The ”Seedling Adaptation Method“ – A novel approach to regenerate forest ecosystems

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The rapid pace of climate change has created a mismatch between existing forest ecosystems and current environmental conditions. In Central Europe and beyond, recent unprecedented disturbances have indicated a high vulnerability of many forests to extreme weather events. Natural regeneration, while often cost-effective, frequently fails to deliver species compositions suited to future climates, especially after large-scale disturbances. Artificial regeneration, therefore, has become essential to accelerate forest adaptation and ensure long-term resilience. However, conventional methods (i.e., direct seeding and containerized planting) face significant limitations. Direct seeding suffers from high early mortality due to frost, drought, predation, and pathogens, while containerized seedlings often experience transplant shock, exhibit insufficient shoot-to-root ratios, and develop constrained root systems due to container walls. These constraints compromise survival, growth, and long-term stability, undermining reforestation efforts. The core challenge addressed by this contribution is the urgent need for a regeneration method that overcomes these constraints, bridging the gap between the ecological advantages of natural development and the practical benefits of controlled nursery production.

To address the limitations of conventional regeneration methods, we developed the Seedling Adaptation Method (SAM), a novel two-phase approach that integrates the strengths of both direct seeding and containerized planting while mitigating their respective drawbacks. In SAM, germination and early seedling development occur under controlled nursery conditions, ensuring high seed survival. Crucially, seedlings are transplanted at the onset of primary leaf formation, that is, when they have developed the capacity for autotrophic nutrition but before significant morphological constraints (e.g., root circling or shoot-to-root imbalances) appear. This enables seedlings to rapidly acclimate to site-specific environmental conditions, while maintaining the benefits of protected early growth.

We evaluated SAM in a field trial using pedunculate oak (*Quercus robur* L.), comparing the saplings of SAM, conventional container-grown and direct seeding. After two years, SAM seedlings demonstrated superior performance across multiple key metrics: significantly greater shoot and root growth, higher root biomass, and markedly improved survival rates. These initial results demonstrate that SAM effectively combines the high germination success of seeding with the site-adaptive potential of natural development, while avoiding the root constraints and transplant shock associated with traditional planting. The method not only enhances regeneration success but also promotes long-term tree stability through natural root architecture (Figure 1). While further testing across species, sites, and climatic gradients is essential to confirm its generality, SAM represents a promising, scalable innovation for adaptive forest restoration. If validated in broader applications, SAM could play a pivotal role in meeting the growing demand for high-quality, climate-resilient regeneration material in the face of accelerating climate change.

SAM may support a broad range of stakeholders involved in forest management, conservation, and climate adaptation. Forest managers and silviculturists are primary beneficiaries, as they face increasing pressure to regenerate large disturbed areas quickly and successfully under harsher site conditions. The method offers a practical tool to improve survival and growth rates, reducing the need for costly replanting and increasing the efficiency of reforestation projects.

Public and private forest enterprises stand to gain from reduced input costs (e.g., fewer seedlings needed, lower mortality), improved stand quality, and enhanced long-term productivity. Conservation organizations and policymakers are also key stakeholders, particularly those involved in large-scale ecological restoration initiatives such as the “Great Green Wall” or national reforestation programs.

SAM is highly practical and ready for broader application. It requires only minor modifications to existing nursery infrastructure: standard sowing trays or compostable containers, controlled greenhouse conditions, and early transplanting at the primary leaf stage (around four weeks after germination). The method does not demand specialized equipment or extensive training, making it accessible to both small-scale nurseries and large commercial operations. The use of biodegradable containers, made from natural materials like hemp, rapeseed wax, and sheep’s wool, ensures environmental compatibility and eliminates the need for container removal. The planting process is straightforward and compatible with standard field machinery and spacing protocols. Crucially, SAM reduces labor and cost over time: lower mortality means fewer replanting cycles, and higher root development translates into better long-term tree stability and reduced risk of windthrow. The method also aligns with emerging trends in forestry, such as climate-smart forestry. While further testing across species and site conditions is needed, the initial results suggest that SAM is a promising approach to restore and adapt forest ecosystems for the future.

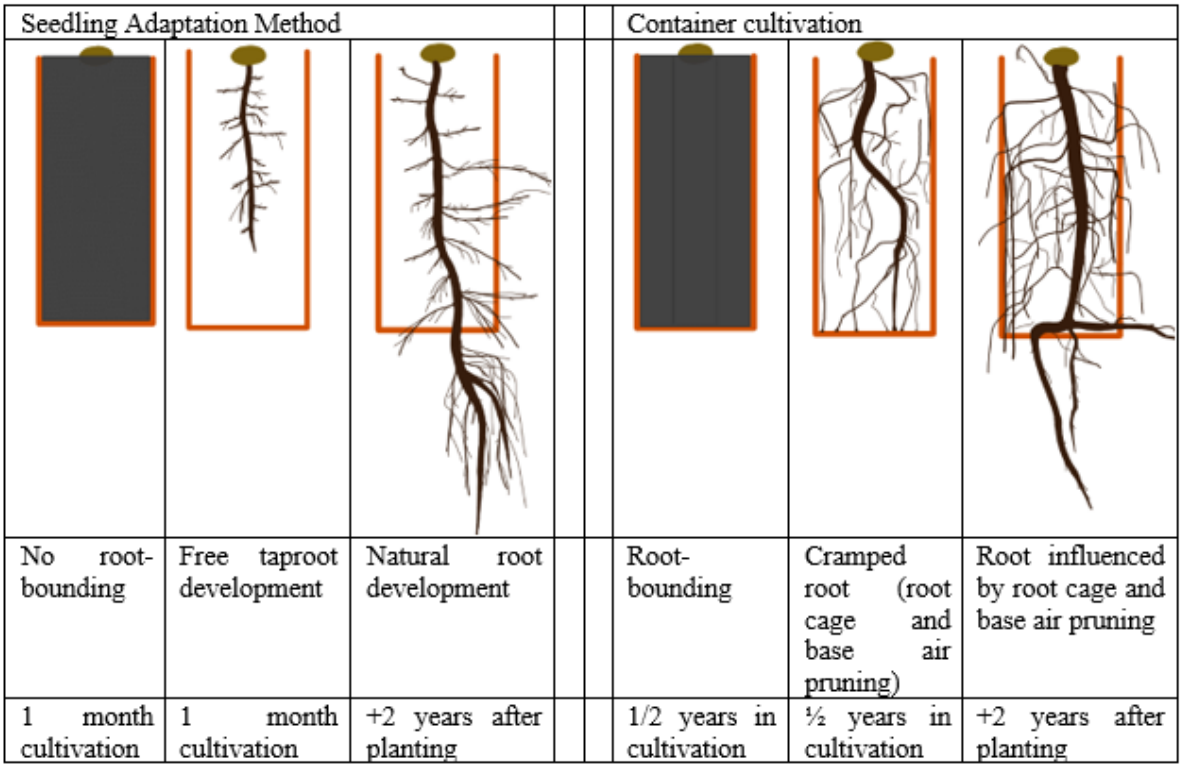

Figure 1: Schematic comparison of root development under the Seedling Adaptation Method (SAM) and conventional container cultivation. The red frame indicates the root ball in nursery conditions. SAM (left): Biodegradable containers decompose in soil, enabling unrestricted, natural root growth. Container-grown seedlings (right): Vertical ribs guide roots toward the container wall, causing downward bends and root circling. Base air pruning interrupts root growth at the container bottom, leading to constrained, non-natural root architecture even after planting.