Balancing genetic integrity and adaptive potential under climate change: The Scots pine case

M. Lasek[1], Ł. Walas[1], D.J. Chmura[1], W. Wachowiak[1,2]*

[1]*Institute of Dendrology, Polish Academy of Sciences, Parkowa 5, 62-035 Kórnik, Poland,*
**mlasek@man.poznan.pl*
[2]*Faculty of Biology, Adam Mickiewicz University in Poznań, Uniwersytetu Poznańskiego 6, 61-614 Poznań, Poland*

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Scots pine (*Pinus sylvestris* L.) is a dominant forest-forming species in Eurasia and a cornerstone of European forestry. Understanding its phenotypic and genetic variation in connection to climate is critical for sustainable management, particularly as extreme climate events increase in frequency. Despite decades of research, a significant knowledge gap persists regarding the complex integration of phenotypic traits, genetics, and climatic factors within Poland's most valuable seed populations. While species distribution models in general predict a dramatic range shift for Scots pine across Europe, variation in growth as related to climatic factors remains to be investigated, especially for the stands specifically designated for seed sourcing.

In this study, we evaluated 27 populations of Scots pine varying in stand age between 110 and 215 years, representing all 24 provenance regions in Poland, including selected seed stands. Height and diameter data from 818 trees were used to compare basic phenotypic features and to derive the Site Index (SI) at a base age of 100 years. Linear models identified three primary sets of climatic drivers of growth efficiency: (1) thermal regimes, (2) summer water deficit, and (3) early spring conditions. These were integrated with MPI-ESM-LR (RCP4.5 and RCP8.5) projections for 2080. Moreover, previously published SNP data for the same individuals were used to assess neutral genetic differentiation.

Results reveal significant phenotypic differences among provenances. While current growth efficiency varies widely, future projections suggest a dramatic shift: high-performing stands are expected to experience substantial productivity declines. Conversely, currently low-productivity stands appear more resilient, sometimes showing slight improvements. Neutral genetic variation showed minimal structure (FSTmax = 0.007) and did not correlate with phenotypic or climatic variation. This suggests that neutral markers may not capture the adaptive potential needed to survive climate change, highlighting the need for seed transfer strategies that prioritize long-term resilience over immediate growth.