Forest Ecology and Management 324 (2014) 147–157

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Comparative genetic responses to climate in the varieties of *Pinus ponderosa* and *Pseudotsuga menziesii*: Reforestation

Gerald E. Rehfeldt [a,*], Barry C. Jaquish [b], Cuauhtémoc Sáenz-Romero [c], Dennis G. Joyce [d], Laura P. Leites [e], J. Bradley St Clair [f], Javier López-Upton [g]

[a] USDA Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, 1221 S. Main, Moscow, Idaho 83843, USA
[b] Research Branch, B.C. Ministry of Forests, Lands and Natural Resource Operations, Kalamalka Forestry Centre, 3401 Reservoir Rd, Vernon, BC V1B 2C7, Canada
[c] Instituto de Investigaciones Agropecuarias y Forestales, Universidad Michoacana de San Nicolás de Hidalgo (IIAF-UMSNH), Km 9.5 Carretera Morelia-Zinapécuaro, Tarímbaro, Michoacán 58880, Mexico
[d] Independent Contractor, 449 Walls Road, Sault Ste. Marie, Ontario P6A 6K4, Canada
[e] Department of Ecosystem Science and Management, Pennsylvania State University, University Park, PA 16802, USA
[f] USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331-4401, USA
[g] Colegio de Postgraduados, Km 35.5 Carretera México-Texcoco, Montecillo, México, CP 56230, Mexico

A R T I C L E   I N F O

Article history:
Available online 13 April 2014

Keywords:
Management strategies
Climate-change impacts
Douglas-fir
Ponderosa pine
Seed transfer guidelines

A B S T R A C T

Impacts of climate change on the climatic niche of the sub-specific varieties of *Pinus ponderosa* and *Pseudotsuga menziesii* and on the adaptedness of their populations are considered from the viewpoint of reforestation. In using climate projections from an ensemble of 17 general circulation models targeting the decade surrounding 2060, our analyses suggest that a portion of the lands occupied today primarily by coastal varieties of each species contain genotypes that should remain suitable for the future climate. A much larger portion, particularly for varieties occupying inland sites, should require either introduction of better suited species or conversion to better adapted genotypes. Regeneration strategies are considered with the goal of matching growth potential of contemporary populations to the future climate where that potential can be realized. For some lands, natural reproduction should be suitable, but most lands will require forest renewal to maintain forest health, growth, and productivity. Projected impacts also illustrate the urgent need for conservation programs for *P. menziesii* in Mexico.

Published by Elsevier B.V.

1. Introduction

Climate affects the distribution of species and molds adaptation of populations within species. Climate change, therefore, will impact land management objectives and procedures. Yet, targeting future climates currently moving along uncertain trajectories presents unprecedented challenges to managers, particularly when dealing with long-lived organisms. This paper is the third in a series dealing with plant-climate relationships for the sub-specific varieties of *Pinus ponderosa* and *Pseudotsuga menziesii*. The first of the series, PART 1 (Comparative Genetic Responses to Climate for the Varieties of Pinus ponderosa and Pseudotsuga menziesii: Realized Climate Niches, this issue), considered the realized climate niche, and the second, PART 2 (Comparative Genetic Responses to Climate in the Varieties of Pinus ponderosa and Pseudotsuga menziesii: Clines in Growth Potential, this issue) addressed the clines in growth potential that occur within varieties. Both papers used future climate projections to assess potential impacts of climate change on these two widespread species. Herein we focus on impacts from the viewpoint of reforestation strategies and procedures.

Ample literature demonstrates that in time, directional shifts in climate will result in deterioration of growth, health and survival in forest ecosystems (e.g., Leites et al., 2012a,b). Climate-induced impacts are currently in evidence, and numerous analyses of potential impacts unanimously portend widespread disruption of forest ecosystems over the course of the current century. We state in PART 2: “Although little is known about the rates of demise as trees become maladapted, provenance testing has repeatedly demonstrated the process: loss of productivity, increased environmental stress, and mortality from numerous potential agents.” To managers, this may mean that operations such as salvage will rise toward the forefront, but our focus is on reforestation: the species,

* Corresponding author. Tel.: +1 208 882 3557.
E-mail addresses: jrehfeldt@gmail.com (G.E. Rehfeldt), barry.jaquish@gov.bc.ca (B.C. Jaquish), csaenzromero@gmail.com (C. Sáenz-Romero), dennis.joyce@vianet.ca (D.G. Joyce), lpl3@psu.edu (L.P. Leites), bstclair@fs.fed.us (J. Bradley St Clair), jlopezupton@gmail.com (J. López-Upton).

http://dx.doi.org/10.1016/j.foreco.2014.02.040
0378-1127/Published by Elsevier B.V.

populations and genotypes to become established for the new generation.

In this paper, we synthesize the results of PART 1 and PART 2 to illustrate approaches for identifying contemporary sources of seeds having reasonable chances of being suited to forest landscapes of the future. While management strategies and options become more complex in a changing climate (see Millar et al., 2007), the underlying goal of reforestation should remain the same, that is, to optimize forest health, growth, and productivity by assuring that new generations are genetically suited to their environment. This goal is imbedded in the seed deployment strategies that are in use today.

For reference, the contemporary distribution of the varieties of these two species is illustrated in Fig. 1 where data points recording taxa occurrence (see PART 1) are mapped. Climatypes (PART 2) refer to climatic ecotypes of Turesson (1925) which, in our case, are delineated by classifying continuous genetic variation in growth potential within varieties. The classification considers the steepness of the cline and variation within populations such that individuals and populations within climatypes should be adaptively similar. Impacts from climate change are commonly viewed as occurring at the trailing edge where habitat is being lost and at the leading edge where new habitat is emerging. The area between the edges is commonly viewed as being stable with regard to the persistence of the contemporary inhabitants. In our work, projected impacts are based on output of an ensemble of 17 general circulation models (GCM) centering on the decade surrounding 2060 (see PART 1).

Central to our discussion of responses to the changing climate is the concept of *phenotypic plasticity*. We adopt the succinct presentation of Mátyás et al. (2010) who noted that the term originated with zoologists for describing an ability of individual genotypes to produce alternative phenotypes in disparate environments (see DeWitt and Scheiner, 2004). Bradshaw (1955), however, warned that in plants, plasticity should be interpreted in a broader context. The definition Mátyás employs was derived from the collective experience of plant breeders: phenotypic plasticity is the ability of the genotype or the population to maintain high fitness across a range of environments (also see Mátyás, 2007). The relative steepness of clines or the breadth of climatypes (PART 2) is indicative of the strength of local adaptation on the one hand and plasticity on the other as alternative mechanisms for accommodating environmental heterogeneity. If one views phenotypic plasticity as the ability of a genotype to express a different phenotype under different environmental conditions without considering fitness (e.g. Franks et al., 2013), then plastic and maladaptive responses are hopelessly confused.

2. Climate change impacts

2.1. Short- and long-term responses to climate change

Responses to a changing climate can be viewed as (a) short-term plastic responses that accrue in endemic populations as physiological systems adjust to change, and (b) as long-term evolutionary responses that realign genetic variation with environmental diversity (see Rehfeldt et al., 2004). Both responses are unquestionably occurring today (Franks et al., 2013). Immediate short-term responses draw on the innate plasticity that allows forest trees to endure temporal environmental variation during their long lives. Yet, as unequivocally demonstrated by provenance testing (see PART 2), plastic responses are limited to a finite range of environmental variability; exposure to climates beyond these limits will produce maladaptive effects, commonly involving dieback and mortality. Provenance tests also have demonstrated for

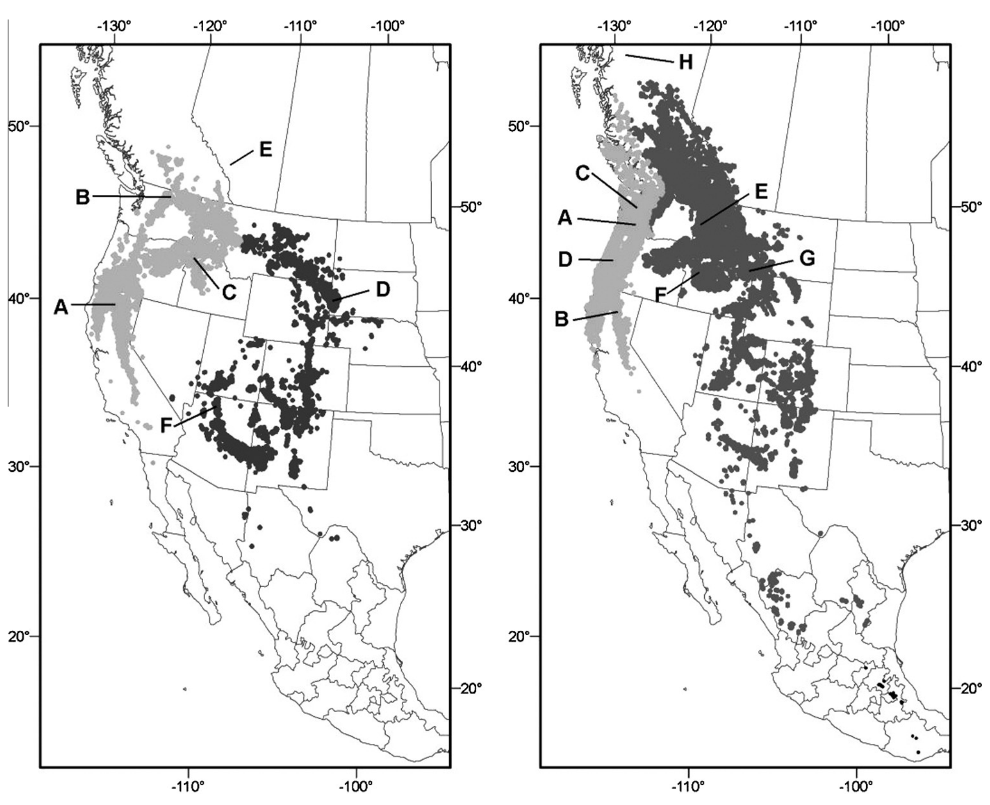

Fig. 1. Location of ground plots containing *Pinus ponderosa* (left) var. *ponderosa* (light gray) and var. *scopulorum* (dark gray) and *Pseudotsuga menziesii* (right) var. *menziesii* (light gray), var. *glauca* (dark gray), and the unnamed Mexican variety (black). Ground plots were used to construct the climate profile models (PART 1). Letters identify map locations enlarged in Figs. 5 and 6.