Rotation-Aged Genetic Parameters for Shortleaf Pine (*Pinus Echinata* Mill.) and Their Implications for Tree Improvement, Disturbance Response, and Species Restoration in a Changing Climate

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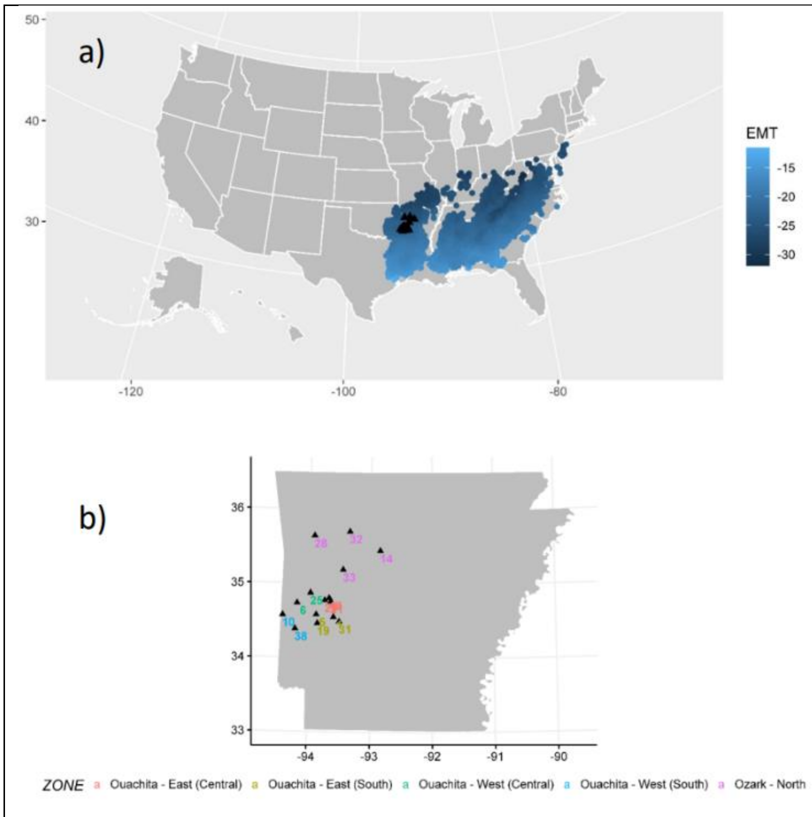
Local adaptations are commonly observed in naturally regenerating tree populations, with diverse abiotic and biotic environmental factors influencing both phenotypic and genetic variations in adaptive and growth traits (Keller *et al.*, 2011; Wang *et al.*, 2014; Zhang *et al.*, 2019; Ding and Brouard, 2022; Hu *et al.*, 2022). At the same time, local maladaptation, when present, and associated tree mortality are typically related to multiple abiotic and biotic stresses exacerbated by the increasing frequency of extreme weather events (Worrall *et al.*, 2013; Anderegg *et al.*, 2015; Aitken and Bemmels, 2016; Ware *et al.*, 2021). To address this situation, tree improvement may be utilized to provide the needed adaptability and productivity traits for trees planted under future environmental conditions. Clearly, ensuring adaptability to extreme weather events while maintaining competitive growth increments for long-lived tree species is critical for successful reforestation efforts, including species restoration. As a precursor to tree improvement, provenance tests (seed source studies) are often conducted on multiple sites to investigate genetic and genetic × environmental responses of growth and adaptive traits. In recent years, these studies have become important to further study the association between phenotypes, genotypes, and environments, where climate variables at the source location of the genotypes as well as the test planting locations are considered (Isabel *et al.*, 2020).

Shortleaf pine (*Pinus echinata* Mill.), an important commercial tree species that often co-occurs with loblolly pine (*Pinus taeda* L.), is under considerable threat with significant range-wide declines (Hossain *et al.*, 2021). The species which plays an important role in many forest ecosystems across the southeastern US, is usually found on drier sites where fire is more frequent (Stewart *et al.*, 2016). However, the biology and genetics of shortleaf pine have not been broadly investigated, including its ecological adaptations and traits important to stand productivity (Stewart *et al.*, 2016). Shortleaf pine is typically managed for sawlog production and planted for ecosystem restoration at cooler and drier sites compared to those managed for and planted to loblolly pine. However, as reforestation of loblolly pine expands into the shortleaf pine range due to its faster growth rate, the potential for hybridization between the species will likely increase

(Stewart et al. 2012) as well as changing the stand dynamics of the two species growing under novel conditions.

Utilizing long-term genetic trials and accumulated phenotyping data to better understand the genotype-phenotype-environment associations within and between seed sources should help to inform the development of management strategies optimized for projected climate scenarios. For example, guided with this information, tree improvement programs can produce productive and resilient tree families for planting in commercial- and conservation-oriented projects, thereby increasing the overall resilience of the forested landscapes and the associated local and regional communities. To better understand the potential for tree improvement in shortleaf pine, we estimated genetic parameters of growth and adaptive traits (e.g., ice storm damage) using data collected at rotation age (30 to 40 years) on about 20,000 planted trees, representing 330 full-sib families formed by a series of disconnected half-diallel crosses. The parents of the crosses originated on National Forests selected from two environmental zones (Ouachita Mountains and Ozark Plateau of Arkansas) and the crosses were assessed in 11 and 4 field trials, respectively, in the same two zones (Fig. 1.). The parents tested are maintained by the USFS Southern Region's Genetic Resources Program at the Mt. Ida, AR seed orchard.



Notes, a) The symbols of 15 USDA-FS progeny trial locations and natural species range of shortleaf pine in the USA with the extreme minimum temperature (EMT); b) The progeny tests and the five delineated zones based on the climate and geographical locations in Arkansas. The species range is based on the USDA-FS forest inventory data (Peters *et al.*, 2019); the climate data were retrieved from the ClimateNA (http://climatena.ca/, Wang *et al.*, 2016). The climatic variables include MAT, Mean annual temperature (°C); MAP, mean annual precipitation (mm); MWMT, mean warmest month temperature (°C); MCMT, mean coolest month temperature (°C); EMT, extreme minimum temperature over 30 years (°C); DD5, degree-days above 5°C; bFFP, date-of-year as the beginning of frost free period; eFFP, date-of-year as the end of frost free period (Ding *et al.,* 2023).

Fig. 1. Study area and trial locations in Arkansas in the context of the species range of shortleaf pine with x-axis as the longitude, and the y-axis as the latitude.

Both individual tree- and family-based models provided robust genetic parameter estimates for stem growth and taper; with narrow-sense heritability of height increment from age-5 years to the rotation-age measurement reaching a moderate level (0.1 to 0.4) across the trials that were not highly impacted by ice storms (Ding *et al.*, 2023). Although, the trials were differentially impacted by ice storms, as indicated, we found that these severe weather events changed the pattern of genetic parameters, with those trials most highly impacted providing an opportunity for selection for tolerance to ice damage (Ding *et al.*, 2023). Overall, the results underscore the potential of tree improvement for developing shortleaf pine planting stocks with enhanced resilience to extreme weather events, such as ice storms, thus, benefitting ongoing species conservation and ecosystem restoration efforts across the southern US.

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