Forest Ecology and Management 410 (2018) 35–47

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Novel climates: Trajectories of climate change beyond the boundaries of British Columbia's forest management knowledge system

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ARTICLE INFO

Keywords:
Novel climates
No-analog
Bioclimate
Mahalanobis distance
Random Forest
Biogeoclimatic ecosystem classification

ABSTRACT

The non-stationary climates of the 21st century are compelling forest managers to seek non-local species, provenances, and silvicultural regimes that are better suited to the anticipated future climates of their operating areas. Ideally, forest managers can source this information from climate analogs within their jurisdictions, but the emergence of unfamiliar climates is a distinct possibility with particular challenges. Here, we present an assessment of the emergence of mid-21st-century climates with no analog in the 20th-century climates of British Columbia (BC), and the extent to which these novel climates are described by climate analogs elsewhere in North America. We use a recently developed linear method of novel climate detection in parallel with Random Forest classification to evaluate the robustness of novel climate inferences. Our results suggest that a majority of the province's area will remain free of novel climates over this time period, and therefore that BC's ecological knowledge system, the Biogeoclimatic Ecosystem Classification, can remain the dominant source of climate analogs for mid-21st-century forest management planning horizons. Nevertheless, we detected a robust pattern of climates that are novel to BC in mid-21st-century climate projections at low elevations in the coastal, southern interior, and northeastern regions of the province. There appears to be potential to inform forest management in some of these novel climates with analogs from adjacent states and provinces. We demonstrate that extrapolations into novel climates typically understate the magnitude of climate change and modeling uncertainty, creating a false impression of robust predictions in locations where model performance is poorest. By identifying portions of their landscapes that are prone to emergence of novel climates, forest managers can avoid management errors and prioritize the search for analogs beyond the boundaries of their knowledge systems.

1. Introduction

1.1. Emerging challenges to the "local is best" ethic in forest management

The necessity to adopt non-local practices in response to climate change is a major new dimension in forest management. Historically, forest managers have developed specialized management regimes for their local ecosystems (Puettmann et al., 2009). The complex interactions of productivity, competition, stress, and disturbance are often idiosyncratic to individual places, leading forest managers towards a "local is best" ethic with respect to silvicultural systems, stand-tending practices, and species and provenance selection (Seymour et al., 2002; Ying and Yanchuk, 2006). These local idiosyncrasies are strongly driven by climate (Pojar et al., 1987), but the climates of the 20th century were sufficiently stable for forest managers to understand climate as a stationary quality of place. The non-stationary climates of the 21st century are a fundamental challenge to this place-based understanding of climate and ecosystem function (Millar et al., 2007). Forest managers have entered an era in which the "local is best" ethic is no longer reliable, and are looking to other locations for species, provenances, and management regimes that may be better suited to the anticipated future climates of their jurisdictions (Potter and Hargrove, 2012; Williams and Dumroese, 2013). This use of non-local climate analogs is an emerging cornerstone of 21st century forestry management, and underlies assisted migration through remote provenance selection (Aitken and Whitlock, 2013), assisted range expansion (Rehfeldt and Jaquish, 2010), and *in situ* tree species conservation (Hamann and Aitken, 2013). Moreover, climate analogs are essential to maintaining the relevance of accumulated practitioner knowledge in a changing climate. As climate zones shift across the landscape, so must the ecological knowledge with which they are associated.

Where analogs for anticipated future climates are available within

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https://doi.org/10.1016/j.foreco.2017.12.036
Received 18 November 2017; Received in revised form 21 December 2017; Accepted 21 December 2017
0378-1127/

local jurisdictional boundaries—e.g., from downhill locations—forest managers are able to draw on their familiar local knowledge systems. However, the projected magnitude of climate change over forest management timescales is compelling forest managers to look for climate analogs in the relatively unfamiliar climates of other jurisdictions (Potter and Hargrove, 2012). While some locally unfamiliar climates may have historical analogs in nearby jurisdictions, previous research suggests the potential for novel climates that have no historical analogs at continental (Rehfeldt et al., 2012; Mahony et al., 2017) and even global (Williams et al., 2007; García-López and Allué, 2013) scales. These truly novel climates represent conditions for which little knowledge is available from observational experience (Williams and Jackson, 2007), and therefore for which ecological predictions are unreliable (Fitzpatrick and Hargrove, 2009). Forest management in a changing climate will inevitably involve some extrapolation of accumulated knowledge into novel, unfamiliar conditions. Nevertheless, the risk of management failures will likely increase with the degree of extrapolation (Peterson et al., 2011, pp. 126–8). Measurement of novelty in projections of climate change indicates the degree of confidence that can be placed in climate analogs for forest management guidance.

1.2. Novel climates in the British Columbia forest management context

The use of climate analogs for climate change adaptation is in the early stages of being operationalized in British Columbia. For the past 50 years, forest practices and legislation in British Columbia have been organized under a province-wide structured knowledge system named the Biogeoclimatic Ecosystem Classification (BEC; MacKenzie and Meidinger, 2017; Haeussler, 2011). BEC includes, as one of its central pillars, a hierarchical climate classification with 16 zones (Fig. 1), ~100 subzones, and ~200 subzone-variants. Though BEC climates were originally conceived as static map units, spatial shifts in BEC climate units have been projected by using these units as analogs for the future climates projected by global climate models (Hamann and Wang, 2006; Wang et al., 2012). BEC unit projections are being used in an overhaul of the BC government's tree seed transfer framework, in which seed transfer limits are defined by BEC units and shifted in space in accordance with their projected future spatial distribution (O'Neill et al., 2017). BEC unit projections are also being used to incorporate climate change into provincial government's tree species suitability guidelines, by demoting or promoting individual species based on their historical suitability to the range of BEC units projected for a planting site. In providing a pool of climate analogs that are richly embedded with ecological knowledge, BEC is a coherent framework to guide the transfer of locally-adapted forest management strategies among regions and sites as their climates change.

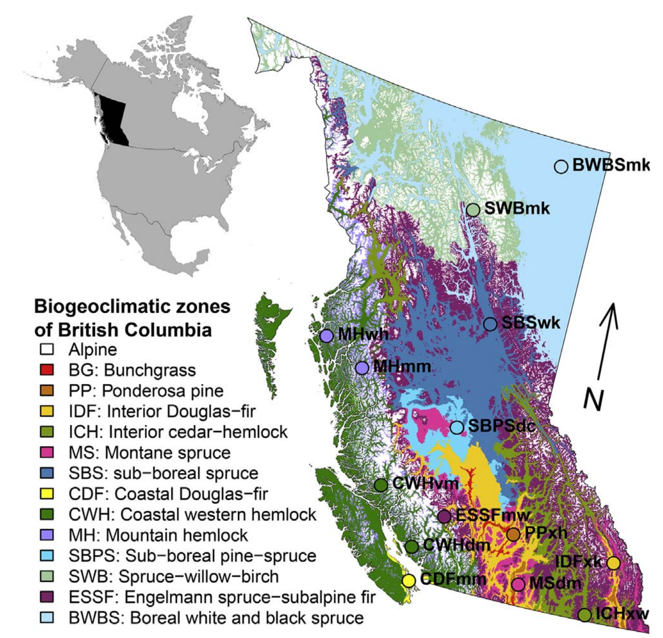

Fig. 1. Biogeoclimatic zones of British Columbia, the highest level of the BEC climate classification. Representative locations for a small sample of BEC subzones (see Supplementary Table S1 for full names) are provided for reference in subsequent figures.

The emergence of climates that are not described by the BEC system is an open problem in the use of climate analogs for forest management in British Columbia. Mismatch between future conditions of some locations and their BEC analogs should be expected, since current BEC projections do not draw on analogs from outside British Columbia. Two-dimensional seasonal temperature-precipitation envelopes for BC indicate that the warm edge of the BC climate envelope will develop novel climates (relative to historical BC climates) as it shifts due to climate change (Fig. 2). These simplified representations of climatic shifts suggest that the potential for novel climates is not limited to the warmest and driest areas of the province (e.g., the CDFmm subzone in the Georgia Basin and the PPxh subzone in the Okanagan Valley), but spans the warm margin of the climate envelope along the full range of precipitation regimes. The emergence of climates that are unfamiliar to the BEC system is an inevitable consequence of climate change. Further, previous research indicates the potential for future climates in British Columbia with no analogs in North America (Rehfeldt et al., 2012; Mahony et al., 2017).

The apparent potential for climate change to produce climate types that are novel to BC indicates that BEC projections are susceptible to extrapolation errors. Current BEC projections (Wang et al., 2012) provide the analog with the best match to projected conditions. The best match, however, is not necessarily a good match. Where extrapolation into novel climates results in a poor match between the projected future climate condition and its assigned analog within the BEC system, the BEC analog is likely to provide misleading guidance (Fitzpatrick and Hargrove, 2009). Undiagnosed use of poor-quality analogs has the potential to produce management failures due, for example, to inappropriate provenance or species selection for reforestation. It is essential to identify poor-quality analogs associated with novel climates, so that other more informative sources of guidance for management can be sought.

1.3. Measuring climatic novelty

Climatic novelty is subjective to the ecological context under consideration. The many variables with which climate can be characterized—growing season frosts, wind speed, fog, solar insolation, extreme events, snow-free period, and so on—have varying relevance to different species in different environments. The scales and thresholds at which these climate elements are relevant is similarly context-specific, due to differences in species' ecological tolerances. It follows that a climatic condition that is novel from the perspective of one ecological community may be functionally familiar to another.

The context-dependence of climatic novelty has important implications for how it is measured. The most prominent approach to novel climate detection defines novelty as the climatic distance (D_{min}) between the projected climate and its closest historical analog (Williams et al., 2007; Mahony et al., 2017). This distance is measured using a set of climate variables that is universal to all locations in the study. The relative magnitude (the scaling) of these climate variables is defined by standardizing them to their local interannual climatic variability. Although this linear scaling approach is localized, it does not necessarily reflect the complex and non-linear biological responses to climate that are idiosyncratic to each ecosystem. In contrast, BEC projections are currently produced using a machine learning algorithm, Random Forest (Breiman, 2001), that models the relationship between BEC units and climate using localized climate variable selection and non-linear scaling. Climatic novelty measured within the model