Scenario-based modelling of climate change impacts and adaptive management pathways in the dry montane forests of Aspindza, Georgia

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Abstract

Dry montane forests are vital for biodiversity conservation and provide protective and other essential ecosystem services that support local livelihoods. However, they are increasingly threatened by climate change. Rising temperatures, altered precipitation regimes and prolonged drought periods pose major challenges to their productivity, stability and resilience. The study region of Aspindza in Georgia represents a vulnerable forest ecosystem within one of Georgia's most sparsely forested regions. It is among the country's most water-limited areas, with mean annual precipitation of about 520 mm and frequent late-spring and early-autumn frosts. These constraints are amplified by rapid climatic change: since the mid-20th century, mean annual air temperature in Georgia has increased by roughly 1°C, and wildfire frequency in the study region has risen significantly. Against this backdrop, this contribution addresses a central decision problem for forest managers and policy-makers: the high uncertainty surrounding the long-term resilience of drought-prone forest ecosystems and the effectiveness of alternative management pathways under future climate conditions.

Historically, management in the study area has relied primarily on empirical observation and reactive measures rather than predictive, scenario-based evidence, an approach that is increasingly inadequate under emerging "no-analogue" climate conditions. In particular, it remains unclear how different forest types ranging from artificial *Pinus nigra* (Black pine) monocultures to natural successional stands dominated by *Pinus sylvestris* var. *hamata* (Caucasian pine) and *Quercus petraea* subsp. *iberica* (Georgian oak) will respond to intensified drought stress over the coming century. While current phytosanitary assessments often classify these stands as "satisfactory," such static evaluations may mask underlying physiological vulnerabilities. In the study area, *Pinus nigra* plantations were established primarily for protective functions but were never thinned; as a result, high stand densities intensify competition for water. Without science-based interventions to reduce competition and enhance structural diversity, these forests face elevated risks of decline and dieback, potentially compromising protective functions against soil erosion and the regulation of regional water balance.

To address these challenges, this contribution introduces a scientifically robust and operationally feasible modelling framework by applying the PICUS v1.5 hybrid forest patch model to the region for the first time. In contrast to traditional yield-table approaches, PICUS is a process-based model that simulates forest dynamics through physiological responses to climate, soil conditions, and competitive interactions. Future climate conditions are represented through downscaled

temperature and precipitation time series derived from global climate model projections, enabling explicit comparison of management effects under both historical and projected climates. Workability is ensured through a structured design that separates climate signals from management influences. Simulations extend to 2100 and include four scenarios: (1) historic climate with passive management (baseline conditions without climate change or intervention); (2) historic climate with active management (performance of standard practices under stable climate); (3) projected climate with passive management (no-intervention trajectories under warming and drying, quantifying potential losses in biomass, regeneration capacity, and biodiversity); and (4) projected climate with active adaptive management (targeted interventions such as thinning to reduce competition and facilitating the establishment of native species within pine stands to enhance resilience).

The modelling is grounded in empirical data from the 2016 forest inventory and plot-level information from simulation sites across the Aspindza study area, spanning roughly 1,650–2,032 m a.s.l. and capturing a wide range of stand compositions, including pure black pine plantations and mixed oak and pine assemblages. This empirical foundation strengthens initialization and increases confidence that simulated trajectories are ecologically plausible for local conditions.

The practical relevance of this work lies in its capacity to translate climate projections into actionable silvicultural guidance. The preliminary simulations of the contribution suggest natural successional forests composed of native species exhibit greater long-term drought resilience than introduced *Pinus nigra* plantations. In parallel, the simulations are designed to demonstrate that passive "no-intervension" approaches may be maladaptive under rapid climatic change: in dense stands of *Pinus nigra*, timely thinning is expected to be essential to reduce water stress and improve survival probabilities during increasingly dry summers.

Beyond evaluating individual interventions, this contribution outlines a strategic roadmap for the "forest of the future" in Aspindza, advocating a transition from monoculture-oriented management toward an adaptive systems perspective. Anticipated results support the gradual conversion of pure pine plantations into mixed, multi-layered stands that better buffer climatic extremes and stabilize ecosystem functioning. The modelling framework also enables assessment of the potential expansion of broadleaved species into areas historically dominated by pine plantations and provides a basis to align management with natural successional pathways rather than opposing them. By identifying climatic and competitive thresholds at which native species can outperform plantation configurations, the study offers a means to develop timelines and spatially targeted strategies for assisted transition.

In conclusion, this contribution moves beyond descriptive assessment by combining advanced process-based simulation with local ecological data to provide decision-relevant evidence for adaptation. It offers a structured basis for designing climate-resilient forest trajectories that maintain productivity while safeguarding protective and regulating functions in the dry montane landscapes of the Southern Caucasus.

The implications extend across multiple stakeholder levels. The National Forest Agency of Georgia, as the institution responsible for forest management nationwide, stands to benefit directly from the introduction of locally innovative modelling tools that address a persistent evidence gap limiting the implementation of adaptive strategies. Model outputs, especially when made spatially explicit can support justification and prioritization of interventions such as thinning regimes or species transitions in future management plans. Local communities in Aspindza are also strongly affected, as these forests provide essential ecosystem services in a dry environment, including water regulation, erosion control on steep south-facing slopes, carbon sequestration and various non-timber resources. Degradation of forest condition would likely translate into heightened water scarcity, increased exposure to natural hazards, and direct livelihood impacts. Finally, as Georgia advances its commitments under the UNFCCC, the project provides a concrete example of climate-smart forestry in practice. The methodological approach is transferable to other drought-exposed mountain regions of the Caucasus and can inform broader policy discussions on dryland afforestation, restoration priorities, and long-term adaptive forest management.

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Keywords: Climate adaptation, dry montane forests, scenario modelling, PICUS, forest resilience.