



Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A.

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ABSTRACT

Forest disturbance regimes are beginning to show evidence of climate-mediated changes, such as increasing severity of droughts and insect outbreaks. We review the major insects and pathogens affecting the disturbance regime for coastal Douglas-fir forests in western Oregon and Washington State, USA, and ask how future climate changes may influence their role in disturbance ecology. Although the physiological constraints of light, temperature, and moisture largely control tree growth, episodic and chronic disturbances interacting with biological factors have substantial impacts on the structure and functioning of forest ecosystems in this region. Understanding insect and disease interactions is critical to predicting forest response to climate change and the consequences for ecosystem services, such as timber, clean water, fish and wildlife. We focused on future predictions for warmer wetter winters, hotter drier summers, and elevated atmospheric CO₂ to hypothesize the response of Douglas-fir forests to the major insects and diseases influencing this forest type: Douglas-fir beetle, Swiss needle cast, black stain root disease, and laminated root rot. We hypothesize that (1) Douglas-fir beetle and black stain root disease could become more prevalent with increasing, fire, temperature stress, and moisture stress, (2) future impacts of Swiss needle cast are difficult to predict due to uncertainties in May–July leaf wetness, but warmer winters could contribute to intensification at higher elevations, and (3) laminated root rot will be influenced primarily by forest management, rather than climatic change. Furthermore, these biotic disturbance agents interact in complex ways that are poorly understood. Consequently, to inform management decisions, insect and disease influences on disturbance regimes must be characterized specifically by forest type and region in order to accurately capture these interactions in light of future climate-mediated changes.

1. Introduction

Disturbance regimes in forests of western North America are showing evidence of climate-mediated shifts associated with global climate change in the form of historically unprecedented tree mortality (Anderegg et al., 2012; van Mantgem et al., 2009). Instigating factors for these mortality events include extreme drought (Allen et al., 2015; Asner et al., 2015), increased fire severity and extent (Abatzoglou and Williams, 2016), and expansion of bark beetles into previously climatically unsuitable habitat (Bentz et al., 2010; Björkman and Niemelä 2015). The frequency and severity of forest disturbances will likely continue to increase given predicted climate-related changes in environmental conditions over the 21st century (Allen et al., 2015), which will influence a range of characteristics of these forests including the

ecosystem services that they provide (Johnstone et al., 2016; Seidl et al., 2016).

Projected changes in climate will make forests more vulnerable to tree mortality resulting from physiological stress interacting with other climate-influenced events, such as insect and disease outbreaks, droughts and fires (Beedlow et al., 2013; Kolb et al., 2016; Weed et al., 2013). Current predictions for major climate-related trends affecting forests in western North America include increased fire season length and burned area (Abatzoglou and Williams, 2016; Flannigan et al., 2013), increased occurrence of severe drought (Allen et al., 2015), reduced mountain snowpack (Kapnick and Hall, 2012), and generally increasing temperature, with seasonal trends including warmer wetter winters, and hotter drier growing seasons (Rupp et al., 2016).

There is a growing interest in understanding the interactions of

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multiple disturbance factors (Anderegg et al., 2015; Johnstone et al., 2016; Law and Waring, 2015) in forest ecosystems because their combined effects can differ from that of any single agent acting alone (Seidl et al., 2016). However, interactions for any given forest type vary by landscape character, forest structure, specific insect herbivores and forest pathogens, as well as seasonal climatic factors, storms, and fire patterns. Consequently, to inform management decisions, disturbance regimes must be characterized specifically by forest type and region in order to accurately capture these interactions and allow for prediction of future climate-mediated changes. If conducted at a scale at which management actions are implemented, such as forests with the same dominant tree species and climatic conditions, assessments of potential climate-related changes to disturbance regimes can greatly improve our ability to adaptively manage our forests and the ecosystem services they provide.

Here, we examine the primary insects and diseases (referred to throughout as biotic disturbance agents) of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). Although western hemlock is commonly found as a co-dominant in Douglas-fir forests, especially in old growth forests, Douglas-fir is the dominant species on most of the forested land from near sea-level to roughly 1200 m elevation in western Oregon and Washington, U.S.A. Further, Douglas-fir is the principle timber species, and it is ecologically important for carbon sequestration, and wildlife habitat, as well as being vital for the production of hydropower, irrigation, and drinking water (Curtis and Carey, 1996; Harmon et al., 2004; Kline et al., 2016; Ruggiero et al., 1991). Ecological effects of the major disturbance regimes, especially fire and logging, have been studied extensively in this forest type (Cohen et al., 2002; Creutzburg et al., 2016; Healey et al., 2008; Tepley et al., 2013; Wimberly and Spies, 2001). However, the role of insects and diseases within the disturbance regime has not been adequately addressed, even though there is currently a major foliage disease (Swiss needle cast) epidemic occurring in the region (Ritókóvá et al., 2016).

Here, we: (1) identify the impacts of the major insects and diseases affecting Douglas-fir and their interactions, (2) integrate our understanding of temperature and moisture stress in trees with future climate projections to hypothesize changes in disturbance agent behavior under climate change, and (3) highlight important knowledge gaps in the understanding of the current and projected disturbance regimes in coastal Douglas-fir forests.

2. Ecological setting

Coastal Douglas-fir forests extend from British Columbia through northwestern California. However, we constrain the geographical extent to Washington and Oregon, west of the crest of the Cascade Mountain Range where Douglas-fir is the dominant tree species (Fig. 1), which has traditionally been called the “Douglas-fir region” (Franklin, 1979; Jensen, 1955). This is a moist temperate forest region is dominated by conifers and has relatively long time periods between high severity natural disturbances (Franklin, 1979). The climate is characterized by mild, wet winters, lack of soil freezing, most precipitation falling as rain, a summer drought, and a strong influence from large-scale oscillations such as the El Niño-Southern Oscillation (ENSO), the Pacific North American pattern, and the Pacific Decadal Oscillation (PDO) (Abatzoglou et al., 2014; Dalton et al., 2013). Douglas-fir forests are some of the most productive in the world, with biomass accumulations far exceeding those of both tropical and other northern temperate forests (Law and Waring, 2015; Waring and Franklin, 1979). The large biomass accumulation results from the sustained height growth, foliage retention, and longevity of the dominant trees rather than from high annual net productivity (Waring and Franklin, 1979).

Douglas-fir forests span multiple ecoregions (Fig. 1A) and are generally found within the *Picea sitchensis* and *Tsuga heterophylla* zones, with some of their range in the *Abies amabilis* zone (Franklin, 1979; Franklin and Dyrness, 1988), and generally correspond to the Maritime

Coniferous Forests of the Pacific Northwest, U.S.A. (Peterson et al., 2014). Depending on geographic location and stand history, the pre-dominant tree species is Douglas-fir (Franklin and Dyrness, 1988). Douglas-fir comprises approximately 77% of saw timber stumpage volume in western Washington and Oregon (Howard, 2007), as well as 50% of aboveground carbon storage in Oregon (Donnegan et al., 2008). These forests often contain variable proportions of western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), Sitka spruce (*Picea sitchensis* [Bong.] Carrière), western redcedar (*Thuja plicata* Donn ex D. Don), and grand fir (*Abies grandis* [Douglas ex D. Don] Lindley) at lower elevations, while Pacific silver fir (*A. amabilis* Douglas ex J. Forbes) and noble fir (*A. procera* Rehder) can be found at higher elevations.

The region includes a range of topographical features and environmental conditions. The productivity and survival of trees in these forests can be influenced by various limiting factors related to climate. Although nutrients can have substantial influence on productivity and survival, forests are typically either water-limited or energy-limited (Beedlow et al., 2013; Littell et al., 2010). Within this region, water limitation may result from either reduced precipitation (Bumbaco and Mote, 2010), a reduction of winter snowpack which normally provides water to lower elevation forests during a growing season (Albright and Peterson, 2013), or excessively well-drained soils (Littell et al., 2008). Energy limitation primarily involves light availability (Beedlow et al., 2013) but can involve temperature, particularly in the case of higher-elevation forests with decreased growing seasons due to lower temperatures (Littell et al., 2008). Light is often limited due to cloud cover or dense forest conditions leading to low light availability and reduced photosynthesis (Runyon et al., 1994).

Contemporary climate trends are apparent in the region. Annual mean temperature increased by approximately 0.7–0.9 °C from 1901 to 2012; other climate trends in the region include a lengthened freeze-free season, increased temperature of the coldest night of the year, and increased growing-season potential evapotranspiration (Abatzoglou et al., 2014). Warming has led to approximately a 20% loss of winter snowpack since 1950 (Mote, 2006), while spring snowmelt has occurred up to 30 days earlier depending on location (Stewart et al., 2005). Observations show a long-term increase in spring precipitation, but decreased summer and autumn precipitation and increased potential evapotranspiration have resulted in larger climatic water deficits over the past four decades (Abatzoglou et al., 2014).

The natural disturbance regime of the region is driven by long-term forest succession with local patch-scale dynamics, followed by stand replacement fire (Franklin et al., 2002). Large-scale disturbances prior to European settlement resulted primarily from marine-generated windstorms and wildfire, while volcanic eruptions, floods and landslides were less common (Franklin et al., 2002, 2017). However, the disturbance regime has been altered. Throughout much of this forest type, the primary disturbance is now forest management (Berner et al., 2017; Cohen et al., 2002). Berner et al. (2017) estimated that in Oregon and Washington, timber harvesting resulted in ~80% of observed tree mortality from 2003 to 2012.

With the exception of wilderness and other protected areas, forest management is pervasive throughout the Douglas-fir region. For this reason, forest management provides a backdrop for understanding the interactions with biotic disturbance agents affecting these forests. The long-term effect of timber harvesting has been a regional shift from old to young forests. Old growth forests (250+ years) occupied around half of the forested area before industrial logging (Franklin et al., 2017). Currently, 41% of the region that is forested is occupied by trees aged under 50 years and 7% of the forested region is greater than 250 years old (Fig. 2).

We define forest management as active management (i.e., road construction, logging, prescribed fire, replanting, understory vegetation management), but the magnitude of the disturbance created by forest management is nonetheless highly variable. For example, public lands (federal, state and local), which occupy 50.8% of the region (Fig. 3), tend

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