TECHNICAL REPORT 125

Development of a Drought Risk Assessment Tool for British Columbia Forests Using a Stand-level Water-balance Approach

2019

BRITISH
COLUMBIA

Development of a Drought Risk Assessment Tool for British Columbia Forests Using a Stand-level Water-balance Approach

S. Craig DeLong, Hardy Griesbauer, Craig R. Nitschke,
Vanessa Foord, and Bruce Rogers

BRITISH
COLUMBIA

ISBN 978-0-7726-7363-3 – Print version
ISBN 978-0-7726-7364-0 – Digital version

Citation
DeLong, S.C., H. Griesbauer, C.R. Nitschke, V. Foord, and B. Rogers. 2019. Development of a drought risk assessment tool for British Columbia forests using a stand-level water-balance approach. Prov. B.C., Victoria, B.C. Tech. Rep. 125. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr125.htm

S. Craig DeLong*
2476 Thompson Ave.
Box 2359
Rossland, BC V0G 1Y0

Hardy Griesbauer, Vanessa Foord, and Bruce Rogers
B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development
499 George St.
Prince George, BC V2L 1R5

Craig R. Nitschke
School of Ecosystem and Forest Sciences
University of Melbourne
500 Yarra Blvd
Richmond, Victoria 3121
Australia

*Address correspondence to this author.

Copies of this report may be obtained, depending upon supply, from:
Crown Publications, Queen’s Printer
2nd Floor, 563 Superior Street
Victoria, BC V8W 9V7
1-800-663-6105
www.crownpub.bc.ca

For more information on other publications in this series, visit www.for.gov.bc.ca/scripts/hfd/pubs/hfdcatalog/index.asp

When using information from this report, please cite fully and correctly.

ABSTRACT

We used an annual water-balance approach to assess the relative risk of current and future drought-induced stress and mortality at the stand level for tree species in British Columbia, Canada. The aim was to develop a drought risk–mapping tool that can be used by forest managers to inform harvest and silvicultural decisions at the stand level. We used the concept of absolute soil moisture regime (ASMR), which equates to the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET), to compare estimates of ASMR class based on expert opinion with ASMR class calculated by a water-balance equation using long-term climate data and reference site and soil conditions for different site types. The quantitative estimates of ASMR class generally agreed with those based on expert opinion. Current tree distribution on ecologically classified units for which we could calculate AET/PET was used to determine the AET/PET limits for 10 common tree species in British Columbia. With climate warming we estimate that seven of the tree species examined may be at risk of drought-induced stress and/or mortality. Risk varied for these species across different climate and edaphic conditions. Under future climate, moist to wet site types were never projected to be in a moisture-deficit situation, suggesting that these sites are the most stable sites from a drought perspective under a changing climate and therefore should warrant extra consideration for forest conservation. We describe a variety of ways in which this research can be used to make forest management decisions.

ACKNOWLEDGEMENTS

We thank Benita Kaytor for assistance with climatic analyses and Diane Roberge for assistance with GIS analyses. We also thank Deb McKillop, Phil Burton, and David Spittlehouse for advice and constructive comments through all components of this study, as well as our peer, technical, and client reviewers. We are indebted to the forest ecologists working for the government of British Columbia for the development of the BEC system and their work on ASMR classes. The initial work on this tool was funded through British Columbia's Future Forest Ecosystems Scientific Council, which ran from 2008 to 2012.

CONTENTS

TABLES

FIGURE

1 INTRODUCTION

Increased drought, caused by recent regional warming, is believed to be one of the leading causes of tree mortality in forest ecosystems of western North America (van Mantgem et al. 2009) and worldwide (McDowell et al. 2008; Allen et al. 2010). Kozlowski et al. (1991) define drought from a forest perspective as a period of below-average precipitation that reduces soil moisture and results in prolonged plant water stress and reduced growth. However, an increase in temperatures can also cause drought conditions by increasing evapotranspiration (ET) (Hember et al. 2017). Drought can therefore be caused by an increase in evaporative demand due to increases in temperature, decreases in water availability, or both (van Mantgem et al. 2009). The incidence and effects of drought vary with site characteristics such as soil texture, exposure, and slope, as well as biological determinants such as forest cover and stand/tree characteristics (Kozlowski et al. 1991). Drying events that result in plant stress are common in many forested ecosystems, ranging from frequent seasonal events (Kozlowski et al. 1991) to infrequent supra-seasonal or decadal drought events (Lake 2011). The frequency and severity of drought events can have differential effects on forests at different development stages. Mitchell et al. (2016) showed that recruitment of trees is influenced by seasonal to supra-seasonal events while mortality of mature trees is driven by decadal or centurial events. Drought frequency and severity are projected to increase in the future in many forested ecosystems in association with temperature increases and complex temperature–precipitation interactions (Christensen et al. 2007; Pike et al. 2008). Substantial increases in drought and drought-induced forest mortality could have considerable socio-economic and ecological consequences at both regional and global scales (McDowell et al. 2008; Allen et al. 2010).

Drought-caused mortality in trees occurs either directly through hydraulic failure or carbon starvation, or indirectly through increasing susceptibility to attacks by biological agents (e.g., bark beetles) (McDowell et al. 2008; Klos et al. 2009; Gaylord et al. 2015). Van Mantgem and Stephenson (2007) found that an increase in drought-caused mortality was correlated with increases in frequency of soil moisture deficits. The more widespread occurrence of drought conditions projected by climate models in certain areas may lead to differential mortality of species, which could shift species composition at the stand and landscape levels (Mueller et al. 2005; Koepke et al. 2010). In forest management, the need to address this potential vulnerability over time and space is critical if current planning decisions and objectives are to be achievable (Turner et al. 2003). Spatial and temporal assessments of climate change impacts can be used to increase our understanding of the potential responses of species and ecosystems to climatic change and thereby remove some of the uncertainty about how to manage these systems (Nitschke and Innes 2008a). In the context of increasing drought mortality risk, both the current and future drought risk of species at the stand level is important for determining relevant management actions that may reduce the potential impacts of drought mortality on stand composition, structure, and productivity. For example, McDowell and Allen (2015) predict that tall forests, and particularly old-growth stands, will be at greatest risk to drought-induced mortality under climate change.

Through interactions with wildfires and pest outbreaks, tall forests could be replaced by shorter and drought-adapted vegetation, which will affect forest structure and carbon storage (McDowell and Allen 2015). Reducing stand density through thinning at sustainable harvest rates could reduce competition for moisture and thus increase the resilience of these forests to future droughts (McDowell and Allen 2015).

In British Columbia, a biogeoclimatic ecosystem classification (BEC) system is used to classify forests and other ecosystems (Pojar et al. 1986). The BEC system breaks the province into biogeoclimatic (BGC) units using a classification of zonal ecosystems to define areas of similar climate. BGC units are largely characterized at a range of scales by homogeneous tree and shrub species assemblages (communities), which develop in a consistent manner and reflect the local and regional climate. The zonal ecosystem is a mature vegetation community that occurs on "zonal sites"—defined as mid-slope areas with average soil and site conditions—that best reflect the regional climate, as soils are subject to neither a deficit nor an excess of soil moisture (Pojar et al. 1986). Within each BGC unit, an edatopic grid, with a relative soil moisture regime (RSMR) scale on the y-axis and relative nutrient scale on the *x*-axis, is used to classify other sites that are drier or wetter and poorer or richer than the zonal site, based on their physiographic position and soil characteristics. A key component of the BEC system is the concept of actual soil moisture regime (ASMR) (Pojar et al. 1986). ASMR is a classification scheme based on the number of months that rooting-zone groundwater is absent during the growing season and defined by the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET). For each combination of BGC unit and RSMR, an ASMR can be estimated. This has been done for all BGC units in British Columbia by experienced ecologists (forest science ecologists with the B.C. provincial government). The ratio of AET/PET is a common framework for assessing drought stress and is the basic building block for many forest models (e.g., Prentice et al. 1993).

In this Technical Report we compare ASMR class based on AET/PET calculated for the climate normal period (1961–1991) for different BGC units throughout British Columbia to ASMR provided by experts. We then estimate AET/PET values for future climate to forecast the potential risk of tree species to drought stress or mortality based on the tree-specific AET/PET thresholds that we develop. We provide examples of how this information can be applied to inform forest management decisions that can facilitate adaptation of British Columbia's forests to climate change.

2 METHODS

We used the water-balance component of the Tree and Climate Assessment (TACA) tool developed by Nitschke and Innes (2008b) and Nitschke et al. (2012) to calculate AET/PET ratios. TACA is a mechanistic species distribution model that analyzes the response of trees to climate-driven phenological, biophysical, and edaphic variables and makes use of the AET/PET ratio to predict drought using an annual water-balance approach (Oke 1987). Climate variables of precipitation and minimum and maximum temperature are used to estimate

AET/PET for sites with a given set of soil characteristics (percentage coarse fragments, soil texture, rooting depth) and slope position (shedding, receiving, or neutral). Slope position, soil coarse fragment content, soil texture, and depth of the rooting zone are the major determinants of relative soil moisture regime (RSMR) used in the BEC edatopic grid. The soil moisture function of TACA incorporates the Hargreaves model of evaporation (Hargreaves and Samani 1985) and estimates of daily solar radiation based on equations from Bristow and Campbell (1984) and Duarte et al. (2006). The Hargreaves equation has been found to compare favourably with estimates using the Penman-Monteith equation using daily meteorological data (Xu and Singh 2002; Temesgen et al. 2005). Estimating AET based on the Hargreaves equation, and adjusting for latitude, allowed for validation of model outputs, as the Hargreaves equation is used across British Columbia to calculate evaporation. Once AET/PET has been calculated, a site is assigned to an ASMR class. This provides the link between modelled AET/PET and the RSMR determinations routinely made in the field by ecologists and forest practitioners. Plot data used to develop the classification (including site, soil, and vegetation information along with an assessment of RSMR) provide a final link between soil moisture and tree species presence or absence, which can then be used to establish an AET/PET threshold for individual tree species. We used RSMR keys provided in BEC field guides (e.g., Delong 2004) to determine a set of soil conditions and slope positions that would result in xeric to subhygric RSMRs (Table 1). With our focus on drought, we excluded hygric and subhydric RSMRs, as by definition these sites have saturated soils throughout the growing season. The values in Table 1 were used for calculating AET/PET values for the different RSMRs within a BGC unit.

TABLE 1 *Representative combinations of slope position and soil conditions for different relative soil moisture regime classes used in the model*

RSMR	Slope position	Coarse fragments (%)	Soil texture	Rooting depth (cm)
Xeric	Shedding	55	Sand	25
Subxeric	Shedding	40	Loamy Sand	50
Submesic	Shedding	40	Sandy Loam	50
Mesic	Neutral	40	Loam	50
Subhygric	Receiving	20	Silty Clay Loam	30

We assigned the 10-year average AET/PET values to ASMR classes described by Pojar et al. (1986) (Table 2) and compared them to estimates provided by experienced ecologists. The estimates of the ecologists were based on their knowledge of the relative length of drought experienced by different BGC unit/RSMR combinations, the plants typifying sites with different RSMRs within a BGC unit, and any available soil moisture data. The ecologists started with estimating the ASMR class for the units with which they were most confident, and then compared plant assemblages of other units to decide which class they were best assigned. In most cases there was more than one ecologist with expertise with the units, so assignments were jointly decided. These expert-based estimates were felt to be the best comparison available, as actual field-based measurements with replication are unavailable. There is also the problem that soil moisture sensors measure moisture in only certain parts of

TABLE 2 *Classification of actual soil moisture regime (ASMR). Rooting-zone groundwater is absent during the growing season. Water deficit occurs (soil-stored reserve water is used up and drought begins if current precipitation is insufficient for plant needs). Adapted from Pojar et al. 1986 and Klinka et al. 1984.*

Differentia	**ASMR**	**AET/PET**
Deficit > 5 months	Excessively Dry (ED)	< 0.55
Deficit > 4 months but ≤ 5 months	Very Dry 1 (VD1)	≥ 0.55 < 0.65
Deficit > 3 months but ≤ 4 months	Very Dry 2 (VD2)	≥ 0.65 < 0.75
Deficit > 1.5 months but ≤ 3 months	Moderately Dry (MD)	≥ 0.75 < 0.85
Deficit > 0 months but ≤ 1.5 months	Slightly Dry (SD)	≥ 0.85 < 0.95
Deficit occurs rarely. Utilization and recharge occurs. Current need for water exceeds supply and soil-stored water is used.	Fresh (F)	≥ 0.95 < 1.0
No water deficit occurs. Current need for water does not exceed supply. Temporary groundwater may be present. Drought does not occur even in driest years.	Moist (M)	≥ 1.0
Rooting-zone groundwater present during the growing season. Water supply exceeds demand.	Very Moist (VM) to Very Wet (VW)	> 1.0

the soil profile so cannot completely reflect the water available to trees as roots grow in all parts of the rooting profile and it is unknown how much of the rooting profile trees require to avoid drought stress.

For climate stations with at least a 25-year record, we computed ASMR classes using the 10 years from the record with the highest heat index, in order to simulate future climate conditions that may result in lower soil moisture availability and refer to this as ASMR extreme. This allowed us to use daily data, which are required to run TACA but not readily available for future climate conditions. TACA allows for the inclusion of climate change projections through a direct adjustment approach where the monthly projected change in temperature is applied to the observed climate data either by adding or subtracting the mean monthly difference from each daily value for temperature or by multiplying each daily precipitation value by a modifier based on projected increase or decrease in precipitation. For all stations, the AET/PET values for ASMR extreme was in the mid-range of those computed from three 2020s climate scenarios selected to estimate climate change for the period 2005–2035. The three climate scenarios chosen to best represent the spread of scenarios available at the time of tool development were (1) the A2 scenario implemented through the Canadian Global Circulation Model, version 3 (CGCM3), of the Canadian Centre for Climate Modelling and Analysis; (2) the B1 scenario implemented through the Hadley Centre Coupled Model, version 3 (HadCM3); and (3) the A1B scenario implemented through the Hadley Centre Global Environmental Model, version 1 (HadGEM1). Future climate data using these scenarios were calculated using the ClimateWNA model (Wang et al. 2006).

The database used to develop the BEC system (B.C. MFLNRO 2008) is based on the prior establishment of over 50 000 field plots, most of which are assigned a BGC unit and an RSMR estimate. Once an estimated value of AET/PET for BGC unit/RSMR combinations was calculated using TACA, we searched the database for situations where a tree species occurs in the main canopy of plots with a specified BGC unit/RSMR but is never present in the main canopy of plots in the next driest RSMR. The AET/PET value for this next driest RSMR was then used as a drought threshold for that tree species. There was always more than one of these situations observed at multiple locations around the province, so we took the average of the AET/PET threshold values. Through this process a threshold value or ASMR tolerance was assigned to selected tree species and compared with the ASMR extreme for particular BGC unit/RSMR combinations to determine the implications of a drying climate for specific tree species.

3 RESULTS

The selected BGC units cover a wide range of regional climates from grasslands with hot dry climates (e.g., Thompson variant of the Very Dry Hot Bunchgrass subzone; BGxh2) to high-elevation forests with wet and cold climates (e.g., Cariboo variant of the Wet Cool Engelmann Spruce–Subalpine Fir subzone; ESSFwc3) (Table 3). Many of the climate stations had wide ranges in values over the measurement period for the selected climatic variables, especially those in wetter climates (Table 3).

TABLE 3 *Range in key climate data for climate stations selected to represent the biogeoclimatic (BGC) units examined*

BGC unit	Location	Years of record	Elevation (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)	Annual heat index
Very Dry Hot Bunchgrass–Thompson variant (BGxh2)	Kamloops	1951–2006	346	153–389	6.5–10.9	44–128
Very Dry Hot Ponderosa Pine–Okanagan variant (PPxh1)	Kelowna	1951–1969	485	210–370	5.7–9.3	49–82
Very Dry Hot Interior Douglas-fir–Okanagan variant (IDFxh1)	Vernon	1946–1996	482	248–608	6.2–9.2	28–70
Dry Mild Interior Douglas-fir–Kootenay variant (IDFdm2)	Marysville	1973–2003	985	272–657	3.7–7.2	21–61
Dry Warm Interior Cedar-Hemlock–West Kootenay variant (ICHdw1)	Crescent Valley	1941–1964	610	651–940	4.8–8.3	16–32
Dry Cool Sub-boreal Spruce subzone (SBSdk)	Smithers	1943–2008	522	312–761	1.7–5.4	18–45
Moist Warm Interior Cedar-Hemlock–Thompson variant (ICHmw3)	Nakusp	1913–1988	457	494–971	4.1–8.4	17–32
Dry Cold Engelmann Spruce–Subalpine fir–Cascade variant (ESSFdc2)	Peachland Brenda Mines	1969–1991	1463	413–753	2.1–4.7	17–36
Wet Cool Sub-boreal Spruce–Willow variant (SBSwk1)	Aleza Lake	1953–1980	625	709–1157	2.0–4.9	10–18
Wet Cool Engelmann Spruce–Subalpine fir–Cariboo variant (ESSFwc3)	Barkerville	1936–2006	1265	873–1845	–0.7–3.5	6–15

There was very strong agreement (36 of 50 BGC unit/RSMR combinations) between the ASMR class values estimated by TACA and those determined by expert opinion (Table 4). Of the 50 combinations examined, the TACA model estimate of ASMR was one class drier compared with expert estimate for 13 sites, with one case where the expert estimate was one class wetter than the TACA estimate (Table 4). In most of these 14 cases, the AET/PET value calculated by TACA was very close to the class break (Tables 2 and 4).

TABLE 4 *Estimates of Actual Soil Moisture Regime (ASMR) class by biogeoclimatic (BGC) unit and Relative Soil Moisture Regime class. Where model and expert estimate disagreed, the expert estimate is in brackets. Actual AET/PET values are below the class. ASMR classes are described in Table 2.*

	Relative Soil Moisture Regime				
BGC unit	**Xeric**	**Subxeric**	**Submesic**	**Mesic**	**Subhygric**
Very Dry Hot Bunchgrass–Thompson variant (BGxh2)	ED 0.43	ED 0.47	ED 0.51	VD1 (ED) 0.56	F 0.99
Very Dry Hot Ponderosa Pine–Okanagan variant (PPxh1)	ED 0.50	VD1 (ED) 0.56	VD1 (ED) 0.60	VD2 0.65	F 0.99
Very Dry Hot Interior Douglas-fir–Okanagan variant (IDFxh1)	VD1 (ED) 0.64	VD2 0.70	VD2 0.73	MD 0.77	F 0.99
Dry Mild Interior Douglas-fir–Kootenay variant (IDFdm2)	VD2 0.68	VD2 0.72	MD (VD) 0.75	MD 0.79	F 0.99
Dry Warm Interior Cedar-Hemlock–West Kootenay variant (ICHdw1)	MD (VD) 0.76	MD (VD) 0.83	SD (MD) 0.85	SD 0.90	F 0.98
Dry Cool Sub-boreal Spruce subzone (SBSdk)	MD 0.76	MD 0.82	SD 0.85	SD 0.90	M[a] 1.0
Moist Warm Interior Cedar-Hemlock–Thompson variant (ICHmw3)	MD 0.77	MD 0.82	SD 0.85	SD (F) 0.89	M 1.0
Dry Cold Engelmann Spruce–Subalpine fir–Cascade variant (ESSFdc2)	SD (MD) 0.86	SD (MD) 0.90	SD 0.92	F 0.96	M 1.0
Wet Cool Sub-boreal Spruce–Willow variant (SBSwk1)	SD (MD) 0.89	SD 0.94	F 0.96	F 0.99	M 1.0
Wet Cool Engelmann Spruce–Subalpine fir–Cariboo variant (ESSFwc3)	F (MD) 0.97	F (SD) 0.99	F 0.99	M 1.0	M 1.0

[a] An AET/PET value of 1 indicates no water deficit over the growing season.

When the years with the highest annual heat index were assessed within the selected BGC units, 13 of the 35 BGC unit/RSMR combinations would have been assigned to a drier ASMR class. The BGC units where the most changes occurred were the Kootenay variant of the Dry Mild Interior Douglas-fir subzone (IDFdm2), where all the RSMR classes, except subhygric, shifted one ASMR class, and the Okanagan variant of the Very Dry Hot Interior Douglas-fir subzone (IDFxh1), where the subxeric, submesic, and mesic RSMR classes all shifted one ASMR class (Table 5). There were very few shifts within the wetter BGC units and no shifts were estimated on subhygric RSMR sites within any of the BGC units (i.e., no moisture deficit, even in the driest predicted climatic conditions for this RSMR class).

TABLE 5 *Estimates of Actual Soil Moisture Regime (ASMR) class by biogeoclimatic (BGC) unit and Relative Soil Moisture Regime class when the 10 most extreme values of annual heat index were used. AET/PET values are shown below ASMR class. Where class changed from those generated using climate normal data (see Table 4) the original value is shown in brackets. ASMR classes are described in Table 2. BGC units where climate data were limited were not included.*

	Relative Soil Moisture Regime				
BGC unit	**Xeric**	**Subxeric**	**Submesic**	**Mesic**	**Subhygric**
Very Dry Hot Bunchgrass–Thompson variant (BGxh2)	ED 0.38	ED 0.44	ED 0.47	ED (VD1) 0.52	F 0.98
Very Dry Hot Interior Douglas-fir–Okanagan variant (IDFxh1)	VD1 0.55	VD1 (VD2) 0.60	VD1 (VD2) 0.63	VD2 (MD) 0.68	F 0.98
Dry Mild Interior Douglas-fir–Kootenay variant (IDFdm2)	VD1 (VD2) 0.60	VD1 (VD2) 0.64	VD2 (MD) 0.67	VD2 (MD) 0.72	F 0.99
Dry Cool Sub-boreal Spruce subzone (SBSdk)	VD2 (MD) 0.70	MD 0.76	MD (SD) 0.80	SD 0.85	M 1.0
Moist Warm Interior Cedar-Hemlock–Thompson variant (ICHmw3)	VD2 (MD) 0.74	MD 0.79	MD (SD) 0.81	SD 0.85	M 1.0
Wet Cool Sub-boreal Spruce–Willow variant (SBSwk1)	SD 0.88	SD 0.92	F 0.95	F 0.98	M 1.0
Wet Cool Engelmann Spruce–Subalpine fir–Cariboo variant (ESSFwc3)	SD (F) 0.92	F 0.96	F 0.98	M 1.0	M 1.0

Based on field data from the BGC database, there was good agreement for the AET/PET where a tree species occurred in the main canopy on sites with a certain RSMR but not on the next driest RSMR for different BGC units. Table 6 shows these values for hybrid white spruce (*Picea engelmannii* × *glauca*). The lowest AET/PET value (0.79) for any of the sites where hybrid spruce was represented in the main canopy was for mesic sites in the Dry Mild Interior Douglas-fir subzone. This is the same value for xeric sites in the Dry Warm Sub-boreal Spruce subzone, where hybrid spruce is not represented in the main canopy (Table 6). Thus, the AET/PET tolerance for hybrid spruce appears to be in the range of 0.79. Only the high-elevation Dry Cool Montane Spruce subzone had a higher estimated tolerance of 0.81–0.87 (Table 6). Using the same procedure, the AET/PET tolerance limits of other common tree species were calculated.

TABLE 6 *Values for the ratio of actual to potential evapotranspiration (AET/PET) for sites where hybrid white spruce (*Picea engelmannii *x* glauca*) reaches its limit for different biogeoclimatic (BGC) unit and Relative Soil Moisture Regime (RSMR) combinations*

BGC unit	**AET/PET (RSMR) Spruce present**	**AET/PET (RSMR) Spruce absent**
Dry Cool Sub-boreal Spruce	0.81 (subxeric)	0.77 (xeric)
Dry Mild Interior Douglas-fir	0.79 (mesic)	0.75 (submesic)
Dry Cool Montane Spruce	0.87 (subxeric)	0.81 (xeric)
Dry Warm Sub-boreal Spruce	0.82 (subxeric)	0.79 (xeric)
Moist Hot Sub-boreal Spruce	0.80 (submesic)	0.77 (subxeric)

With an expected shift to drier soil moisture conditions in the future, a number of tree species would experience drought stress and/or suffer drought-induced mortality, resulting in potential reductions within their current range based on their current AET/PET threshold in the BGC units examined. For example, using the data from Table 5:

- Western larch (*Larix occidentalis* Nutt.) AET/PET threshold (0.72): stress and/or mortality could be expected on subxeric to mesic sites in the IDFdm2.
- Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) AET/PET threshold (0.76): stress and/or mortality could be expected on submesic to mesic sites in the Kootenay variant of the IDFdm2.
- Western redcedar (*Thuja plicata* Donn ex D. Don) AET/PET threshold (0.77): stress and/or mortality could be expected on xeric to subxeric sites in the Thompson variant of the Moist Warm Interior Cedar–Hemlock subzone (ICHmw3).
- Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) AET/PET threshold (0.82): stress and/or mortality could be expected on submesic to mesic sites in the Shuswap variant of the Moist Warm Interior Cedar–Hemlock subzone (ICHmw2).
- Interior spruce (*Picea glauca* (Moench) Voss × *engelmannii* Parry ex Engelm.) AET/PET threshold (0.79): stress and/or mortality could be expected on mesic sites in the IDFdm2 and submesic to subxeric sites in the Dry Cool Sub-boreal Spruce subzone (SBSdk).
- Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) AET/PET threshold (0.60): stress and/or mortality could be expected on xeric sites in the IDFdm2 and subxeric to xeric sites in the IDFxh1.
- Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) AET/PET threshold (0.58): stress and/or mortality could be expected on xeric sites in the IDFxh1.

4 DISCUSSION

Across the range of tree species investigated in this study, mature individual trees (>80 years old) have experienced a wide range of precipitation and temperature conditions. Based on the climate records, representing many of the climatic regions in British Columbia, precipitation can vary in such a manner that drier climatic areas can receive annual precipitation more typical of moister regions (e.g., IDFxh1), and moist regions (e.g., ICHmw2) can receive annual precipitation similar to that expected in drier areas. Mean annual temperature is also highly variable with warmer low-elevation BGC units (e.g., ICHmw2) being as cold in some years as colder high-elevation BGC units, and cooler high-elevation units being as warm as low-elevation units in warmer years (e.g., ESSFwc2). Trees within British Columbia therefore appear to tolerate a wide range of inter-annual climatic fluctuations. Within these distinct yet overlapping climatic regimes, species occur across edaphic gradients driven in large part by soil moisture availability, which suggests that climate effects are mediated through edaphic constraints as well as extreme climate years. Zimmermann et al. (2009) identified that the distributions of some tree species are sensitive to the extremes of a region's climate, in particular to summer moisture availability (drought) and winter temperatures (frost).

Under projected climate change, the climatic regimes for many of the current ecosystems are expected to shift toward the warmer and drier extremes, which would lead to long-term reductions in available soil moisture (Hember et al. 2017). Soil moisture appears to be sensitive to even modest changes in average temperatures (Daniels et al. 2011). An increase in average temperature of 1°C over the past century in western North America has been linked to increased tree mortality rates (van Mantgem et al. 2009; Daniels et al. 2011), possibly through changes in snowpack (Mote et al. 2005; Knowles et al. 2006) and summer drought (Westerling et al. 2006). Van Mantgem et al. (2009) suggested that this phenomenon is already occurring across a wide range of forest types, elevations, tree sizes, and genera in western North America, leading to increased rates of mortality in mature trees. Breshears et al. (2005) attributed regional-scale die-off of overstorey trees across southwestern North American woodlands to depleted soil water and suggested that even more profound impacts will be forthcoming under future climatic warming. Hogg et al. (2008) described growth declines and substantial mortality in trembling aspen (*Populus tremuloides* Michx.) stands in western Canada associated with a severe drought from 2001 to 2002. Increased drought stress can also limit regeneration after disturbance, possibly leading to a semi-permanent conversion of forest to grassland (Hogg and Wein 2005; Johnstone et al. 2010).

Differences in drought tolerance undoubtedly explain differential species and population mortality after drought (Mueller et al. 2005; Martinez-Meier et al. 2008) as well as species distributions and ranges (Swetnam and Betancourt 1998; Aber et al. 2001). Within a species, drought may initially and most strongly affect populations growing near climatic-controlled (Griesbauer et al. 2011) or edaphic-controlled species distribution limits (Gitlin et al. 2006; McDowell et al. 2008), as plants growing on resource-limited sites may experience long-term stress that weakens their ability to resist relatively rapid stressors such as drought events (Mueller 1987). Understanding species and spatial variation in drought-induced mortality patterns will become increasingly important to natural resource managers (Mueller et al. 2005) for selecting suitable species and genotypes for reforestation (Millar et al. 2007), as well as for projecting future forest compositions and species distributions (Tardif et al. 2006). Our model addresses this for British Columbia by providing a tool that can identify which tree species/populations are likely to be at a high risk to drought-caused stress and mortality under a range of climatic and edaphic conditions.

The corroboration of ASMR class estimates using the Hargreaves equation with those of experienced ecologists supports our approach to estimating AET/PET values and ASMR class. The Hargreaves equation has been used successfully to calculate ET rates in various climates and generally performs as well as the more complicated Penman-Monteith equation, particularly where solar radiation data are unavailable (Di Stefano and Ferro 1997; Xu and Singh 2002; Temesgen et al. 2005), which was the case for this study.

The close agreement in the AET/PET threshold values shown for hybrid white spruce indicates that the model provides consistent estimates of ET across a wide range of environmental conditions in British Columbia. This soft validation (i.e., absence of field-based measurements) demonstrates that the model is useful for making decisions regarding tree species deployment across forest landscapes in consideration of a changing climate. Not including the future risk of trees to drought in current planting decisions may lead to recruitment failures, increased risk of future fire or pest impacts, reduced ecological integrity, and loss in investments made in reforestation and afforestation programs.

In much of British Columbia, climate change is projected to result in an increase in winter precipitation with declines in summer precipitation along with warming temperatures (Hamann and Wang 2006). These projections consistently indicate drier and warmer conditions for many regions in the south and central interior of British Columbia (Hamann and Wang 2006; Nitschke and Innes 2008b; Pike et al. 2010; Nitschke et al. 2012). The increasing summer aridity under future climate change is expected to lead to decreases in available soil moisture (Christensen et al. 2007; Pike et al. 2008). Our findings are consistent with these predictions and highlight increased drought risk for some tree species. The finding of large shifts in ASMR class in dry to moist BGC units under climate change indicates that these sites are locations where climate adaptation plans relating to forest management are most urgently needed.

Wetter edaphic sites, such as those found at high-elevation, in riparian areas, and in moisture-receiving areas, have acted as refugia for mesic species during droughts and fires associated with past climatic events (Burke 2002; Rouget et al. 2003). Such areas also are hypothesized to play a critical role under future climate change (Aide and Rivera 1998). The finding of no drought limitations in wetter climate areas and on subhygric sites, even in the driest of climates, supports this hypothesis and emphasizes the importance of these sites for the future conservation of forest species (Meave et al. 1991). These sites may also represent the best choice for long-term storage of carbon (Dymond et al. 2016), provision of old-forest characteristics for maintenance of faunal species that require them, maintenance of genetic diversity, and other intrinsic values of natural forests. These sites may also be the most risk-free sites for maintaining future productive capacity for current in situ species (Nitschke et al. 2012); however, once harvested, higher-risk sites could be converted to more drought-tolerant species to facilitate the maintenance of forest cover and productivity.

Our finding that the risk of drought-induced stress or mortality is both site and species specific should allow forest managers to focus their efforts and resources for climate change mitigation and adaptation on fewer sites rather than across broad landscapes. Adaptation strategies may include the use of uneven-aged versus even-aged systems on at-risk sites where mid-summer water stress can be reduced by providing multi-aged stands, which lower temperatures, raise humidity, and reduce evaporative demand (O'Hara and Nagel 2006). Forests that provide higher humidity, cooler temperatures, and wetter edaphic conditions are important for maintaining species that cannot tolerate climatic change that brings warmer and drier conditions (Meave et al. 1991; Aide and Rivera 1998). Thinning of dense stands on sites with high drought risk may also be an option to reduce mortality but this would depend on the response of the understorey vegetation to opening of the stand (McDowell and Allen 2015). Enrichment planting could also be used to establish shade-tolerant species that are otherwise vulnerable to climate-induced drought stress in the understorey of established stands (Nitschke and Innes 2008b). Dobrowski et al. (2015) found that microclimatic conditions provided by a forest overstorey may mediate the response of shade-tolerant species to climate change. Likewise, enrichment planting also can be used following artificial or natural regeneration planting to fill in the gaps that result from disturbance or climate-based mortality (Nitschke and Innes 2008b). Planting can be used to facilitate the persistence of species and ecosystems through "human-assisted migration" and to introduce new species or genotypes better adapted to the altered climate (Hogg and Bernier 2005). The use of enrichment planting for this latter objective could allow for a gradual and controlled transition from species at risk of climate-induced drought to species more tolerant of future soil moisture regimes.

Much of the work to date in British Columbia and other jurisdictions has focussed on projections of future potential tree species distributions at broad regional scales (Hamann and Wang 2006; McKenney et al. 2007; Rehfeldt et al. 2008; Coops and Waring 2011). Our research attempts to bridge the gap between these broad analyses and the scale at which forest management decisions are typically made. The transition from these broad predictions to more site-level predictions based on drought risk are arguably more useful for directing forest management activities that will facilitate adaptation to climate change. The drought threshold calculations for tree species demonstrated here can be repeated for any plant species in the provincial database for British Columbia or other jurisdictions using a similar classification system. The AET/PET calculations for combinations of climate and site conditions shown along with ecosystem mapping provide a tool for making stand-level decisions about climate adaptation.

5 APPLICATION

Aside from those presented, we have calculated AET/PET values for xeric, subxeric, submesic, and mesic RSMR classes for an additional 50 BGC units within British Columbia. Along with the coniferous tree species described earlier, we have determined AET/PET limits for trembling aspen (*Populus tremuloides* (Michx.)), paper birch (*Betula papyrifera* Marshall), and black cottonwood (*Populus balsamifera* ssp. *trichocarpa* L. (Torr. & A. Gray ex Hook.) Brayshaw). We have combined this information into a Microsoft Excel–based tool that graphically shows estimated drought risk in response to climate change for each tree species for any combination of BGC unit/RSMR class for the 60 BGC units. The tool can be found at www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/silviculture/tree-species-selection/tool-introduction/ecological-factors under the Drought Risk heading. To use the tool, enter the BGC unit and RSMR value you are interested in; the graph will then show the drought risk of each tree species in response to climate change for future time periods. If the line for a particular future climate falls below the bar, the tree species' drought tolerance will be exceeded, indicating that drought-related mortality can be expected. The other risk categories are relative to the tree species' tolerance. The High Risk category indicates that the tree species is nearing its tolerance, and therefore trees may be stressed and more susceptible to damage from insects and disease. The Moderate Risk category indicates that the tree species should only be stressed in abnormally dry years, and the Low Risk category indicates that there is little or no risk of drought-induced mortality. This information can be used to determine a tree species' suitability to a particular site based on drought risk. The drought risk tolerances and ratings can also be used in combination with ecosystem mapping to provide useful information for forest management decisions. Most ecosystem mapping does not report the RSMR for a polygon, so site-series information must be used. Since a site series often has a range in RSMR, one has to choose the RSMR. A risk-averse strategy is to use the driest RSMR for the site series while a more broadly applicable strategy is to use the most common RSMR for that unit, especially if it is based on local knowledge. Often, map units are also combinations of site series, in which case the more broadly applicable strategy is to use the dominant sites series, while the risk-averse strategy is to use the driest site series. Once this has been completed, AET/PET values can be assigned to each polygon for a particular climate period. The AET/PET polygon assignments can then be overlaid with tree species information to forecast the species' drought risk.

The AET/PET value and drought risk maps provide an important tool for strategic planning. They allow forest planners to focus on areas of greatest concern from the impacts of climate change related to decreases in available moisture, and to consider possible solutions. The following are examples of such strategic decisions:

1. Forest to Range Conversion: An AET/PET value of 0.55 is estimated to be the limit for any tree species native to British Columbia (e.g., ponderosa pine). Mapped polygons with an ASMR value below 0.55 are estimated to no longer support tree growth and may slowly convert to grassland.
2. Tree Species Deployment: AET/PET value maps can be overlaid on maps of current or future harvest areas to determine potential tree species suitability and thus help make silvicultural prescriptions and plan sowing requests made to forest nurseries.
3. Harvesting Sequence: Species-specific drought risk maps can be used to determine risk of future mortality and direct harvesting to sites where harvesting can precede mortality.
4. Invasive Species Potential: Invasive species will have an AET/PET lower limit that relates to their drought tolerance. Invasive species location maps can be overlaid on the current AET/PET maps to determine the range of values for sites invasive species currently occupy. Once a limit has been determined for a species, a range of potential occupancy based on drought tolerance can be developed for future climates. It is important to note that current distribution may not match potential distribution over the range of AET/PET values, so mapping should be periodically updated to see if the limit is changing. To be most effective, other information affecting invasive species establishment (e.g., mineral soil exposure) would also be considered.
5. Agronomic Species Potential: Agronomic species will have an AET/PET lower limit that relates to their drought tolerance. Agronomic species location maps can be overlaid on the current AET/PET value maps to determine the range of values for sites that agronomic species currently occupy. Once a limit has been determined for a species, a range of potential occupancy based on drought tolerance can be developed for future climate to reduce

the need for irrigation. It is important to note that current distribution may not match potential distribution over the range of AET/PET, so mapping should be periodically updated to see if the limit is changing.

6. Wildfire Risk: Trees beyond their drought threshold on a site will have a higher risk of fire ignition and spread because their moisture content will be very low. Maps of drought risk can be used to improve the prediction of wildfire risk and target areas for fuel-reduction prescriptions.

A map of drought risk for lodgepole pine based on the climate normal period (1961–1990) compared with the future period (2005–2035) is shown in Figure 1. This type of mapping would be used for tree species deployment as in point 2 above, and has been done for the Prince George, Cranbrook, and Williams Lake Timber Supply Areas and also for the city of Prince George.

Field verification of the tool is still proceeding but it presently can be applied as indicated above. Monitoring will provide useful feedback to continually improve and update the tool and its applications. The tool provides an important link between climate change and site-level drought-related impacts.

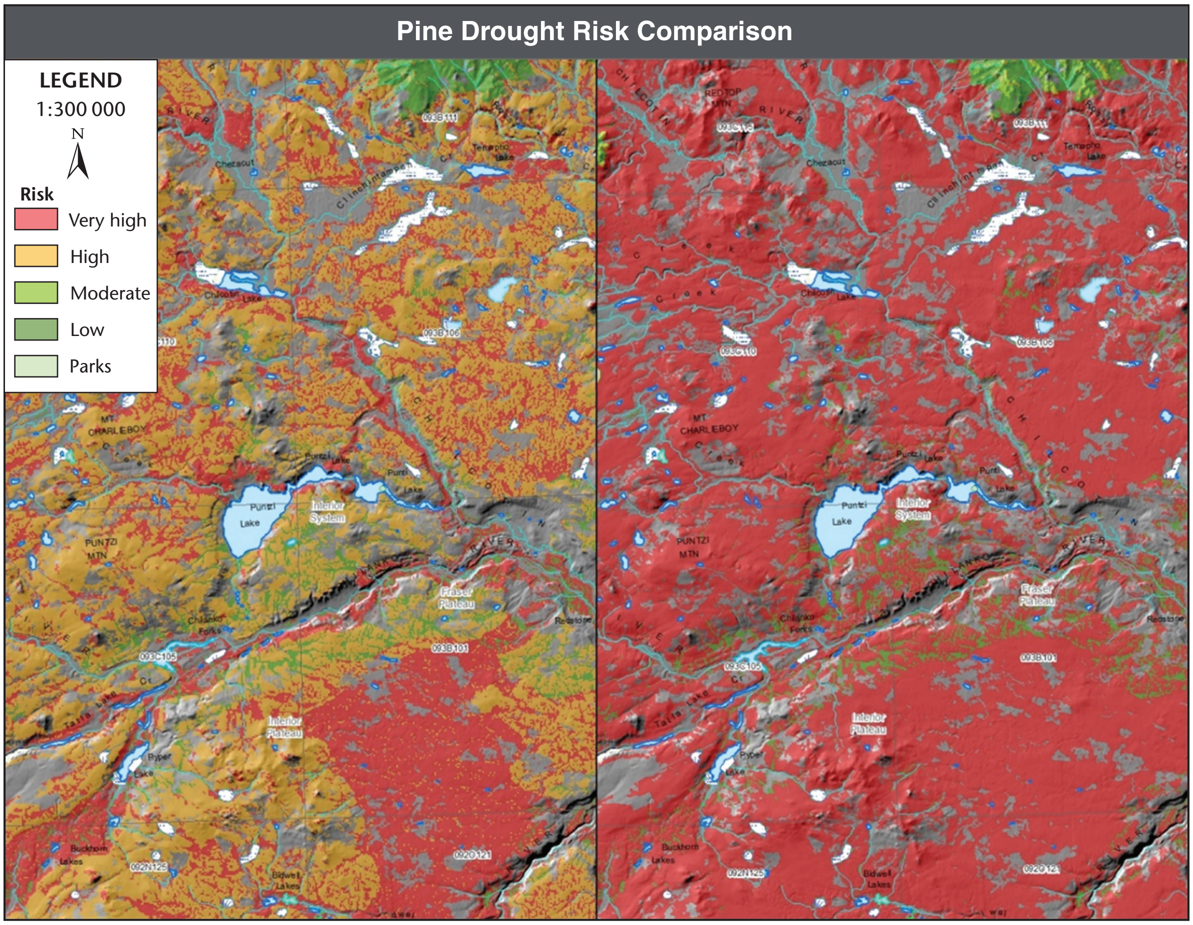

FIGURE 1 *Comparison of drought risk for lodgepole pine during the climate normal period (1961–1990; left panel) and a future time period (2005–2035; right panel) in an area near Puntzi Lake in central British Columbia.*

LITERATURE CITED

Aber, J.D., P. Ronald, S.M.C. Nulty, J.M. Lenihan, D. Bachelet, R.J. Drapek, R.P. Neilson, and S. McNulty. 2001. Forest processes and global environmental change: predicting the effects of individual and multiple stressors. Bioscience 51(9):735–751. doi:10.1641/0006-3568(2001)051[0735:FPAGEC]2.0.CO;2.

Aide, T.M. and E. Rivera. 1998. Geographic patterns of genetic diversity in *Poulsenia armata* (Moraceae): implications for the theory of Pleistocene refugia and the importance of riparian forest. J. Biogeogr. 25(4):695–705. doi:10.1046/j.1365-2699.1998.2540695.x.

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259(4):660–684. doi:10.1016/j.foreco.2009.09.001.

Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J.J. Anderson, O.B. Myers, and C.W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proc. Natl. Acad. Sci. 102(42):15144–15148. doi:10.1073/pnas.0505734102.

Bristow, K.L. and G.S. Campbell. 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agric. For. Meteorol. 31(2):159–166. doi:10.1016/0168-1923(84)90017-0.

British Columbia Ministry of Forests, Lands and Natural Resource Operations (B.C. MFLNRO). 2008. BECdb: Biogeoclimatic Ecosystem Classification Codes and Names, Version #7. [MSAccess 2010 format]. For. Anal. Inv. Br., Victoria, B.C. www.for.gov.bc.ca/hre/becweb/resources/codes-standards/standards-becdb.html

Burke, A. 2002. Island–matrix relationships in Nama Karoo inselberg landscapes. Part I: Do inselbergs provide a refuge for matrix species? Plant Ecol. 160(1):79–90. doi:10.1023/A:1015899729968.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton. 2007: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (editors). Cambridge University Press, Cambridge, U.K. and New York, N.Y.

Coops, N.C. and R.H. Waring. 2011. A process-based approach to estimate lodgepole pine (*Pinus contorta* Dougl.) distribution in the Pacific Northwest under climate change. Clim. Change 105(1):313–328. doi:10.1007/s10584-010-9861-2.

Daniels, L.D., T.B. Maertens, A.B. Stan, S.P.J. McCloskey, J.D. Cochrane, and R.W. Gray. 2011. Direct and indirect impacts of climate change on forests: three case studies from British Columbia. Can. J. Plant Pathol. 33(2):108–116. doi:10.1080/07060661.2011.563906.

Delong, C. 2004. A field guide to site identification and interpretation for the north central portion of the Northern Interior Forest Region. Res. Br., B.C. Min. For., Victoria, B.C. Land Manag. Handb. No. 54. www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh54.htm

Di Stefano, C. and V. Ferro. 1997. Estimation of evapotranspiration by Hargreaves formula and remotely sensed data in semi-arid Mediterranean areas. J. Agric. Eng. Res. 68(3):189–199. doi:10.1006/jaer.1997.0166.

Dobrowski, S.Z., A.K. Swanson, J.T. Abatzoglou, Z.A. Holden, H.D. Safford, M.K. Schwartz, and D.G. Gavin. 2015. Forest structure and species traits mediate projected recruitment declines in western US tree species. Glob. Ecol. Biogeogr. 24(8):917–927. doi:10.1111/geb.12302.

Duarte, H.F., N.L. Dias, and S.R. Maggiotto. 2006. Assessing daytime downward longwave radiation estimates for clear and cloudy skies in southern Brazil. Agric. For. Meteorol. 139(3–4):171–181. doi:10.1016/j.agrformet.2006.06.008.

Dymond C.C., S. Beukema, C.R. Nitschke, K.D. Coates, and R.M. Scheller. 2016. Carbon sequestration in managed temperate coniferous forests under climate change. Biogeosci. 13 (6):1933–1947. doi:10.5194/bg-13-1933-2016

Gaylord, M.L., T.E. Kolb, N.G. McDowell, and F. Meinzer. 2015. Mechanisms of piñon pine mortality after severe drought: a retrospective study of mature trees. Tree Physiol. 35(8):806–816. doi:10.1093/treephys/tpv038.

Gitlin, A.R., C.M. Sthultz, M.A. Bowker, S. Stumpf, K.L. Paxton, K. Kennedy, A. Muñoz, J.K. Bailey, and T.G. Whitham. 2006. Mortality gradients within and among dominant plant populations as barometers of ecosystem change during extreme drought. Conserv. Biol. 20(5):1477–1486. doi:10.1111/j.1523-1739.2006.00424.x.

Griesbauer, H.P., D.S. Green and G.A. O'Neill. 2011. Using a spatiotemporal climate model to assess population-level Douglas-fir growth sensitivity to climate change across large climatic gradients in British Columbia, Canada. For. Ecol. Manag. 261(3):589–600. doi:10.1016/j.foreco.2010.11.012.

Hamann, A. and T. Wang. 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. Ecology 87(11):2773–2786.

Hargreaves, G.H. and Z.A. Samani. 1985. Reference crop evapotranspiration from temperature. Trans. ASAE 1(2):96–99. doi:10.13031/2013.26773.

Hember, R.A., W.A. Kurz, and N.C. Coops. 2017. Relationships between individual-tree mortality and water-balance variables indicate positive trends in water stress-induced tree mortality across North America. Glob. Change Biol. 23(4):1691–1710. doi:10.1111/gcb.13428.

Hogg, E.H. and P.Y. Bernier. 2005. Climate change impacts on drought-prone forests in western Canada. For. Chron. 81(5):675–682. doi:10.5558/tfc81675-5.

Hogg, E.H., J.P. Brandt, and M. Michaelian. 2008. Impacts of a regional drought on the productivity, dieback, and biomass of western Canadian aspen forests. Can. J. For. Res. 38(6):1373–1384. doi:10.1139/X08-001.

Hogg, E.H. and R.W. Wein. 2005. Impacts of drought on forest growth and regeneration following fire in southwestern Yukon, Canada. Can. J. For. Res. 35(9):2141–2150. doi:10.1139/X05-120.

Johnstone, J.F., F.S. Chapin, T.N. Hollingsworth, M.C. Mack, V. Romanovsky, and M. Turetsky. 2010. Fire, climate change, and forest resilience in interior Alaska. Can. J. For. Res. 40(7):1302–1312. doi:10.1139/X10-061.

Klinka, K., R.N. Green, P.J. Courtin, and F.C. Nuszdorfer. 1984. Site diagnosis, tree species selection, and slashburning guidelines for the Vancouver Forest Region, British Columbia. B.C. Min. For., Land Manag. Rep. No. 25, Victoria, B.C. 180p.

Klos, R.J., G.G. Wang, W.L. Bauerle, and J.R. Rieck. 2009. Drought impact on forest growth and mortality in the southeast USA: an analysis using forest health and monitoring data. Ecol. Appl. 19(3):699–708. doi:10.1890/08-0330.1.

Knowles, N., M.D. Dettinger, and D.R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. J. Clim. 19(18):4545–4559. doi:10.1175/JCLI3850.1.

Koepke, D.F., T.E. Kolb, and H.D. Adams. 2010. Variation in woody plant mortality and dieback from severe drought among soils, plant groups, and species within a northern Arizona ecotone. Oecologia 163(4):1079–1090. doi:10.1007/s00442-010-1671-8.

Kozlowski, T.T., P.J. Kramer, and S.G. Pallardy. 1991. The physiological ecology of woody plants. Academic Press, Inc., San Diego, Calif.

Lake, P.S. 2011. Drought and aquatic ecosystems: effects and responses. Wiley Online Library. doi:10.1002/9781444341812.

Martinez-Meier, A., L. Sanchez, M. Pastorino, L. Gallo, and P. Rozenberg. 2008. What is hot in tree rings? The wood density of surviving Douglas-firs to the 2003 drought and heat wave. For. Ecol. Manag. 256(4):837–843. doi:10.1016/j.foreco.2008.05.041.

McDowell, N.G. and C.D. Allen. 2015. Darcy's law predicts widespread forest mortality under climate warming. Nat. Clim. Change 5(7):669–672. doi:10.1038/nclimate2641.

McDowell, N., W.T. Pockman, C.D. Allen, D.D. Breshears, N. Cobb, T. Kolb, J. Plaut, J. Sperry, A. West, D.G. Williams, and E.A. Yepez. 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytol. 178(4): 719–739. doi:10.1111/j.1469-8137.2008.02436.x.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell, and M.F. Hutchinson. 2007. Potential impacts of climate change on the distribution of North American trees. Bioscience 57(11):939–948. doi:10.1641/b571106.

Meave, J., M. Kellman, A. MacDougall, and J. Rosales. 1991. Riparian habitats as tropical forest refugia. Glob. Ecol. Biogeogr. Lett. 1(3):69. doi: 10.2307/2997492.

Millar, C.I., N.L. Stephenson and S.L. Stephens. 2007. Climate change and forests of the future: managing in the face uncertainty. Ecol. Appl. 17(8): 2145–2151. doi:10.1890/06-1715.1.

Mitchell, P.J., A.P. O'Grady, E.A. Pinkard, T.J. Brodribb, S.K. Arndt, C.J. Blackman, R.A. Duursma, R.J. Fensham, D.W. Hilbert, C.R. Nitschke, J. Norris, S.H. Roxburgh, K.X. Ruthrof, and D.T. Tissue. 2016. An eco-climatic framework for evaluating the resilience of vegetation to water deficit. Glob. Change Biol. 22(5):1677–1689. doi:10.1111/gcb.13177.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bull. Am. Meteorol. Soc. 86(1):39–49. doi:10.1175/BAMS-86-1-39.

Mueller, D. 1987. Natural dieback in forests. Bioscience 37(8):575–583. doi: 10.2307/1310668.

Mueller, R.C., C.M. Scudder, M.E. Porter, R. Talbot Trotter, C.A. Gehring, and T.G. Whitham. 2005. Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. J. Ecol. 93(6): 1085–1093. doi:10.1111/j.1365-2745.2005.01042.x.

Nitschke, C.R., M. Amoroso, K.D. Coates, and R. Astrup. 2012. The influence of climate change, site type, and disturbance on stand dynamics in northwest British Columbia, Canada. Ecosphere 3(1):11. doi:10.1890/ES11-00282.1.

Nitschke, C.R. and J.L. Innes. 2008a. A tree and climate assessment tool for modelling ecosystem response to climate change. Ecol. Model. 210(3): 263–277. doi:10.1016/j.ecolmodel.2007.07.026.

______. 2008b. Integrating climate change into forest management in south-central British Columbia: an assessment of landscape vulnerability and development of a climate-smart framework. For. Ecol. Manag. 256(3):313–327. doi:10.1016/j.foreco.2008.04.026.

O'Hara, K.L. and L.M. Nagel. 2006. A functional comparison of productivity in even-aged and multiaged stands: a synthesis for *Pinus ponderosa*. For. Sci. 52(3):290–303.

Oke, T.R. 1987. Boundary layer climates. 2nd ed. Routledge, Abingdon, U.K.

Pike, R.G., K.E. Bennett, T.E. Redding, A.T. Werner, D.L. Spittlehouse, R.D. Moore, T.Q. Murdock, J. Beckers, B.D. Smerdon, K.D. Bladon, V.N. Foord, D.A. Campbell, and P.J. Tschaplinski. 2010. Climate change effects on watershed processes in British Columbia. Ch. 19 in Compendium of forest hydrology and geomorphology in British Columbia. R.G. Pike, T.E. Redding, R.D. Moore, R.D. Winkler, and K.D. Bladon (editors). B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Manag. Handb. 66, Vol. 2. Available from www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm.

Pike, R.G., D.L. Spittlehouse, K.E. Bennett, V.N. Egginton, P.J. Tschaplinski, T.Q. Murdock, and A.T. Werner. 2008. Climate change and watershed hydrology: part I – recent and projected changes in British Columbia. Streamline Watershed Manag. Bull. 11(2):1–7.

Pojar, J., K. Klinka, and D.V. Meidinger. 1986. Biogeoclimatic ecosystem classification in British Columbia. Internal Report of the B.C. Min. For. Res. Program.

Prentice, I.C., M.T. Sykes, and W. Cramer. 1993. A simulation model for the transient effects of climate change on forest landscapes. Ecol. Model 65:51–70.

Rehfeldt, G.E., D.E. Ferguson, and N.L. Crookston. 2008. Quantifying the abundance of co-occurring conifers along inland northwest (USA) climate gradients. Ecology 89(8):2127–2139. doi:10.1890/06-2013.1.

Rouget, M., R.M. Cowling, R.L. Pressey, and D.M. Richardson. 2003. Identifying spatial components of ecological and evolutionary processes for regional conservation planning in the Cape Floristic Region, South Africa. Divers. Distrib. 9(3):191–210. doi:10.1046/j.1472-4642.2003.00025.x.

Swetnam, T.W. and J.L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. J. Clim. 11:3128–1347.

Tardif, J.C., F. Conciatori, P. Nantel, and D. Gagnon. 2006. Radial growth and climate responses of white oak (*Quercus alba*) and northern red oak (*Quercus rubra*) at the northern distribution limit of white oak in Quebec, Canada. J. Biogeogr. 33(9):1657–1669. doi:10.1111/j.1365-2699.2006.01541.x.

Temesgen, B., S. Eching, B. Davidoff, and K. Frame. 2005. Comparison of some reference evapotranspiration equations for California. J. Irrig. Drain. Eng. 131(1):73–84. doi:10.1061/(ASCE)0733-9437(2005)131:1(73).

Turner, B.L., P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, J.X. Kasperson, R.E. Kasperson, A. Luers, M.L. Martello, S. Mathiesen, R. Naylor, C. Polsky, A. Pulsipher, A. Schiller, H. Selin, and N. Tyler. 2003. A framework for vulnerability analysis in sustainability science. Proc. Nat. Acad. Sci. 100(14):8074–8079.

Van Mantgem, P.J. and N.L. Stephenson. 2007. Apparent climatically induced increase of tree mortality rates in a temperate forest. Ecol. Lett. 10(10):909–916. doi:10.1111/j.1461-0248.2007.01080.x.

Van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fulé, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, and T.T. Veblen. 2009. Widespread increase of tree mortality rates in the western United States. Science 323(5913):521–524. doi:10.1126/science.1165000.

Wang, T., A. Hamann, D.L. Spittlehouse, and S.N. Aitken. 2006. Development of scale-free climate data for western Canada for use in resource management. Int. J. Climatol. 26(3):383–397. doi:10.1002/joc.1247.

Westerling, A.L., H.G. Hildalgo, D.R. Cayan, and T.W. Swetnam 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313(5789):940–943. doi:10.1126/science.1128834.

Xu, C.Y. and V.P. Singh. 2002. Cross comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland. Water Resour. Manag. 16(1):197–219. doi:10.1023/A:1020282515975.

Zimmermann, N.E., N.G. Yoccoz, T.C. Edwards, E.S. Meier, W. Thuiller, A. Guisan, D.R. Schmatz, and P.B. Pearman. 2009. Climatic extremes improve predictions of spatial patterns of tree species. Proc. Natl. Acad. Sci. 106(Suppl. 2):19723–19728. doi:10.1073/pnas.0901643106.