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**Forest Management
Genetic Resource Management Program**

Genetic Resource Management
and Climate Change:
**Genetic Options for Adapting
National Forests to Climate Change**



Photo: Andrei Rycoff

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Genetic Resource Management and Climate Change: Genetic Options for Adapting National Forests to Climate Change

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This report provides an overview of current climate change knowledge and potential implications for forest tree species, as well as goals, principles, and recommendations for enhancing forest resilience and resistance through a re-aligned “climate-smart” National Forest System (NFS) Genetic Resource Management Program. Although national forests may differ in terms of species and population vulnerability to climate change, as well as appropriate management response, our recommendations and adaptation options all follow three overarching principles: (1) genetically diverse and adapted seed and planting stock will provide the foundation for healthy forests and ecosystems in the future; (2) gene conservation is key to preserving vulnerable species and populations for the future; and (3) establishing and maintaining partnerships will be more important than ever. Implementation of the adaptation options will require new tools, practices, and re-focused investments in NFS Genetic Resource Management activities, as well as a trained workforce, supporting plant production infrastructure, and strong support from research and management.

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Genetic Resource Management and Climate Change: **Genetic Options for Adapting National Forests to Climate Change**

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Executive Summary

Understanding Adaptation and Vulnerability

Maintaining healthy ecosystems in the face of climate change will require new tools, practices, and re-focused investments in all areas of Forest Service land management, including genetic resource management. This report provides an overview of current climate change knowledge and potential implications for forest tree species, as well as findings, goals, principles, and recommended “no regrets” strategies and actions derived from a national genetics workshop for National Forest System (NFS) and research geneticists held in 2010. The primary focus is on forest tree species.

Our understanding of the adaptive response of forest tree species to their local climates relates to key adaptive traits such as survival, growth, cold hardiness, drought tolerance, vegetative bud phenology, and disease resistance. Patterns of genetic variation vary

greatly among tree species: some species are climatic “specialists” while others are “generalists.” Adaptive variation is most commonly associated with the seasonal temperature and moisture regimes of the source environment.

Such information has contributed to the development of seed zones and seed transfer guidelines to help ensure reforestation and restoration success through the use of locally adapted seed sources and planting stock.

However, if climate change proceeds as predicted, a major concern is that planting stock originating from fixed contemporary seed zones will be growing in sub-optimal conditions by the end of the century or sooner.

Climate change will require trees to cope with new biotic and abiotic environments and stresses, including: habitat shifting and alteration, fragmentation, drought, temperature extremes, flooding, wildfire, and novel insect and disease pressures. The specific effects of climate change will vary greatly over time and space. The box on the following page outlines the kinds of species and habitats most vulnerable to climate change.

“No Regrets” Option:
Actions that are beneficial given a variety of climate futures and desired future conditions.

Source: Howard et al. 2010, Wilby and Vaughan 2010



A USFS genetic study of geographic variation in ponderosa pine in the Pacific Northwest. Results from this and similar studies are used to develop seed zones and plant movement guidelines to help ensure reforestation success and ecosystem resiliency and productivity. Photo credit: U.S. Forest Service

Genetic specialists—exhibit strong genetic differentiation over small geographic and climate scales

Genetic generalists—show low genetic differentiation across a wide range of environmental gradients

Principles and Goals *

* See the full Strategy document for detailed priority action items associated with each principle for enhancing forest resilience and resistance through a re-aligned “climate-smart” NFS Genetic Resource Program.

PRINCIPLE 1: Genetically diverse and adapted seed and planting stock provide the foundation for healthy forests and ecosystems in the future.

Strategic Goal 1.1. Develop and deploy plant material that will be resilient to climate change.

Strategic Goal 1.2. Manage for uncertainty and adaptation through natural selection by placing an increased emphasis on genetic diversity (species and seed sources), as well as a diversity of silvicultural approaches across the landscape.

Strategic Goal 1.3. Consider climate change when determining plans and priorities for disease and insect resistance selection and breeding programs.

Strategic Goal 1.4. Create opportunities for rapid natural selection for species, habitats, and geographic areas with high observed or predicted potential for adverse impacts due to climate change.

PRINCIPLE 2: Gene conservation is key to preserving vulnerable species and populations for the future.

Strategic Goal 2.1. Preserve representative samples of species and populations threatened by climate change.

PRINCIPLE 3: Establishing partnerships will be more important than ever.

Strategic Goal 3.1. Support and expand internal and external partnerships that will improve our response to climate change.

SPECIES AND POPULATIONS MOST VULNERABLE TO CLIMATE CHANGE

- Rare species
- Species with long generation intervals (e.g., long-lived species)
- Genetic specialists (species that are locally adapted)
- Species with limited phenotypic plasticity
- Species or populations with low genetic variation
 - small populations
 - species influenced by past genetic bottlenecks
 - inbreeding species
- Species or populations with low dispersal and colonization potential (fragmented, disjunct populations)
- Populations at the trailing edge of climate change
- Populations with “nowhere to go” (lack of nearby suitable habitat)
- Populations threatened by habitat loss, fire, disease, or insects

Source: St. Clair and Howe 2011

Introduction: Understanding Adaptation and Vulnerability

Background

Climate considerations have always been integral to the work of plant geneticists. For more than 100 years, geneticists have studied how native plant populations adapt to their local environment, including climate. From these studies, geneticists have provided invaluable recommendations to land managers—such as seed movement guidelines and transfer zones—to help ensure that the most appropriate plant materials are collected and used in reforestation and revegetation activities.

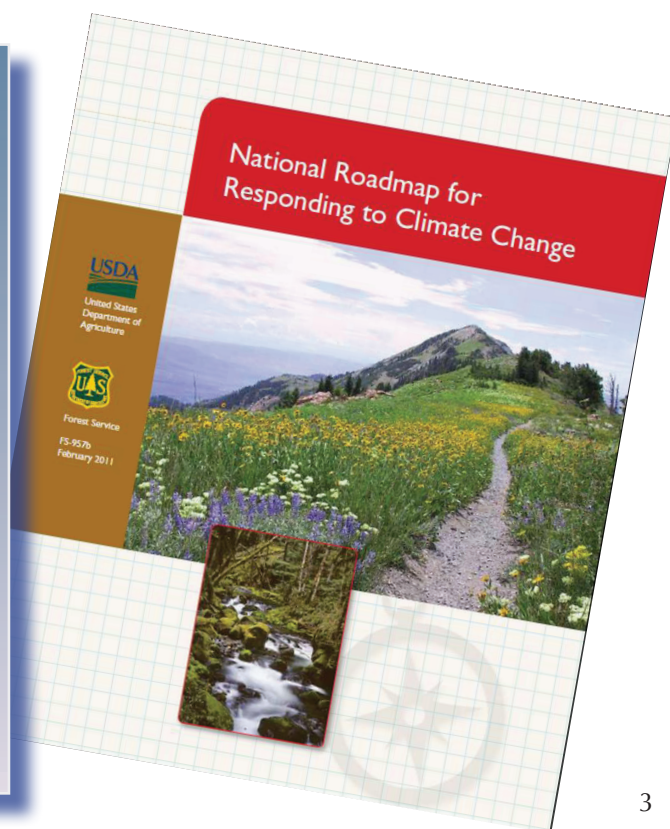
These recommendations have directly contributed not only to planting success, but also to gene conservation, ecosystem resiliency, and enhanced forest health and productivity. In the face of ongoing warming trends and the rapid rate of climate change predicted for the future (IPCC 2007), revised genetic strategies and action plans are needed to help reorient and guide national and regional efforts to respond to climate change, particularly with respect to highly vulnerable species, habitats, and geographic areas.

To better understand projected forest responses to climate change and to develop effective “no regrets” options (see box on page 1) for managing genetic resources in a dynamic and uncertain future, a national workshop for National Forest System (NFS) and research geneticists was held in Corvallis, OR, in March 2010.

This document provides an overview of current climate change knowledge and predictions, as well as findings and recommendations from the workshop as they relate to the NFS Genetic Resource Program (GRP) and its internal and external partnerships and clients. The primary focus is on forest tree species, although context and information with relevance to other native plant taxa are also provided. This is intended to be a dynamic document, with updates and information to be added over time as scientists and managers gain additional knowledge and experience in designing and applying effective genetic strategies for adapting national forests to climate change.

This report builds on the Forest Service's National Roadmap for Responding to Climate Change (USDA Forest Service 2011). The Roadmap highlights the importance of genetics in establishing and maintaining resilient healthy forests and rangelands. The Roadmap stresses the need to have seed sources adapted to both current and future climates and clearly states that “the agency will use more genetically diverse populations and breed for appropriate abiotic and biotic resistances.” This report builds on these ideas.

Likewise, the Roadmap discusses the need to assess the vulnerability of threatened and endangered species and to develop adaptation and conservation measures in light of climate change. The implementation of these conservation activities are further discussed in this report.



Genecology is the study of geographic patterns of genetic variation in traits related to climate adaptation, such as bud burst and bud set, cold and drought hardiness, and growth rates (St. Clair and Howe 2007). Information from genecology studies has been used to map genetic variation across the landscape, and to develop seed zones and seed movement guidelines for species commonly used in reforestation and restoration.

The studies are typically conducted in short-term seedling tests in controlled environments (e.g., growth chambers, greenhouses, farms, or nurseries). Longer-term field tests in natural environments (e.g., reciprocal transplant and provenance studies) may also be used to examine the relationship between trait variation and source climates (Matyas 1994, Rehfeldt et al. 1999, Wang et al. 2006).

The underlying assumption is that because seed sources are grown together in a common environment, any differences among them

are due their genetic composition. Genetic variation that is correlated with physiographic or climatic variables of the seed source locations suggests that the trait has responded to selection pressure and may be of adaptive importance.

More recently, these genetic approaches are being used to help determine whether existing populations will be adapted to future climates or if seed zones and plant movement guidelines should be modified. Longer term tests are being established to model responses of plant populations to various climatic conditions by planting seed sources obtained from many locations in multiple test sites spanning a wide range of climatic conditions.

The underlying concept is that the spatial climatic variation of the test sites is substituted for temporal trends reflecting future climate change. An example is the Douglas-fir Seed Source Movement Trials of the Forest Service Pacific Northwest Research Station, in which families from 60 populations from northern California and western Oregon and Washington are grown at nine climatically diverse test sites.

The studies can be used to predict the performance of sampled populations under both current and predicted future climates, and to identify the most suitable populations for each planting site under a particular climate change scenario.



Photo credit: Chris Poklemba

Tree Population Genetics

An understanding of the genetics of tree populations is important not only to predict the effects of climate change on forests, but also to develop and evaluate management options for responding to climate change. Forest tree species often maintain high levels of genetic variation and gene flow, which should facilitate their ability to evolve in response to changing climate (Hamrick et al. 1992). Yet, because populations of trees are genetically adapted to their local climates, the climatic tolerance of individual populations is often considerably narrower than the tolerance of a species as a whole. This is significant, especially because the ability of forest trees to respond to rapid climate shifts in their existing location is limited by their long life spans, long generation intervals, and long juvenile phases.

“Adaptation” in the climate change literature has been broadly defined as the “adjustment in natural or human systems in response to actual or expected climatic stimuli and their effects, which moderates harm or exploits beneficial opportunities” (IPCC 2007). With

respect to forests, climate change adaptation — whether natural or human-mediated— will depend on the evolutionary capabilities of tree populations, including all of the genetic and phenotypic changes that allow them to survive, reproduce, and thrive under changing environmental conditions.

In the following pages we provide an overview of how trees are genetically adapted to their local climates and what is known about their ability to cope with new and changing climates via acclimation, migration, and natural selection and adaptation. Genetic strategies and priority action items developed and agreed to by NFS geneticists at the 2010 meeting are then presented for enhancing forest resilience and resistance through a reinvigorated, “climate-smart” NFS Genetic Resource Program. Throughout the paper, we also highlight examples of genetic work already underway around the country to identify and address challenges in priority species and populations, and influence positively how national forests respond to climate change.

Table 1. Conifer species and the amount of environmental difference needed to show a genetic difference

Species	Elevational difference to find genetic difference in meters (feet)	Frost-free days to find genetic difference	Evolutionary mode
Douglas-fir (<i>Pseudotsuga menziesii</i> (Mirb.) Franco [Pinaceae])	200 (656)	18	Specialist
Lodgepole pine (<i>Pinus contorta</i> Douglas ex Loudon [Pinaceae])	220 (722)	20	Specialist
Engelmann spruce (<i>Picea engelmannii</i> Parry ex Engelm. [Pinaceae])	370 (1,214)	33	Intermediate
Ponderosa pine (<i>Pinus ponderosa</i> c. Lawson [Pinaceae])	420 (1,378)	38	Intermediate
Western larch (<i>Larix occidentalis</i> Nutt. [Pinaceae])	450 (1,475)	40	Intermediate
Western redcedar (<i>Thuja plicata</i> Donn ex. D. Don [Cupressaceae])	600 (1,970)	54	Generalist
Western white pine (<i>Pinus monticola</i> Douglas ex. D. Don [Pinaceae])	None	90	Generalist

Source: From Rehfeldt 1993. Used with permission.

Climatic Adaptation

Our understanding of the adaptive response of forest tree species to their local climates is derived from a rich history of genecological studies, which focus on the relationship between important adaptive traits (such as survival, growth, cold hardiness, drought tolerance, vegetative bud phenology, and disease resistance) and the climatic conditions of a plant's source environment.

Two approaches typically are used in forest trees:

(1) long-term field tests such as provenance tests or reciprocal transplant studies, and (2) short-term seedling studies in controlled environments, such as growth chambers, greenhouses, or common garden plots in nurseries or agronomic settings (St. Clair and Howe 2007). From these studies, it is apparent that patterns of genetic variation vary greatly among species; some species are climatic specialists that exhibit strong differentiation over small geographic and climate scales, while others are generalists that show less differentiation across a wide range of environmental gradients (Rehfeldt 1993, Table 1). Some species can also exhibit multiple adaptive strategies over different portions of their range; in the Rocky Mountains, for example, Douglas-fir is a specialist at lower elevations but a generalist at higher elevations (Rehfeldt 1989, 1974). Similarly, ponderosa pine variety *ponderosa* exhibits an intermediate adaptive strategy at low to mid elevations in the Inland West but becomes a specialist at high elevations (Rehfeldt 1991). Thus, there is a range of differentiation across environmental gradients even *within* species that affects flexibility to respond to stress (climate change).

When adaptive variation is detected, it is most commonly associated with the seasonal temperature and moisture regimes of the source environment (for example, winter minimum temperature, summer

maximum temperature, number of frost-free days, mean annual precipitation, and drought indices). Geneticists have used this information to develop seed zones and seed transfer guidelines to help ensure reforestation and restoration success through the use of locally adapted seed sources and planting stock. These genetically based seed transfer systems have become the foundation of successful Forest Service reforestation programs.

An important caveat to these guidelines, however, is the general assumption of a static climate, an assumption that may be unlikely under projected changes in climate, especially over the long term. If climate change proceeds as predicted, for example, a major concern is that planting stock originating from fixed contemporary seed zones will be growing in sub-optimal conditions by the end of the century or sooner (Johnson et al. 2010, Ledig and Kitzmiller 1992). In some parts of the country, plants may already be growing outside their optimal climate as a result of environmental changes that are occurring at a faster rate than species' response capabilities. This mismatch of genotypes and the

environments in which they evolved—referred to as “adaptational lag”—can result in reduced growth and productivity, poor forest health, high rates of plant mortality, and even potentially threaten a species' overall survival (McKenney et al. 2009, Gray et al. 2011). Long-lived tree species with long generation durations (and hence slow generation turnover) are at greatest risk of becoming maladapted to changing climates at their existing locations, especially compared to short-lived annuals and perennials with more frequent generation turnover and opportunities for natural selection (Lenoir et al. 2008, St. Clair and Howe 2011).

SPECIES AND POPULATIONS MOST VULNERABLE TO CLIMATE CHANGE:

- Rare species
- Species with long generation intervals (e.g., long-lived species)
- Genetic specialists (species that are locally adapted)
- Species with limited phenotypic plasticity
- Species or populations with low genetic variation
 - small populations
 - species influenced by past genetic bottlenecks
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- Species or populations with low dispersal and colonization potential (fragmented, disjunct populations)
- Populations at the trailing edge of climate change
- Populations with “nowhere to go” (lack of nearby suitable habitat)
- Populations threatened by habitat loss, fire, disease, or insects

Source: St. Clair and Howe 2011

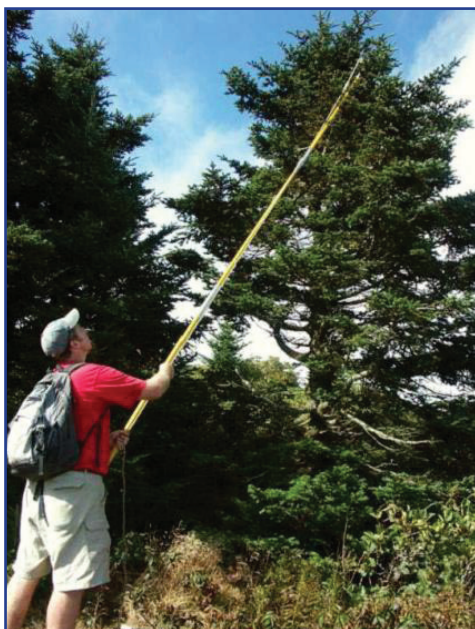
Assessing Vulnerability to Climate Change

Climate change will require trees to cope with new biotic and abiotic environments and stresses, including habitat shifting and alteration, fragmentation, drought, temperature extremes, flooding, wildfire, and novel insect, disease, and competitive pressures. Tree populations may cope with new climates by acclimating, migrating to new locations, or evolving via natural selection. If they cannot cope, species and populations may disappear from local ecosystems. The specific effects of climate change, however, will vary greatly over space and time depending on the degree of exposure, sensitivity, and the adaptive capacity of individual species and populations (Chimura et al. 2011, Parry et al. 2007).

Based on our knowledge of silvics and population genetics, as well as on studies of forest responses to past climate conditions, we anticipate that plants that are genetic specialists will be most vulnerable to climate change. This would be especially apparent during the regeneration and juvenile phases of growth, and in moisture-limited areas such as the southwestern United States or the dry central and eastern portions of the Rocky Mountains and Pacific Northwest. High-

elevation trees with limited potential to move upslope or across complex topography, either at the population level (such as whitebark pine or Table Mountain pine and red spruce in the southern Appalachians) or at the species level in the case of regional endemics (such as Brewer spruce), are also extremely vulnerable and at high risk of extirpation (Spies et al. 2010).

Species with small ranges or low abundance at the peripheries of their geographic distribution (such as southerly sources of butternut and ash) may also be particularly susceptible to range contraction and regional extinction at the trailing edge of the species range, and will likely have a diminished capacity to expand at the leading edge. Other important factors contributing to climate change vulnerability include: low genetic variability, low dispersal and colonization potential (such as isolated or fragmented populations), stressed stand conditions, insect and disease pressures, invasive plants, high levels of competing vegetation, changes in land management, and alteration of natural disturbance regimes (Aitken et al. 2008, Chimura et al. 2011, St. Clair and Howe 2011).



Collecting cones from Fraser fir (*Abies fraseri*) for ex situ genetic conservation. The species occupies a very restricted native range in high elevations of the southern Appalachian Mountains, where it is affected by multiple threats, including invasive pests (woolly adelgid), fragmentation, air pollution, and climate change. Photo credit: Kevin Potter



Whitebark pine is a keystone species of fragile high-elevation ecosystems in western North America. It is at risk throughout most of its range owing to white pine blister rust (an introduced and deadly fungus), mountain pine beetle attacks, altered fire regimes, and climate change. The Forest Service has been actively engaged in the conservation and restoration of whitebark pine for a number of years, but the need and urgency of this work is intensifying. In 2011, the species was declared a candidate for Federal listing under the Endangered Species Act. Photo credit: Kristin Chadwick

Preparing for the Future: How Can Geneticists Help National Forests Adapt to Changing Climates?

Assessment Tools and Examples

In order to develop and implement cohesive climate change adaptation strategies for national forests nationwide, geneticists at the Corvallis workshop identified a need for detailed and spatially explicit assessments of species and population vulnerability to climate change as a critical starting point. This information was deemed important for planning and prioritization of program resources and work, including: enhanced monitoring, expanded gene conservation and operational seed collection activities,

and revised genetic guidelines for restoration and silvicultural treatments to increase biodiversity and forest resistance and resilience to disturbance and environmental change.

Examples of this process are efforts in the Pacific Northwest Region (Forest Service Region 6) (Table 2) and the Southern Region (Forest Service Region 8) (Table 3) to complete vulnerability assessments and action plans for high-priority forest tree species in the Pacific Northwest and Southern Appalachian regions.

Table 2. Summary of risk factor scores and overall scores in a climate change vulnerability assessment of 15 major western Washington tree species; higher scores indicate greater vulnerability

Species	Common name	Risk factor scores					
		Distribution	Reproductive capacity	Habitat affinity	Adaptive genetic variation	Insects and disease	Overall score ¹
<i>Abies amabilis</i>	Pacific silver fir	19	100	100	100	86	81
<i>Abies lasiocarpa</i>	Subalpine fir	38	67	65	84	100	71
<i>Picea engelmannii</i>	Engelmann spruce	100	67	54	84	25	66
<i>Abies procera</i>	Noble fir	59	67	50	100	31	61
<i>Abies grandis</i>	Grand fir	57	67	4	50	92	54
<i>Tsuga mertensiana</i>	Mountain hemlock	38	33	88	67	31	51
<i>Cupressus nootkatensis</i>	Alaska yellow-cedar	63	67	58	67	0	51
<i>Pinus monticola</i>	Western white pine	83	33	15	0	58	38
<i>Pseudotsuga menziesii</i>	Douglas-fir	0	67	8	50	28	31
<i>Acer macrophyllum</i>	Bigleaf maple	35	0	15	50	47	29
<i>Populus balsamifera</i> ssp. <i>trichocarpa</i>	Black cottonwood	63	0	23	34	20	28
<i>Picea sitchensis</i>	Sitka spruce	57	33	39	0	3	26
<i>Thuja plicata</i>	Western redcedar	44	67	0	17	3	26
<i>Tsuga heterophylla</i>	Western hemlock	13	0	39	34	25	22
<i>Alnus rubra</i>	Red alder	19	0	19	50	14	20

¹ Calculated by averaging the scores from the five risk factors, each with a range of 0 to 100.

Source: Aubry et al. 2011.

Table 3. Tree species of the southern Appalachian Mountains with the highest overall climate change vulnerability scores using the Forest Tree Genetic Risk Assessment System

Rank	Species	Score
1	Carolina hemlock (<i>Tsuga caroliniana</i>)	63
2	September elm (<i>Ulmus serotina</i>)	63
3	Fraser fir (<i>Abies fraseri</i>)	55
4	Blue ash (<i>Fraxinus quadrangulata</i>)	55
5	Butternut (<i>Juglans cinerea</i>)	55
6	Shumard oak (<i>Quercus shumardii</i>)	54
7	Table Mountain pine (<i>Pinus pungens</i>)	53
8	Carolina silverbell (<i>Halesia carolina</i>)	53
9	American chestnut (<i>Castanea dentata</i>)	53
10	Black ash (<i>Fraxinus nigra</i>)	52
11	Ohio buckeye (<i>Aesculus glabra</i>)	52
12	Eastern hemlock (<i>Tsuga canadensis</i>)	52
13	Swamp white oak (<i>Quercus bicolor</i>)	51
14	Red pine (<i>Pinus resinosa</i>)	50
15	Carolina ash (<i>Fraxinus caroliniana</i>)	50
16	Virginia roundleaf birch (<i>Betula uber</i>)	49
17	Spruce pine (<i>Pinus glabra</i>)	49
18	Rock elm (<i>Ulmus thomasi</i>)	49
19	Red spruce (<i>Picea rubens</i>)	49
20	Chalk maple (<i>Acer leucoderme</i>)	49
21	Painted buckeye (<i>Aesculus sylvatica</i>)	49
22	Balsam fir (<i>Abies balsamea</i>)	48
23	Black maple (<i>Acer nigrum</i>)	48
24	Nutmeg hickory (<i>Carya myristiciformis</i>)	48
25	Yellow buckeye (<i>Aesculus flava</i>)	48

Source: (<http://www.forestthreats.org/current-projects/project-summaries/potter-iufro-2010-updated.pdf>).

The Forest Tree Genetic Risk Assessment System (Potter et al. 2010) was used in both examples to rank forest tree species for a number of factors and attributes that may increase species vulnerability to climate change. In the Appalachian Mountain assessment, eight primary risk factors were used to develop the rankings displayed in Table 3. These include population structure, rarity, regeneration capacity, dispersal ability, habitat affinity, genetic variation, pest and pathogen threats, and climate change pressure.

In the Pacific Northwest subregional assessments, tree characteristics were organized into five primary risk factors: distribution, reproductive capacity, habitat affinity, adaptive genetic variation, and threats from insects and diseases. Non-forested habitats vulnerable to climate change were also identified through the use of expert panels and review of scientific literature. Species- and habitat-specific recommendations and priority action items were then developed to help close information gaps and create baseline data regarding species and habitat location, historical extent, and current conditions. Management actions for maintaining and enhancing biodiversity and increasing forest resilience to climate change effects were also provided.

The Integrated Restoration and Protection Strategy developed by the Northern Region (Region 1) is another assessment tool that is being applied to help inform and adapt genetic resource management activities and priorities in light of climate change (<http://fsweb.r1.fs.fed.us/gis/templateweb>).

The management recommendations and actions items contained in these vulnerability assessments follow several overarching goals and guiding principles that were developed and agreed to by NFS geneticists during the 2010 Corvallis workshop. These goals and principles, outlined below, are based on our consensus view of the genetic strategies most appropriate for implementation on National Forest System lands after considering their cost, effectiveness, risk, and potential unintended consequences (ecological, social, financial). Recommended action items are framed within the context of current NFS policies, regulations, and management objectives, as well as the high degree of uncertainty of climate change projections and potential effects on forest vegetation and genetic resources.

Principles, Goals, and Action Items

Principle 1: Genetically diverse and adapted seed and planting stock provide the foundation for healthy forests and ecosystems in the future.

Under any climate change scenario, the production of adapted and diverse seed sources for reforestation and restoration will undoubtedly remain the central mission of the U.S. Forest Service Genetic Resource Program. This work will become even more critical in the future because aggressive revegetation strategies and seeding and planting will be primary adaptation tools for re-aligning species and genetic resources to changing climates, particularly after major disturbances such as wildfires, floods, hurricanes, tornadoes, windstorms, and insect and disease outbreaks.

In selecting plant materials for current as well as unknown future climates, NFS geneticists advocate an adaptive, “no regrets” approach (see box on page 1) that includes use of the species and seed sources that have performed successfully in the past as an initial starting point. This will provide genotypes adapted to the relatively fixed aspects of the local environment, such as photoperiod cycle and soil type. Then, as predictions and problems relating to climate change become more certain or there is evidence for adaptation lag, emphasis may shift from obtaining seed solely from local sources to obtaining seed based on matching seed sources to future climates or to climates that take into account changes that have occurred during the past century. Matching seed sources to climates has become easier with the advent of models that interpolate between weather stations, and may be facilitated by bulking seed collections across smaller geographic scales. Typically, population transfers for changed climates would be from lower latitudes and elevations with warmer, drier conditions to higher latitudes and elevations. Some species, however, may contradict this recommendation, most likely because of downhill shifts to warmer but wetter conditions associated with increased precipitation (Crimmins et al. 2011). The important point is to make changes in population movement guidelines based on knowledge of responses of species and populations to climate, as well as on knowledge of interspecific interactions. This knowledge may come

from studies of species and population vulnerability and adaptive responses to environmental change, and may be supported by forest health and productivity monitoring data.

In order to minimize the high degree of uncertainty and risk associated with management decisions based on climate projections into the more distant future, development of species-specific adaptation strategies with a relatively short time-frame, such as a 10–20 year planning horizon would be most effective. This will also promote the planting of species and genotypes that will be optimally adapted to predicted climates during the highly vulnerable seedling and sapling stage. Higher-risk actions, such as introduction of novel species or broad movement of seed sources, are options to be considered and implemented over small areas on an experimental basis (e.g., assisted migration trials) or for genetic rescue of species and populations at imminent risk of extirpation due to loss of habitat, range shifts, and damage from insects and disease or other disturbance agents.

To further facilitate the adaptive response of forests to changing future climates, we also strongly advocate for an increased emphasis on strategies and methods that will enhance genetic diversity, including the use of multiple species and diverse seed sources in reforestation, and the maintenance of large populations with high connectivity and opportunity for migration of adapted genes (via seed and pollen movement) in the direction of trending climates (e.g., southern to northern populations in range, or low to high elevation change).

STRATEGIC GOAL 1.1 DEVELOP AND DEPLOY PLANT MATERIALS THAT WILL BE RESILIENT TO CLIMATE CHANGE.

Action Item 1.1.1. Expand operational seed banks to include a wider array of species, seed zones, and elevation bands. Place a priority on species whose seeds store well and have good post-disturbance establishment capabilities. Evaluate seed inventories and replenish low seed stores for species, habitats, and geographic areas most likely to experience climate change effects, especially large-scale disturbances. Conduct comprehensive risk and seed need assessments, for example, by assessing genetic diversity of existing inventories and by overlaying seed zones with climate change and disturbance

threat maps (e.g., WWETAC ThreatMapper, http://www.fs.fed.us/wwetac/threat_map, see map sidebar).

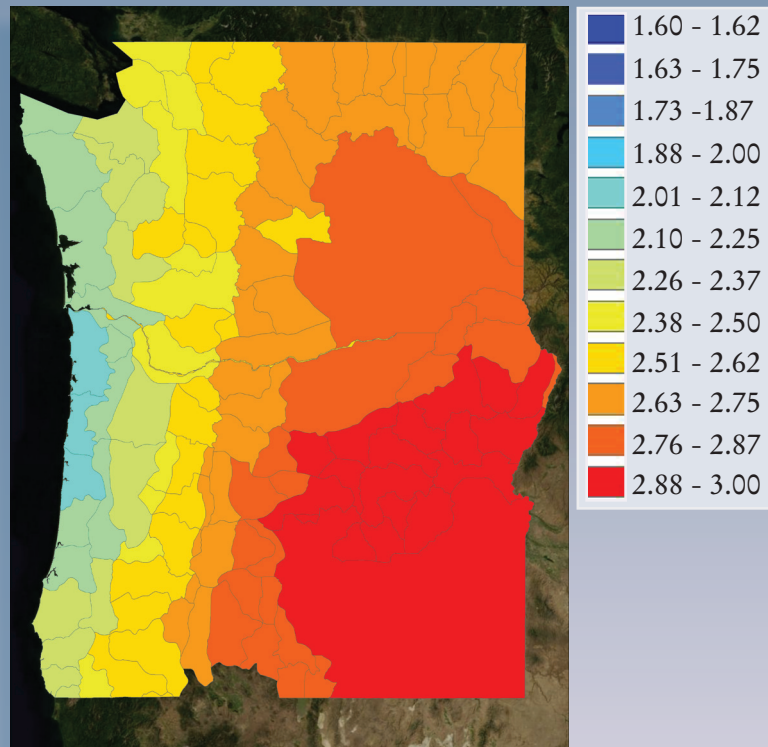
Action Item 1.1.2. Protect and maintain existing seed orchards, breeding orchards, and clone banks to serve as the most efficient and cost effective source of high-quality seed for reforestation. Characterize the mean and range of climates for the germplasm and deployment zones of existing orchards to better understand where that material may be appropriately used in the future.

Action Item 1.1.3. Assess needs for additional seed orchards and cutting orchards for long-term plant material sources for new species or geographic areas where there is likely to be greater demand in the future (approximately 50–80 years from now). Plant material suited to these future climates may not currently exist on National Forest System lands, and may need to be obtained from other land ownerships. Seed orchards established with this material could be designed to also perform as assisted migration trials to evaluate plant adaptation to novel environments.

Average projected increase

in summer temperature (June, July, August) for conifer seed zones (outlined in black) in the Pacific Northwest. Baseline for this increase is the period 1970–1999 and is projected for mid century (2030–2059). The red and orange areas are the seed zones where temperature increases are predicted to be greatest in the Pacific Northwest, while blue and green seed zones show the least departure from the baseline period. Values for the seed zones are the mean of 5-km cells of mid century temperature change over historical conditions. These data were developed from an ensemble of 10 global climate models by Littell et al. 2011.

CHANGE IN TEMPERATURE (°C) JUNE, JULY, AUGUST, MEAN FOR SEED ZONE



Action Item 1.1.4. Review the state of the knowledge of seed collection and storage for key species, as well as propagation and planting requirements. Develop plant collection and nursery propagation protocols for new or difficult-to-grow species that may have an increased emphasis in future reforestation practices due to changing climate. Consider both commercial and non-commercial species, and species that are now regenerated naturally but may need to be augmented or moved outside their current ranges in the future.

Action Item 1.1.5. Evaluate seed production capacity, seed storage, and nursery capacity to determine whether they are adequate to meet long-term needs or whether additional focused investments are required.

Action Item 1.1.6. Maintain detailed spatial information on seed source locations (such as latitude, longitude, and elevation) in seed inventory management systems (such as the Nursery Management Information System, NMIS), continued support of seed transfer expert systems, and development of GIS applications to track seedlot origin and use and to facilitate seed sharing in the future. When seed sources are combined, consider bulking seed across smaller geographic scales and elevation bands to facilitate the creation of custom seedlots and provide flexibility in deployment decisions in the future. For example, buffer possible changes in seed movement guidelines in the future by adding a percentage of seed from outside the current seed zone or recommended elevation band, with emphasis on areas that could be reasonable analogs for the future.

Action Item 1.1.7. Implement monitoring programs (such as those in seed orchards and genetic test sites or offsite plantations) to establish baseline information on vegetative and reproductive phenology and track changes over time. Provide support to other monitoring efforts, such as the Forest Service's Forest Inventory and Analysis (FIA), Forest Health and Protection (FHP), and Research and Development programs. Support and participate in citizen scientist efforts such as the U.S. National Phenology Network.

Action Item 1.1.8. Install common garden studies in multiple climates to help choose seed sources for species and geographic areas where this information is lacking. Many key species currently lack even the most basic information on adaptive genetic variation.

In these situations, consider available climate-based tools such as SeedZone Mapper (http://www.fs.fed.us/wwetac/threat_map/SeedZones_Intro.html) and the Seedlot Selection Tool (<http://sst.forestry.oregonstate.edu/PNW/index.html>) to identify the best locations to obtain and deploy plant materials. Support the refinement and development of these and other decision tools to better predict and plan for where to obtain seed that will be optimal for future climates.

Action Item 1.1.9. Collaborate with researchers to establish and maintain common garden and provenance studies, as well as assisted migration trials for key species.

Action Item 1.1.10. Acquire and maintain historical provenance data and share broadly so that NFS and others can collaboratively use it to predict responses to climate change and choose appropriate seed sources. For example, the Pacific Northwest Research Station has collaborated with Oregon State University in a simple Web-based data management system, called the Center for Forest Provenance Data. The systems may be used for archiving provenance data and make it available for others (see <http://cenfor.gen.forestry.oregonstate.edu/index.php>).

STRATEGIC GOAL 1.2 MANAGE FOR UNCERTAINTY AND ADAPTATION THROUGH NATURAL SELECTION BY PLACING AN INCREASED EMPHASIS ON GENETIC DIVERSITY (SPECIES AND SEED SOURCES), AS WELL AS A DIVERSITY OF SILVICULTURAL APPROACHES ACROSS THE LANDSCAPE.

Action Item 1.2.1. Where appropriate, actively manage stands using a variety of silvicultural and restoration tools (planting, seeding, prescribed fire, thinning, etc.) to promote establishment, growth, and survival of desirable species and genotypes. Consider the need for artificial regeneration, especially for species that are highly vulnerable to climate change effects and in areas of rapidly changing climate where natural regeneration has been the traditional method of reforestation.

Action Item 1.2.2. Ensure that seed planted on national forests includes offspring from an adequate number of parents. Use multiple species and a diverse mix of appropriate seed sources; consider the need to add germplasm from warmer/drier geographic areas that may be more suited to trending future climates (10–20 year timeframe). Emphasize under-represented

species in both planting and thinning prescriptions. Consider the need for increased planting densities to allow for enhanced natural selection opportunities and/or human mediated selection via thinning to remove maladapted phenotypes. Conversely, if drought conditions or highly altered moisture regimes are projected, lower planting densities may be prescribed to reduce stress and inter-plant competition.

STRATEGIC GOAL 1.3 CONSIDER CLIMATE CHANGE WHEN DETERMINING PLANS AND PRIORITIES FOR DISEASE AND INSECT RESISTANCE SELECTION AND BREEDING PROGRAMS.

Action Item 1.3.1. Assess existing selective breeding programs to determine if ongoing efforts (species and geographic areas) are in alignment with potential shifts in host species and insects/diseases due to climate change.

Action Item 1.3.2. Climate change and species migration will result in novel combinations of hosts and pests, and the potential for insect or disease outbreaks that are more widespread and damaging than otherwise expected. Develop an understanding of the dynamics that would create these situations, and evaluate the need, cost, and effectiveness of new selective breeding programs to mitigate risk.

Action Item 1.3.3. For species facing the dual threats of damaging exotic pathogens and climate change (e.g., butternut, hemlock, ash, American chestnut, 5-needle pines), create openings specifically for establishment of disease-resistant stock, or augment natural regeneration with supplemental plantings for more effective utilization of resistant germplasm in species recovery and gene conservation efforts. Initiate targeted outplantings to increase frequency of desirable genotypes and representation of at-risk species throughout their range (e.g., plant blister-rust-resistant western white pine or whitebark pine in gaps or openings created by planned and unplanned

disturbances such as wildfires or pre-commercial thinning).

STRATEGIC GOAL 1.4 CREATE OPPORTUNITIES FOR RAPID NATURAL SELECTION FOR SPECIES, HABITATS, AND GEOGRAPHIC AREAS WITH HIGH OBSERVED OR PREDICTED POTENTIAL FOR ADVERSE IMPACTS DUE TO CLIMATE CHANGE.

Action Item 1.4.1. Promote abundant regeneration, mixing of appropriate genotypes and seed sources, and possibly also shortened generation times if appropriate and feasible.

Action Item 1.4.2. When prescribing species and seed sources in reforestation programs, ensure that any changes to established practices are based on a variety of robust and reliable data sources such as common garden studies and reciprocal transplant experiments, climate model projections, remote sensing, dendro-climatology, and other empirical research and forest health and productivity monitoring approaches. Avoid generic, ad hoc, and non-science-based management decisions. This approach very much aligns with our current, robust and scientifically derived guidelines for plant material selection. To minimize the high degree of uncertainty and risk associated with longer-term climate projections, develop adaptation strategies with a relatively short timeframe, such as a 10–20-year planning horizon. This will promote the planting of species and genotypes that will be optimally adapted to predicted climates during the highly vulnerable seed and sapling stage.

Action Item 1.4.3. Implement mechanisms for tracking reforestation success and the growth and health of forest stands to allow for recursive improvements to species and seed source prescriptions over the long term.

Principle 2: Gene conservation is key to preserving vulnerable species and populations for the future.

Genetic resources are irreplaceable and critical to the maintenance of ecosystems that are productive, sustainable, and resilient to new stresses such as insects, pathogens, and climate change.

As changes in climate continue, some populations will become maladapted to the “new” climate in their

existing locations. In some cases, entire species may become maladapted throughout their entire current range. It is imperative, therefore, for national forests to take prompt action to protect genetic diversity for current and future generations, especially for vulnerable species and populations that exist at very few other locations.

Conservation of genetic resources can be accomplished through a variety of *in situ* and *ex situ* approaches (St.

Clair and Howe 2011). *In situ* methods protect plants in their native habitats where they are subject to natural evolutionary processes. *Ex situ* methods involve storing genetic material in off-site locations such as seed banks, genetic resource plantations (such as provenance and progeny tests), and seed and breeding orchards.

A robust gene conservation strategy combines elements of both approaches and is based on knowledge of the genetic structure of a species and the perceived threat to a species—whether from natural disturbance processes, introduced insect and pathogens, or sensitivity to changing climate. These strategies are underpinned by effective management policies.

STRATEGIC GOAL 2.1 PRESERVE REPRESENTATIVE SAMPLES OF SPECIES AND POPULATIONS THREATENED BY CLIMATE CHANGE.

Action Item 2.1.1. Develop and evaluate tools for assessing the vulnerability of species and populations to changes in climate. Give focus to both rare and common species.

Action Item 2.1.2. Conduct monitoring to identify species and populations for which gene conservation is most urgent because of climate change, and prioritize them by importance and urgency. Include both rare and common species in monitoring efforts.

Action Item 2.1.3. Develop and implement gene conservation plans for protecting a representative sample of genes from vulnerable species and

populations, including long-term storage at Forest Service nurseries and extractories, regional genetic resources centers, the Forest Service National Seed Laboratory (Macon, GA), and the Agricultural Research Service (ARS) National Center for Genetic Resources Preservation (Ft. Collins, CO).

Action Item 2.1.4. Protect and maintain existing seed orchards, breeding orchards, clone banks, and provenance and progeny test sites to serve as *ex situ* gene conservation areas. Protect and maintain the network of designated plus trees as *in situ* conservation.

Action Item 2.1.5. Develop techniques for *ex situ* preservation of novel species (for example, how to preserve large-seeded, recalcitrant species that don't store well, such as oak acorns, or American chestnut or butternut nuts).

Action Item 2.1.6. Evaluate the need for additional infrastructure for *ex situ* gene conservation; for example, additional freezers to house working collections.

Action Item 2.1.7. Evaluate the need for additional *in situ* conservation, such as designed networks of protected areas to capture adaptive genetic variation across a species range and promote gene flow. Consider *in situ* reserves in areas of high environmental diversity to promote connectivity and gene flow between populations adapted to different environments.

Principle 3: Establishing partnerships will be more important than ever.

Addressing climate change impacts will require unprecedented cooperation among resource disciplines and deputy areas within the Forest Service, as well as across administrative, political, and land ownership boundaries.

STRATEGIC GOAL 3.1 SUPPORT AND EXPAND INTERNAL AND EXTERNAL PARTNERSHIPS THAT WILL IMPROVE OUR RESPONSE TO CLIMATE CHANGE.

Action Item 3.1.1. Support and contribute to integrated gene conservation and monitoring program initiatives, such as the Forest Health Protection (FHP) Gene Conservation Framework for at-risk forest tree species and Monitoring on the Margins (MoM), an integrated, enhanced FHP monitoring program for critical ecosystems threatened by insects, disease, and climate change.

Action Item 3.1.2. Initiate and expand partnerships with other land owners to broaden the portfolio of *ex situ* and *in situ* gene conservation resources.

Action Item 3.1.3. Partner with other land managers to create cooperative virtual seedbanks for germplasm exchange to facilitate reforestation and restoration after disturbances.

Action Item 3.1.4. Contribute to the development of databases that will facilitate the sharing and exchange of data and seed among national forests, as well as with other Federal and State agencies.

Action Item 3.1.5. Partner with other land managers to manage forest nurseries to facilitate reforestation and restoration activities.

Action Item 3.1.6. Evaluate and modify, as needed, policies and practices to simplify transfer of Forest Service-owned seed to other entities, including private landowners.

Conclusions

Maintaining healthy ecosystems in the face of climate change will require new tools, practices, and re-focused investments in all areas of Forest Service land management, including genetic resource management. Critically, the Forest Service Genetic Resource Program has, since its inception, explicitly addressed climate-related issues in its program of work. Consequently, many of the conclusions and recommendations provided in this document involve minimal changes in guiding principles or approaches of ongoing Forest Service Genetic Resource Program activities and guidance. The principal changes and investments include the following:

- Expand the use of data from existing common garden and provenance studies to address climate change issues (for example: re-analyze spatial patterns of genetic variation in relation to predicted future climates; validate species suitability models; and monitor germination, growth, phenology, and resistance to insects and diseases).

- Initiate new common garden and provenance tests for lesser known species and geographic areas.
- Initiate assisted migration trials for key species.
- Protect and maintain existing seed orchards and establish new orchards for priority species and geographic areas.
- Enlarge and expand seed banks for reforestation/restoration and gene conservation.
- Update seed management systems to provide maximum flexibility in an uncertain future.

Maintaining a trained workforce and supporting plant production infrastructure (such as nurseries, extractories, disease resistance screening centers, and seed and breeding orchards), in addition to strong support from research and management, are also vital for sustaining a viable Genetic Resource Program and healthy, diverse, and productive national forests in a changing climate.

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Glossary

Abiotic—Non-living (such as wind or rocks).

Adaptation [climate change]—“Adjustment in natural or human systems in response to actual or expected climatic stimuli and their effects, which moderates harm or exploits beneficial opportunities” (IPCC 2007).

Adaptational lag—Mismatch of genotypes and the environments in which they evolved.

Assisted migration—The human-mediated movement of plant materials on the landscape. This can happen at different spatial scales but most commonly refers to the movement of plant materials at distances greater than which they could migrate naturally.

Biotic—Living.

Common garden study—A test that provides a uniform environment in which different individuals within a species can be grown and compared to detect genetic variation. Differences observed in the field across a species’ range may disappear when individuals from those areas are grown under uniform conditions.

Dendroclimatology—The science of determining past climates from trees (primarily properties of the annual tree rings). Tree rings are wider when conditions favor growth, narrower when conditions are stressful.

Designated plus trees—Trees that are phenotypically superior.

Disjunct population—A population that has a large geographic separation from the next closest population of the same species.

Endemic—A native species that is restricted to a well-defined and often small area. This is a relative term and is used in conjunction with the area to which its total natural range is confined (for example, a state, county, or geographic area). For example, “endemic to Colorado” means that it is native only to Colorado.

Extirpation—The local extinction of a species in a specific geographic area.

Genecology—The study of geographic patterns of genetic variation in traits related to climate adaptation, such as bud burst and bud set, cold and drought hardiness, and growth rates (St. Clair and Howe 2007).

Gene flow—Movement of alleles between populations due to migration of individuals (such as seeds) or pollen distribution; also called gene migration or genetic migration.

Generation turnover—Time between when parents produce offspring and when those offspring reach reproductive age.

Genetic bottleneck—A restriction in population size that is sufficiently severe and long-lasting that it causes a loss in genetic diversity.

Genetic variation—Variation in the alleles of genes that occurs both within and among populations.

Genotype—An individual’s hereditary constitution, expressed or hidden, underlying one or more characters; the gene classification of this constitution expressed in a formula. The genotype is determined chiefly from breeding behavior and ancestry. It reacts with the environment to produce the phenotype.

Germplasm—The sum total of the genes and cytoplasmic factors governing inheritance.

Inbreeding species—A species in which mating occurs predominately between closely related individuals.

Phenotype—The observable manifestation of a specific genotype. That is, those properties of an organism produced by the genotype in conjunction with the environment.

Phenotypic plasticity—Wide range of character expression (phenotypic response) of a given genotype. For example, if different copies of a clone (such as rooted cuttings taken from a quaking aspen) are grown in different environments, the different growth rates, leaf sizes, or branch angles seen in the different trees are expressions of plasticity.

Photoperiod—The time interval during a 24-hour period in which a plant is exposed to sunlight.

Provenance test—An experiment, usually replicated, comparing trees grown from seed or cuttings collected in many parts of a species' natural range.

Recalcitrant species—Species whose seeds are readily killed by drying, especially if their moisture content falls below 12–30 percent. Even if kept moist, recalcitrant seeds are relatively short-lived, with viabilities maintained from only a few weeks to a few months, depending on the species. They also generally cannot withstand temperatures lower than 20° C, partly because of the high moisture content, which renders the seed prone to chilling or freezing injury.

Reciprocal transplant study—An experiment where plant sources are moved from each of two or more environments into the other(s). Transplant experiments are typically performed to test if there is a genetic component to differences in populations.

Recursive [improvement]—Procedure that can be applied repeatedly.

Seed orchard—A plantation established primarily for the production of seed of proven genetic quality.

Seed transfer—The collection and deployment of plant germplasm (most typically seed) for revegetation purposes.

Seed zone—A geographic area within which plant germplasm (most typically seed) can be collected and deployed with minimal risk of maladaptation to planting site conditions. Seed zones are most often developed through genecological common garden studies.

Silvics—The study of forests and their ecology.

Source environment—The environmental conditions of a given location that has been sampled as part of a genecological study, whereby a source can be an experimental plant or seed collection. Most often the source environment refers to the environmental site characteristics of the original natural stand of a plant population that was sampled for a common garden and or provenance study.

Maintaining healthy ecosystems in the face of climate change will require new tools, practices, and re-focused investments in all areas of Forest Service land management, including genetic resource management.



Photo: Andrei Rycoff

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