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Figure 1. A climate-adapted forest planting site was established in a forest canopy gap in Pennsylvania State University's Stone Valley Experimental Forest overlying sandstone bedrock. Photo by Denise Alving, 2021.

Preliminary Takeaways From a Small-Scale, Climate-Adapted Experimental Forest Setup

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Abstract

Climate change and climate adaptation are at the forefront of many current forest management conversations. This article describes the process of designing, planting, and monitoring a climate-adapted forest on small plots in Pennsylvania State University's Stone Valley Experimental Forest and the Pennsylvania Department of Conservation and Natural Resources' Rothrock State Forest. Plots were established on contrasting shale and sandstone geologies due to their anticipated influence on seedling survival and growth for novel species and extant species under future climate conditions. Publicly available tools and resources, including the Climate Change Response Framework, Climate Change Tree Atlas, and Eastern Seed Zone Forum, were used to select management strategies, species for the study, and seedling sources. This paper was presented

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Introduction

The climate is changing. For example, temperatures in Pennsylvania are expected to rise up to 8 °F (4.5 °C) on average by the end of the century. This rise in temperature will be paired with a change in precipitation patterns. During the fall, winter, and spring, precipitation is projected to rise up to 7 to 12 percent (Butler-Leopold et al. 2018, Frankson et al. 2017, Union of Concerned Scientists 2008). During the summer, when temperatures are expected to increase the most, precipitation is expected to remain consistent, resulting in hotter and drier conditions.

Pennsylvania currently sits at the intersection of two major forest types: the northern hardwoods (dominated by maple [*Acer* spp.], beech [*Fagus* spp.], and birch [*Betula* spp.] trees), and the oak-hickory forests to the south (*Quercus* spp. and *Carya* spp.). Changing temperature and precipitation patterns will likely result in stress and eventually mortality of more cold-adapted tree species and populations, while those with higher tolerance for hot, dry conditions will begin to find their footing in the region. This shift may result in the oak-hickory forests moving farther north in the State and northern hardwoods also retreating north.

Researchers and forest managers are considering strategies to mediate the loss of northern hardwoods, maintain oak-hickory forests, and facilitate establishment of novel species expected to thrive under future conditions. Underground conditions may provide some direction. Analysis of 565 forest inventory plots across the Valley and Ridge province of Pennsylvania showed that chestnut oak (*Quercus prinus* L.) stored more carbon in plots overlying sandstone bedrock, while northern red oak (*Q. rubra* L.) stored more carbon in plots overlying shale bedrock (Reed and Kaye 2020). These differences in carbon storage can be attributed to differential species growth over the two bedrocks. Soils derived from shale bedrock typically have higher nutrient availability and water retention compared to soils derived from sandstone (Hoagland et al. 2017, Jin et al. 2010). Hence, shale bedrock facilitates higher growth rates than sandstone bedrock for species that can take advantage of the available resources. These differences lead to tree species that can tolerate poorer sites (e.g., chestnut oak) and grow well over sandstone but are outcompeted by other tree species (e.g., northern red oak) on more nutrient-rich shale sites. Understanding characteristics of sites where species have good growth allows for targeted tree planting to mitigate climate stress and can support the establishment of new species. This article describes an ongoing project to explore the climate adaptation potential of specific tree species in the context of site conditions due to bedrock.

Materials and Methods

Site Selection and Plot Establishment

This project was established on a site in Pennsylvania State University's Stone Valley Experimental Forest (Huntingdon County, PA) and on a site in Pennsylvania Department of Conservation and Natural Resources (DCNR)'s Rothrock State Forest (Huntingdon and Mifflin Counties, PA).

The first step in establishing a forest management plan is understanding the land area to be managed. Tree seedlings establish in areas where there is sufficient light to provide energy for germination and growth, such as canopy gaps (Muscolo et al. 2014). In Stone Valley Experimental Forest, plots were established in four gaps (two overlying shale and two overlying sandstone geology, identified using U.S. Geological Survey maps of Pennsylvania) where natural disturbances, including windthrow, insect damage, and fire, had opened areas of higher light infiltration (figure 1). Each rectangular plot (25 by 10 m [82 by 33 ft) was planted with seedlings spaced in a 1 by 1 m (3.3 by 3.3 ft) grid. In the Rothrock State Forest, rectangular plots (30 by 10 m [98 by 33 ft] and 30 by 15 m [98 by 49 ft]) were established in two open area harvest sites—one on shale and one on sandstone bedrock (figure 2).

There are distinct advantages and disadvantages to planting in large harvested areas as compared with natural

Figure 2. A climate-adapted forest planting site was established in a harvest site in Pennsylvania's Rothrock State Forest overlying sandstone bedrock. Photo by Denise Alving, 2021.

canopy gaps. Seedlings in the harvested areas in Rothrock State Forest had full direct sunlight. While the higher light intensity allowed these seedlings to easily reach heights up to 1.5 m (5 ft) in the first 2 years, they were competing with rapidly resprouting maple and birch seedlings, as well as dense blueberry (*Vaccinium* spp.) bushes (figure 3). On the other hand, seedlings planted in the canopy gaps in the Stone Valley Experimental Forest were growing in partial shade with minimal competing vegetation, with the tallest individuals reaching only 0.9 m (3 ft).

Management Goals and Strategies

Once project sites were selected, the next step was identifying management goals and strategies for these sites. The U.S. Department of Agriculture (USDA) Forest Service's Northern Institute for Applied Climate Science developed the Climate Change Response Framework (https://forestadaptation.org/) based on a growing number of climate-adapted forest field experiments. The framework identifies 10 forest management strategies that are described online (https://adaptationworkbook.org, Swanston et al. 2016). These strategies focus on (1) protecting organisms and habitats at risk of loss, (2) maintaining and expanding the ranges of current species and habitats expected to be successful under future climates, and (3) assisted migration.

Figure 3. This planted oak tree at one of the climate-adapted forest plots on a harvest site reached nearly 1.5 m (5 ft) in height after 2 years. Photo by Alina Iwanowicz, Pennsylvania State University, 2022.

Assisted migration is an ecological management strategy to intentionally plant species predicted to be adapted to future climate conditions into niches likely to be left empty by decline of current native species (Kawecki and Ebert 2004, Lunt et al. 2013, Millar et al. 2007). This experiment included three management strategies: (1) mitigate loss to three native species that are considered at risk; (2) maintain and expand the ranges of two species projected to thrive under future climate conditions; and (3) introduce four southern species with assisted migration.

Species Selection

Climate-adapted forest plantings should incorporate not only species that will grow onsite now but also those that will thrive under future conditions. Predicting species tolerances using only current species distributions can be challenging; however, tools are available that allow land managers to make informed decisions about species selection. The Forest Service's Climate Change Tree Atlas (https://www.fs.usda.gov/nrs/atlas/tree/) is a climate envelope model that projects potential future suitable habitats for 125 tree species across the Eastern United States. The model calculates a current importance value for a given species in a given location using stem density and basal area measurements collected and analyzed at fixed time intervals from the Forest Service's Forest Inventory and Analysis Program plots across the United States. Importance values range from 0 (if the species is completely absent) to 200 (if the stand only has one species growing). Potential future changes in habitat suitability of species were estimated based on 38 soil, topography, and climate variables using 3 different global circulation models across low and high greenhouse gas emission scenarios to project future suitable habitats for each tree species (Iverson et al. 2008, Prasad et al. 2014). These habitat projections are at a 1 by 1 degree resolution.

For the two sites in Pennsylvania, a species with an importance value >1 in Huntingdon County, PA, was considered present. If a species was estimated to stay the same or increase under a high-emission scenario by the end of the century, it was designated a climate winner. If a species was estimated to decrease by >1 under the high-emission scenario, it was designated a climate loser. Any species with a current importance value <1 that increased >1 under a high-emission scenario in the model was considered a new arrival (figure 4). Nine species were selected: four new arrivals, two climate winners, and three climate losers (table 1). Climate losers were included in the study because of their current high regional importance values and potential future decline. Many of these species provide key ecosystem services, and mitigating population loss will allow for these services to continue with minimal disruptions.

Seed Sourcing

Seed source for each seedling species selected was based on the geographic origin of the seedlings and the availability of seedlings from nurseries. Many tree

Figure 4. Sweetgum is considered a “new arrival” species in central Pennsylvania. It is a mesophytic species whose current natural range extends through southeast Pennsylvania. Higher temperatures and changing precipitation patterns may allow this species to become a dominant species in central Pennsylvania by the end of the century. Photo by Denise Alving.

species occur across large latitudinal and altitudinal gradients throughout the United States, with local populations adapted to local climate and having the highest growth rate compared with individuals sourced from populations adapted to warmer or cooler climates. Differences in phenology and adaptation to local seasonal extremes may explain these patterns (Leites et al. 2019).

The USDA divided the United States into hardiness zones based on the minimum temperature reached within a zone during the coldest part of the year. These hardiness zones were used to identify seedling source populations that share the same hardiness zone as the project sites. To source seedlings for novel species adapted to future climate that are typically found in a hardiness zone with a minimum winter temperature tolerance of up to 5.5 °C (10 °F) warmer than the planting area, the Eastern Seed Zone Forum (http://www.easternseedzones.com/) was used. This tool delineates estimated future seed zones based on existing eco-physiological and plant hardiness zone delineations, among other factors (Pike et al. 2020). The predicted plant hardiness zone in Pennsylvania by the end of the century is 7. Distribution maps show that the closest points in plant hardiness zone 7A are currently in northern Virginia and New Jersey. This information was used to select species for the new arrival category (table 1).

Seedlings came from two types of nurseries: (1) local commercial nurseries, including Musser Forests (Indiana, PA) and the Aquatic Resource Restoration Company (Glen Rock, PA) and (2) State nurseries, including the New Jersey State Nursery (Jackson, NJ) and Virginia State Nursery (Crimora, VA). Many of the seedlings sourced for the initial planting were donated by the Keystone 10 Million Tree project (K10), a nonprofit organization whose goal is to plant 10 million trees in Maryland, Pennsylvania, and Delaware before 2025. The K10 organization covered the costs of purchasing and shipping seedlings from local nurseries and loaned planting supplies. All seedlings were 1- to 3-year-old bareroot, primarily because of availability, cost, and ease of shipping.

Planting Schedules and Considerations

Initial planting of 1,700 study trees in Stone Valley Experimental Forest and Rothrock State Forest was completed from May 7 to June 15, 2021, just after the average day of the last frost in Pennsylvania but before periods of heat and drought in July. Student volunteers used best practices for planting bareroot seedlings in the spring as outlined by Penn State Extension (Jackson 2023). Care was taken to be consistent with planting standards and that planting holes were deep enough to avoid compressing roots or leaving root collars exposed. Additional plantings were done in 2022 and 2023 to replace individuals that died in previous seasons. Seedlings will remain in place for the foreseeable future.

Seedling Maintenance

Once planted, seedlings are vulnerable to damage by defoliators and browsers, with spongy moth (*Lymantria dispar* L.) and voles (*Microtus arvalis* Pallas) being the most common at the project sites. To avoid damage, tree tubes were used early in the growing season. The tubes were held in place with a stake, topped with a mesh sleeve, and sunk about 8 cm (3 in) into the ground (figure 5). Tree tubes provide seedlings structural stability and protect them from insects and rodents. Removal of competing vegetation, especially at higher densities, was also easier with tree tubes protecting the base of seedlings. Late in the first season it was evident that tree tubes retained significant

Figure 5. Tree tubes were installed initially to protect seedlings from animal and insect damage. Each 1.5-m (5-ft) tube was zip-tied to a wooden stake that was hammered into the ground to discourage rodent damage. Photo by Cathryn Pugh, Pennsylvania State University.

Table 1. Tree species planted in study sites

Species	Scientific name	Years planted	Producer	No. Planted	Price per seedling	Cost
New arrival species						
Sweetgum	*Liquidambar stryaciflua*	2021	Keystone 10 Million Tree Project	200	Donated	Donated
		2023	Musser Forests	125	$1.57	$196.25
Shortleaf pine	*Pinus echinata*	2021	New Jersey State Nursery	200	Donated	Donated
		2022	Virginia State Nursery	200	Donated	Donated
		2023	Virginia State Nursery	50	Donated	Donated
Loblolly pine	*Pinus taeda*	2021	New Jersey State Nursery	200	Donated	Donated
		2022	Virginia State Nursery	180	Donated	Donated
		2023	Virginia State Nursery	110	Donated	Donated
Southern red oak	*Quercus falcata*	2021	Virginia State Nursery	250	$0.70	$175
Climate winner species						
White oak	*Quercus alba*	2021	Keystone 10 Million Tree Project	200	Donated	Donated
Black oak	*Quercus velutina*	2021	Keystone 10 Million Tree Project	200	Donated	Donated
		2023	Musser Forests	100	$1.49	$149
Climate loser species						
Red maple	*Acer rubrum*	2021	Keystone 10 Million Tree Project	200	Donated	Donated
		2022	Musser Forests	100	$1.40	$140
		2023	Musser Forests	100	$1.40	$140
Sugar maple	*Acer saccharum*	2021	Keystone 10 Million Tree Project	200	Donated	Donated
		2022	Aquatic Resource Restoration Company	110	$0.70	$77
Northern red oak	*Quercus rubra*	2021	Keystone 10 Million Tree Project	200	Donated	Donated
		2022	Musser Forests	100	$1.07	$107
			Total # planted:	**3,025**	**Total cost:**	**$984.25**

Each species was designated as a **new arrival**, **climate winner**, or **climate loser** based on future climate projections. Many seedlings were donated, resulting in lower costs for the project.

moisture, which increased the susceptibility of the seedlings to mold and rot, especially pine seedlings. Thus, tree tubes were removed late in the first season and deer fencing surrounding the whole plot was installed (figure 6).

The deer fence excludes browsing from large mammals, including white-tailed deer (*Odocoileus virginianus* Zimmermann) and black bears (*Ursus americanus* Pallas), but does not exclude small mammals and insects. The deer fencing alone does provide some benefits over the tree tubes, including more light reaching the seedlings, more air circulation to prevent mold and fungus growth, and more space for seedlings' lateral branching. Future plantings could use a combination of seedling protection methods, such as opting to keep the deer fencing as a large-scale preventative and using shorter tree tubes to prevent small mammal access to stem base and roots while still allowing for air circulation around leaves. Some biological controls, such as spraying oak and maple leaves with *Bacillus thuringiensis* in 2022 for spongy moth, were moderately effective at mediating insect damage.

Monitoring and Measurement

Following initial planting and a 2-week adjustment period, baseline measurements were taken at each site. Height from ground to tallest woody point on stem, diameter at base, and survival were recorded for each planted tree. Thereafter, height, diameter, and survival were measured each year in November (end of growing season) and in

Figure 6. Deer fence was established around the climate-adapted forest plots. In this photo, both deer fencing and tree tubes are protecting the seedlings; later in the season, however, tree tubes were removed due to concerns about moisture and fungal damage. Photo by Denise Alving, 2021.

the following April (start of the new growing season). The biannual measurement allows for an account of mortality associated with conditions in the previous season and an assessment of height and diameter growth. Every May, a portion of seedlings that died were replaced with new seedlings of the same original age. From May to September, competing vegetation at each site was managed by hand clipping, specifically targeting grasses, forbs, and volunteer seedlings that shade out the study trees. In addition to these semi-annual measurements and management efforts, soil cores were taken from each of the six plots for chemical content and texture analysis. Also, leaf samples were collected in 2021 for genetic sampling from two of the plots in Stone Valley Experimental Forest and flash-frozen for RNA extraction and gene expression studies. Stomatal conductance, leaf mass to area ratio, and water use efficiency were being measured in the 2023 and 2024 growing seasons to compare seedling physiology between bedrocks and climate adaptation strategy.

Preliminary Findings

Data collection and analysis for the project are ongoing, with survivorship and growth measured thus far for the first 2 years of the experiment. While definitive patterns of survival, growth, and gene expression by bedrock and climate adaptation strategy will take several years to emerge, some general trends have emerged.

First, survival of seedlings planting in 2021 is highest for northern red oak and sweetgum and lowest for loblolly pine and shortleaf pine. Of surviving individuals, loblolly pine and shortleaf pine seedlings have the highest relative growth, while sweetgum has the lowest. Trends have also emerged between the two bedrocks. Overall, survival is higher for loblolly pine, northern red oak, southern red oak, and black oak planted over sandstone bedrock. Relative growth of sweetgum was higher for those planted over sandstone bedrock as compared with those over shale bedrock. These initial results are surprising because the anticipation was for seedling growth and survival to be higher over shale bedrock due to its greater water and nutrient availability compared with sandstone bedrock. Future analyses will evaluate soils, seedling genetic expression, and physiology to explain seedling growth and survival rates of the different species.

Discussion and Future Directions for the Project

This experiment is entering its fourth year in 2024. Continued collection of survival and growth data will be useful to identify long-term patterns among species and bedrocks. Continued analysis of gene expression data, as well as collection and analysis of physiological data, will lead to an increased understanding of the changes in plant biological processes across sites with different bedrock and their effects on survival and growth. The initial intensive data collection and analysis stage is expected to continue through early 2025, after which the project will transition into a long-term maintenance phase. Annual site maintenance and measurements of survival and growth will continue through the Forest Dynamics Lab at Penn State and in collaboration with land managers from the Stone Valley Experimental Forest and Pennsylvania's DCNR. The plots will continue to be available for new student research projects and educational opportunities within the university and local audiences. These sites are also registered with the Climate Change Response Framework with the goal of making the climate-adapted forest site design and research outcomes available to a wider audience seeking to apply this knowledge to their land management.

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