REGE+
Forest regeneration under climate and environmental changes

Context

Forests are essential to the Earth's habitability and play a critical role in mitigating climate change through carbon sequestration and local cooling effect. They also serve as biodiversity hotspots and provide a wide array of ecosystem services. To sustain these multiple functions, including their climate services, forests must be continually regenerated. However, European and, more specifically, Belgian forests face numerous threats. Warm and dry summers weaken trees and seedlings by causing water stresses, which in turn trigger outbreaks of pests and pathogens. In addition, the management of wildlife populations—particularly ungulates like roe deer and red deer—can significantly impact forest dynamics. High populations of these herbivores can affect regeneration development through browsing, preferentially affecting certain tree species and ultimately changing forest composition over time. In this uncertain and rapidly changing environment, forest managers must focus on enhancing forest resistance and resilience. One potential solution is the establishment of uneven-aged and mixed stands. Mixing tree species with contrasting functional traits offers a broad range of responses to various stresses, thus improving a forest's ability to recover after disturbances.

The diversification of forests—both in terms of age and species composition—fundamentally depends on regeneration. It is through regeneration that tree species composition and forest structure can be changed. Yet, regeneration is complex; it results from an interplay of factors, including forest characteristics, silvicultural practices, natural disturbances, pressure from ungulate populations, and climatic conditions. Promoting regeneration is therefore essential—it is the cornerstone of any meaningful effort toward forest diversification.

Objectives

The objective of the REGE+ project was to develop a highly integrated tool that allows testing various forest regeneration strategies while accounting for local climate evolution and varying levels of ungulate density. Simulation experiments were conducted across multiple climate scenarios and case studies (5 representative broadleaved stands to be regenerated over the next 40 years) to test various regeneration and wildlife management strategies. After discussion with stakeholders (private and public forest owners, managers, and hunters), three silvicultural routes were retained: Business As Usual (BAU), which consists in maintaining an even-aged stand and to regenerate it based on the shelterwood method while limiting interventions in the regeneration cohorts; Oak Regeneration (OAK), same as BAU but promoting the regeneration of sessile oak by targeted clearings; Diversification (DIV), aiming to enhance both stand composition and structural diversification by relying on natural regeneration and enrichment plantations.

Methodology

To conduct the simulations, the original version of HETEROFOR was enhanced to incorporate processes such as hydraulic failure, ungulate impacts, carbon sequestration in both soil and forest products, and to provide users with a range of model outputs, including indicators of wood production, profitability, biodiversity, and carbon balance and storage. Additionally, a disaggregation procedure was developed to enable the model to convert daily meteorological data into hourly data. To calibrate and validate these new features in the HETEROFOR model, we needed specific field data. While most data were available, we collected additional information on sapling and pole height growth, the impact of ungulate browsing, and the effects of reduced rainfall on growth.

Regeneration dynamics were monitored *in situ* in both broadleaved and coniferous forests. Browsing damage by ungulates was tracked across an extensive network of paired fenced and unfenced plots. Additionally, a rainfall limitation experiment was conducted to assess the effects of reduced soil water content on seedling growth.

Before launching the simulations with HETEROFOR, we bias-corrected the CMIP6 climate model projections and defined the silvicultural strategies and ungulate population densities to be used.

Results

The climate change projections for the 21st century were derived from several General Circulation Models (GCMs) used in the CMIP6 initiative. These projections are based on the latest IPCC-endorsed scenarios, known as the Shared Socioeconomic Pathways (SSPs), specifically SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

To address model biases, we applied two correction techniques: simple scaling and ISIMIP3BA. The latter, which uses parametric quantile mapping, effectively adjusted biases across the entire distribution.

Based on the bias-corrected climate projections, forests in Wallonia are expected to experience drier conditions and higher temperatures during the summer months. These trends become more pronounced under more severe climate scenarios. The combined impact of these stressors is likely to increase forest vulnerability, as projections indicate a greater overlap between heatwaves and droughts, as well as longer-lasting drought events.

The evaluation focused on each silvicultural strategy's capacity to sustain ecosystem services and enhance forest resilience under the dual pressures of climate change and ungulate browsing. In the absence of ungulate pressure, the DIV (diversified) strategy demonstrated several strengths—not only in terms of biodiversity and resilience but also in productivity and profitability, outperforming the other two silvicultural approaches. However, DIV showed the weakest performance in carbon storage, whereas the BAU (business-as-usual) strategy delivered the highest values for this indicator. BAU also recorded the highest levels of wind resistance while scoring lowest in terms of tree recruitment and biodiversity. In contrast, the OAK strategy stood apart from both DIV and BAU, with lower wind resistance and profitability, and generally intermediate values across the other indicators. Another key finding from the simulation experiment is the significant—and often overriding—influence of site conditions on the indicators assessed. Site-specific characteristics, and particularly the initial stand attributes such as species composition, structural complexity, and stand density, play a critical role in shaping future stand dynamics, the delivery of ecosystem services, and overall forest resilience. The fact that the influence of initial stand characteristics persists throughout the simulation—even as it diminishes over time—highlights the strong inertia of forest ecosystems. Silviculture plays a crucial role in shaping forests into more resilient ecosystems, equipping them to better withstand future changes and disturbances—though these transformations take time.

Moreover, the most effective silvicultural strategies vary from site to site, reinforcing the idea that there is no one-size-fits-all solution.

Our results highlight the substantial and often underestimated influence of ungulate pressure on forest dynamics. At high densities, ungulates consistently reduced productivity, resilience, and economic sustainability across all climate pathways and management scenarios. Their impact was at least as significant as that of climate change for most performance indicators. Notably, the OAK and DIV scenarios were particularly vulnerable to browsing, with frequent regeneration failures observed under intense pressure. In contrast, the BAU scenario remained largely unaffected, likely due to its reliance on species and structural compositions less palatable to ungulates. These results suggest that, in areas with high ungulate densities, diversification efforts may be seriously compromised, as browsing pressure hinders regeneration success and increases protection costs. Effective ungulate management is therefore essential to ensure the feasibility and success of adaptive silvicultural strategies, particularly those aiming to enhance forest diversity and resilience.

The project additionally quantified the economic impacts of ungulates as well as their impacts on forest dynamics. Analysing a large sample of fenced and unfenced plots, we evidenced that, on average, the height growth of seedlings of European Beech and Norway Spruce are little affected by ungulate browsing. At contrast, the height growth of the other admixed species (Birch, Rowan, Oak, Hornbeam, Maple), were clearly negatively affected. Their height growth was reduced by 54 to 83%. As most of these admixed species are supposedly more resistant to future climatic conditions than beech and spruce, ungulate pressure are thought to be a real threat to forest adaptation to future climatic conditions. Moreover, once the trees are bigger (20-40 cm in girth), red deer can produce bark-stripping damages. On average, bark-stripping damages reduce the revenues by 19% which corresponds to a cost of 2647 €/ha (53€/ha/year). The results provided further indications about the main factors (stand fertility, silvicultural interventions, bark-stripping rate) affecting locally this cost.

Conclusions

By highlighting the vulnerability of forest ecosystems to climate change and by quantifying the costs and benefits of various adaptation strategies, the project provides valuable evidence to inform future policy directions.

Our project anticipates the potential decline of broadleaved stands, particularly beech forests, which may increasingly suffer from severe dieback under changing climate conditions. Through experimental trials and comparative analysis, we assessed the effectiveness of various preemptive silvicultural strategies aimed at enhancing the resilience of these ecosystems. This proactive approach provides a scientific foundation for future forest policies that could be modelled after the scenarios tested in this research.

Moreover, our findings clearly identify the ecological and economic costs associated with overabundant ungulate populations, notably through bark stripping and browsing damage. These pressures not only threaten forest regeneration but also compromise the adaptive capacity of forest ecosystems in the face of climate change. These insights are highly relevant to the regional forest management agenda.

Keywords

Climate change, ungulate pressure, forest regeneration, forest management, tree species diversification, ecosystem services, resilience, forest modelling, simulation