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Developing management strategies for tree improvement programs under climate change: Insights gained from long-term field trials with lodgepole pine

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ABSTRACT

The growing concern of the impact of climate change in forestry has prompted tree improvement programs and regulatory agencies to integrate climate change adaptation in the production and use of tree seed. In support of such adaptation strategies, we conducted a case study for lodgepole pine (*Pinus contorta* Dougl.) in Alberta, Canada. We compared the tree height for populations and families planted across 37 progeny and provenance trials when transferred among six physiogeographically and climatically distinct breeding regions. Based on these results we infer how lodgepole populations and families are adapted to current climate conditions and how they might respond to future changes in climate. Interestingly, in almost all regions we found that local populations grew better than introduced sources, suggesting that in the current climate the use of local populations is still an appropriate reforestation strategy with some exceptions. Notably, in cool and wet higher elevation environments (between 1050 and 1650 m), local populations were outgrown by populations originating from warmer lower elevation regions. Moreover, these higher elevation populations were always outgrown when transferred to other regions. A number of transfers among regions were identified that ensure productivity gains under recent climate conditions, and simultaneously represent a short term adaptation measure for warming of about +0.5 °C. Further, we provide a database for selection of families within breeding populations to enhance their resilience to climate change.

1. Introduction

Climate is widely acknowledged to be a key agent of natural selection in plant populations including forest trees (Villalba et al., 1994; Linhart and Grant, 1996; Matyas, 1996; Lo et al., 2010; McLane et al., 2011). Although many environmental factors contribute to genetic differentiation and evolution of locally adapted populations (e.g. Linhart and Grant, 1996), temperature and geographic and topographic variables that affect temperature appear to be the main drivers of natural selection in northern conifers such as white spruce (Li et al., 1997; Rweyongeza et al., 2010; Gray et al., 2016; Liepe et al., 2016), black spruce (Morgenstern, 1978; Beaulieu et al., 2004; Wei et al., 2004), Norway spruce (Oleksyn et al., 1998a; Kapeller et al., 2012; Schueler et al., 2013), lodgepole pine (Wu and Ying, 2004; Wang et al., 2006; Rweyongeza et al., 2007; Liepe et al., 2016), jack pine (van Niejenhuis and Parker, 1996; Thomson and Parker, 2008) and Scots pine (Beuker et al., 1998; Oleksyn et al., 1998b). These and many other studies show that temperature explains most of adaptive genetic variation in survival, shoot phenology, rate of growth, frost hardness, morphology and physiological process such as photosynthesis.

Lodgepole pine (*Pinus contorta* spp. *latifolia*), as a major commercial forestry species, has been particularly well studied with respect to adaptation to climate. In early studies, Rehfeldt (1988) and Rehfeldt and Wykoff (1981) found that the majority of population differentiation in lodgepole pine growth was explained by clinal patterns of variation that in general reflected elevation and the climatic variable frost-free period. In range-wide provenance studies, response functions of lodgepole pine populations have highlighted the sensitivity of height growth and survival to even small fluctuations in temperature of ±1 °C (Rehfeldt et al., 1999, 2001; Wang et al., 2006; O'Neill et al., 2008). Approaches other

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than provenance trials confirm the sensitivity of lodgepole pine to climate change. For example, using dendrochronology, Chhin et al. (2008a) found that heat and moisture stress in later summer reduced annual radial growth of lodgepole pine in Alberta. Further, predicted growth under climate change scenarios suggests negative impacts on the productivity of lodgepole pine in the Alberta Foothills (Chhin et al., 2008b). Given lodgepole pine is the second most important commercial tree species in Alberta, climate change adaptation measures are needed to lower the vulnerability of lodgepole pine in Alberta as well as protect species habitats and commercial investments.

Foresters and tree breeders manage genetic adaptation to climate in commercial forestry by using seed zones and tree breeding regions. Rather than developing breeding strategies that include traits for adaptation, a more logical way to guarantee adaptation for traits such as tolerance to climatic stress, resistance to insects and diseases, and reproductive fitness is to rely on delineation of breeding and deployment zones that are characterized by relatively homogenous environments (e.g. Linhart and Grant, 1996; Vander Mijnsbrugge et al., 2010). The use of such zones may be the easiest way to avoid what Zobel and Kellison (1978) called the rate of growth syndrome in tree breeding, which erroneously overemphasizes height growth at the expense of other traits that are important for population adaptation, yield and product quality.

Studies show that in the past few decades, climate has been changing faster than expected in many regions of Canada (Mbogga et al., 2009; Jiang et al., 2015). Jiang et al. (2015) shows that, from the year 1900–2011, the December – February temperature for northern Alberta, Canada, increased by an average of 0.5 °C/decade. Future projection suggests that between 2020s and 2080s, Alberta's changes in seasonal precipitation could range from a decline of 25% to an increase of 36% with the increases occurring in the period between December and May. In the same period, temperature would increase throughout Alberta with the highest increase occurring in the December – February period (maximum of 6.8 °C). Rapid changes in climate could significantly affect the regeneration success as well as the health and productivity of both natural and managed forests. For example, observed climate shifts in Alberta over the last decade have been linked to drought-related dieback of boreal trees (Hogg et al., 2002; Allen, 2009; Michaelian et al., 2011). Drought in particular would reduce regeneration success thereby increasing the cost of reforestation. Moreover, the loss of biomass production would affect the forest industry and economies of forestry-dependent communities.

In response to observed climate change over the last several decades, a number of adaptation strategies have been suggested to maintain forest health and productivity. They include: (i) planting new species, (ii) planting species mixtures instead of single-species stands, (iii) planting mixtures of many provenances instead of single seed sources, (iv) assisted species migration to new environments to prevent extinction, (v) assisted population migration/translocation beyond their current area of commercial planting, (vi) planting uneven-aged instead of even-aged stands and (vii) retaining higher levels of genetic diversity in reforestation seed (e.g. Ledig and Kitzmiller, 1992; Millar et al., 2007; Vander Mijnsbrugge et al., 2010; Williams and Dumroese, 2013). These strategies are designed to enable the use of seed from sources where populations better suited to the new climate can potentially be found, establish managed forestry with diverse structures that reduce the risk of total stand failure, and maintaining high genetic diversity to buffer forests against unforeseeable climatic stresses that would otherwise decimate genetically depleted even-aged single-species stands. Another long-term adaptation strategy could be to select and breed commercial species for optimum biomass production for the expected future climate. However, even with advances in genomics and marker assisted selection (see Neale and Kremer, 2011; Sork et al., 2013), operational breeding for climate change adaptation in northern conifers is still years away. Therefore, alternative sources of seed for immediate deployment to address climate change are needed.

In this study, we explore the opportunities for population translocation among the six lodgepole pine breeding regions in Alberta to address climate change challenges. Our focus is on sustaining biomass productivity where climate change projections suggest a possible decline, and to enhance productivity where climate change will improve growing condition but local populations are unlikely to utilize it due to their intrinsic low growth potential. The research objectives are: (1) to investigate if local material originating within each breeding region is best for existing seed production needs, (2) to identify the transferability of genetic material between breeding regions, (3) to determine if the current breeding region delineations adequately capture genetic population differentiation, and (4) to infer how lodgepole pine seed sources may be deployed under anticipated climate change based on their performance when transferred to warmer environments.

2. Methods

2.1. Genetic field trials

In this study, we used height growth data from 10 series of progeny trials across six breeding regions. These series contained in total approximately 140,000 trees including 1669 open-pollinated families within 29 trials established at 27 locations (Fig. 1a). In addition, we included data from 6 series of provenance trials with in total approximately 17,000 trees from 203 different populations within 8 trials on 8 locations (Fig. 1a). All trials are summarized in Table 1. Data used in this study are from measurement of trees established with bulk seedlots representing provenances or single-tree cone collections representing half-sib families. However, to simplify terminology and avoid repetitions, the term "population" will be used throughout this article to refer to both provenances and families, except where the distinction is necessary to describe statistical analyses.

2.2. Climatic data

Climatic characterization of the lodgepole pine breeding regions was derived from spatially interpolated climate data for the 1961–1990 climate normal period, generated using the software package ClimateWNA v4.62 (Hamann et al., 2013). This software relies on gridded climate surfaces generated with the Parameter Regression of Independent Slopes Model (PRISM) (Daly et al., 2008). The software makes automatic lapse rate adjustments to temperature estimates for seed collection locations if the elevation of a location does not match the elevation of the gridded PRISM data (Hamann and Wang, 2005). Only climatic variables considered biologically relevant for describing genetic differentiation of plant populations were selected for the current study. They include Mean Annual Temperature (MAT), Mean Coldest Month Temperature (MCMT), Mean Warmest Month Temperature (MWMT), Continentality (TD = MWMT – MCMT), Mean Annual Precipitation (MAP), Growing Season Precipitation (MSP), Climate Moisture Deficit (CMD, calculated as the sum of the monthly difference between reference atmospheric evaporative demand and precipitation), Frost Free Period (FFP), Number of Frost Free Days (NFFD), Growing Degree Days above 5 °C (DD5). A detailed description of how the variables are calculated can be found in Wang et al. (2012).