, with bending being nonlinear with height. The data also have the technical limitation of the anemometer of lacking high frequency data on very low velocities, but the trends for low winds are not in much doubt, and we expect growth rings would not clearly show effects of such minor movement.

In the context of even longer periods, it was notable that the relation of bending to wind was not constant throughout the year, showing that the tree is not a simple mast. The causes of such changes are beyond the scope of our work but might include the state of foliation of the crown (Schindler *et al.*, 2013), the state of trunk hydration or other physiological conditions that vary seasonally (Lundqvist & Valinger, 1996).

Detailed recording is necessary to approximate the full extent of trunk movement, but temporal integration clarifies the simple and direct link of trunk movement to wind. The analysis over a progression of intervals suggests that seasonal and perhaps annual perspectives could give results useful in wood technology or dendrochronology, after appropriate calibration. The causes and relevance of seasonal changes remain to be studied.

Acknowledgements

The authors had total access to the data and are responsible for the integrity and accuracy of the analysis. The contributions of Wayne L. Hamilton were crucial to the conception and design of the work. Permission and logistic support were kindly extended by the owner, administrators and personnel of Rancho Rodeo del Rey.

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