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Spatial coherence and change of opposite white spruce temperature sensitivities on floodplains in Alaska confirms early-stage boreal biome shift

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ABSTRACT

Since the mid 1970s, Interior Alaska white spruce trees experienced markedly lower growth than during the 19th and early 20th centuries. This observation raises the question of forest persistence on certain sites of lowland central and eastern Alaska. We analyzed white spruce growth across a 36-site network (540 trees) on three major river floodplains in boreal Alaska along a longitudinal gradient from eastern Interior to the southwest tree limit to test for the presence of tree growth patterns and climate sensitivities. Chronologies are compared for temperature sensitivity at both stand and individual tree levels, using data from Bethel, McGrath, and Fairbanks NWS stations during the common period of 1952–2001. Cross-dated stand-level ring width chronologies indicate three regions of common signal in tree growth across the gradient. Temperature sensitivity of stand- and individual-tree chronologies is spatially coherent. Most downriver chronologies correlate positively with spring mean monthly temperatures (MMT) at Bethel, mid- and upriver chronologies correlate negatively with MMT of May and previous year July at either McGrath or Fairbanks, and an area in between is a mixed population of positive and negative responders. In downriver positive responders, recent increases from suboptimal cool temperatures accelerated tree growth, while in mid- and upriver negative responders, recent increases from optimal or above-optimal temperatures decreased growth. Fairbanks negative responders are also negatively correlated with a 200-yr index of recorded and reconstructed Fairbanks summer temperatures, and recent sustained record high summer temperatures are associated with the lowest relative growth. Until the 1940s, absolute growth rate of negative responders was greater than positive responders, but from the 1970s the positive responders grew more. These results explain why northern ring width samples can display opposite temperature sensitivity and contribute to understanding recent "divergence" or loss of temperature sensitivity in a changing climate. We find that July MMT and annual precipitation at Fairbanks are now outside the limits that previously characterized the North American distribution of white spruce, and are near the reported physiological limits of the species. Our results of the spatial and temporal change of white spruce temperature sensitivity provide strong empirical evidence of previously proposed early stage biome shift in boreal Alaska due to clear climatic causes. Already, western Alaska, previously extending to tree limit, has become the optimum climate region for the species. With modest additional warming widespread tree death will be unavoidable on warmer lowland interior sites, where persistence of white spruce is unlikely.

1. Introduction

Boreal forest is susceptible to distinct thresholds or tipping points as well as a potentially rapid transition to alternative stable states, specifically in the transition from tundra/shrub to a colder biome or from steppe to a warmer and drier biome (Scheffer et al., 2012). Replacement of the boreal forest where it occurs today with woodland, shrub, or grassland would produce effects of considerable significance for albedo, carbon uptake and sequestration (Bonan, 2008), hydrologic regulation (Callaghan et al., 2011), wildlife habitat (Usher et al., 2005), and human use (Juday et al., 2005). Similarly, treeline advance into tundra has profound implications

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for a range of ecosystem processes (Callaghan et al., 2005; Wilmking et al., 2006).

Negative sensitivity of white spruce (*Picea glauca* Moench Voss; hereafter PIGL) radial growth to summer temperatures is widely reported in a number of Interior Alaska and northwest Canada regions (Barber et al., 2000; Juday et al., 2003; Griesbauer and Green, 2012). This negative growth sensitivity suggests that during recent decades of elevated temperatures, carbon uptake capacity was reduced across a substantial part of the western North American boreal region. If additional temperature increases projected in some scenarios (Kirtman et al., 2013) were to occur, further growth reductions are likely (Juday et al., 2005), raising questions about the persistence of the species in much of the region where its occurs today (Ohse et al., 2009). Site types and subregions identified as supporting populations of negative responder PIGL populations include productive upland sites of eastern and central Alaska (Barber et al., 2000), treeline environments of the Brooks Range and Alaska Range (Wilmking et al., 2004), and floodplain sites in the Yukon Flats and mid Tanana River (Juday and Alix, 2012).

However, positive growth responses of PIGL to temperature are also known from northwestern North American high latitude and altitude sites, often in complex patterns mixed with negative responding populations. At Brooks Range treeline, a general trend in PIGL of decreasing proportion of negative temperature response and increasing proportion of positive response can be demonstrated from east to west with greater proximity to the Bering Sea coast (Wilmking and Juday, 2005). The question remains as to whether these limited observations ($n = 7$ stands) of decreasing negative responders from the eastern Interior toward the coastal and western portions of Alaska represents a true gradient, or is based on local site variability and the peculiarities of the types of forest sampled for dendrochronological analysis (e.g. treeline, upland, or floodplain forests).

In some locations, temperature sensitivity of northern PIGL growth has varied through time. Mountain treeline sites in east central Alaska and in the Alaska Range support both positive and negative responding PIGL populations, but a trend toward increasing negativity of growth to temperature began in the mid 20th century (Lloyd and Fastie, 2002). A similar pattern occurs in adjacent Yukon Territory (Griesbauer and Green, 2012). Across both the Alaska Range and Brooks Range, specific temperature thresholds are associated with a change from non-responsiveness to responsiveness of PIGL growth to temperature, both positive and negative. Since about 1950, these temperature thresholds have been more consistently exceeded, explaining why in these treeline environments temperature sensitivity has not been stable through time (Wilmking et al., 2004).

Overall growth trends of white and black spruce ring width chronologies across Alaska are broadly similar to trends in Normalized Difference Vegetation Index (NDVI) (Beck et al., 2011). However, only about 30 years of NDVI data is available. Direct comparisons of radial tree growth and temperature data over longer time periods and across a large spatial scale with control of site-to-site variability are needed to establish whether (1) a true spatial gradient in climate control of spruce growth occurs in the western North American boreal forest, and (2) whether temperature sensitivity is systematically shifting over time.

The boreal region of Alaska is characterized by major east to west gradients of temperature and precipitation, largely related to the transition from a strongly continental climate in the eastern Interior to a strong maritime influence at the limit of tree distribution near coastal regions in the west (Simpson et al., 2002). Along the major rivers in the Interior, this transition occurs in a smooth uninterrupted gradient, in contrast to the northern Alaska treeline with its complex mosaic of site that differ in aspect, elevation, geology, and soils (Wilmking and Juday, 2005). Mature Interior floodplain forests have developed on the same soil type, from the same processes of primary floodplain succession (Viereck et al., 1993; Brabets et al., 2000; Magoun and Dean, 2000), occupy the same relatively narrow elevation band (maximum elevation = 305 masl at the Alaska/Canada border on the Yukon River to near sea level in the west), and do not vary in slope or aspect. As a result, a continuous river floodplain longitudinal transect of tree growth offers an ideal opportunity to test for a coherent pattern of temperature sensitivity. The purpose of this paper is to examine PIGL temperature sensitivity from the continental climate region of eastern Interior Alaska to the longitudinal treeline of maritime southwestern Alaska and determine whether temperature-related growth responses consistent with early-stage biome shift are underway on a common site surface.

1.1. Study area

The Yukon River basin occupies 832,700 km^2 across central Alaska and south-central Yukon Territory in Canada. The Tanana River within the Yukon River basin is a 980 km long tributary that enters the Yukon River a few kilometers above the Village of Tanana near the center of Alaska. The Kuskokwim river basin, in southwestern Alaska, is the second most prominent river basin of the state and covers an area of 124,319 km^2 (Fig. 1). All three rivers flow west or southwest, crossing Interior Alaska and emptying into the Bering Sea. Along these glacial meltwater rivers, a well-described process of forest succession culminates in the development of mature and old growth PIGL forests on well-drained high terraces (Van Cleve et al., 1996; Chapin III et al., 2006).

Three well-spaced National Weather Service (NWS) First Order stations – Fairbanks, McGrath, and Bethel – are located across the study area (Fig. 1). Annual precipitation is low in the interior of Alaska, and increases westward toward the downriver lower Yukon and Kuskokwim locations (Table 1). Mean summer and July temperatures follow the opposite pattern, with highest values in the Interior, and a gradient of cooler conditions toward the west (Simpson et al., 2005).

PIGL on floodplains sustain higher growth rates than on upland sites (McGuire et al., 2010), and on floodplains of central Alaska and the Yukon Flats, PIGL growth is mostly sensitive to high temperature limitation (Juday and Alix, 2012) and lack of summer precipitation (Yarie, 2008). Growth of mature PIGL on high floodplain terraces has been shown to benefit both from ground water proximity and precipitation. Extreme events such as floods that maintain high water during the growing season may impart distinctive patterns in annual ring width chronologies of boreal trees (Boucher et al., 2011).

Most older PIGL stands in the floodplain are assumed to have originated from primary succession following flooding disturbance. However, other disturbance factors also operate in floodplain PIGL stands. Fires are known to initiate succession in Alaska floodplain forests (Mann et al., 1995) but fire on floodplains is neither frequent nor extensive. Flooding also interacts with insect dynamics as a disturbance agent. Historically, PIGL on large river floodplains have been the focus of attacks of the northern spruce engraver beetle (*Ips perturabus* (Eichoff)), where a steady supply of suitable host trees weakened or injured by bank erosion are sustained (FS-R10-FHP, 2012, p. 10).

Starting in the late 19th century, the Yukon and Kuskokwim Rivers became major commercial travel routes, and riverbank trees were actively harvested and stacked by the river to be used as fuel for steam boilers on riverboats until the mid 20th century (Webb, 1990; Morse, 2003; Wurtz et al., 2006). Although this early history of wood harvesting along the major rivers of Alaska had a profound local impact, many of those harvested stands have eroded into the