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Climate growth limitations of European beech and silver fir along the Carpathian arc – the recent state and future prospects

KEYWORDS: climate-growth limitation; VS model; Carpathians; climate change; silver fir; European beech

Introduction

Changing temperature and precipitation patterns are shaping tree climate-growth limitations. The influence of climate change affects individual tree species differently (Zang *et al.*, 2014; Kašpar *et al.*, 2021), and varies across extensive geographical regions (Gazol *et al.*, 2015). The Carpathians, a vast mountainous area of Europe, host significant numbers of silver fir (*Abies alba* Mill.) and European beech (*Fagus sylvatica* L.; Kholiavchuk *et al.*, 2024), both of which exhibit distinct climate-growth responses despite sharing similar ecological niches (Paluch, 2007). Our study aims to discern the climate growth limitations of silver fir and European beech, identify the effects of climate change on their growth, and forecast the future growth trajectories of silver fir and European beech across Carpathians. To achieve this, we (i) calculated climate-growth limitations of beech and fir based on recent data, and then (ii) extended the simulations based on a future climate scenario to identify potential effects of climate change on long-term growth trends and climate limitations of both species.

Methods

We selected eight sites along the Carpathian arc at similar elevations and edaphic conditions (Figure 1A), where 14 to 17 mature canopy trees of both species were dendrochronologically sampled and measured. Using the purely climate-driven process-based model (Vaganov-Shashkin process-based model, hereafter VS model, Vaganov *et al.*, 2006), we simulated radial growth and computed growing season variables as well as temperature and moisture limitations (the entire process is schematically captured in Figure 1B-H). Model calibration covered the period from 1985 to 2015. E-OBS data were then used to simulate the period from 1985 to 2022 (Cornes *et al.*, 2018), while the bias-corrected prediction of the RCP 4.5 scenario was utilized for predictions from 2023 to 2050 (Berg *et al.*, 2021).

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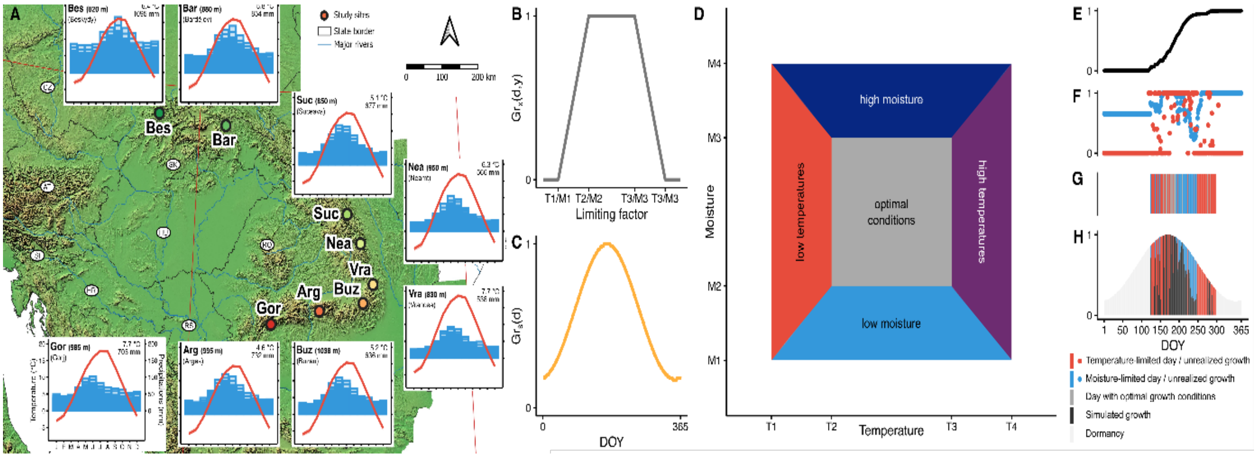

Fig. 1. A – The study area and climate characteristics of individual study sites. And the methodological approach used in this study for simulating climate-growth limitations. B – the response function's shape depicting the relationship between temperature/precipitation and partial growth response; C – the response function's shape illustrating the relationship between growth rate and day duration; D – computation of specific daily growth rates; E – daily growth rates with emphasis on the predominant limiting factor (low moisture and/or low temperatures; F – representation of the growing season's progression categorized by the dominant limiting factor; G – visualization of tree-ring formation throughout the growing season; H – simulation of realized growth and growth not realized due to insufficient temperature and moisture conditions.

Results

VS model predicts earlier, but statistically non-significant start of the growing season (Figure 2A) in the future period (2020-2050). However, together with the later cessation of the growing season, the growing season lengths will be significantly ($p<0.05$) longer in the future (Figure 2B). The proportion of the growing season limited by low temperatures will generally decrease (except sites Vra, Nea and Suc; Figure 2C) in favour of an increase in moisture limitations (Figure 2D), which will significantly ($p<0.05$) increase at most of the sites. Suppression of the main limiting factor at individual sites will result in the preservation of current growth rates or growth acceleration (Figure 2E).

The observed non-significant change in the growing season's start over both periods, estimated at 1-2 days per decade (Figure 3A). Combined with later cessatation, this resulted in a prolongation of the growing season by 3-5 days per decade, with statistically significant trends for both species at all sites ($p<0.05$; Figure 4B). These trends are mirrored in reductions of the proportion of temperature-limited growing season days (at south-western and northern sites;

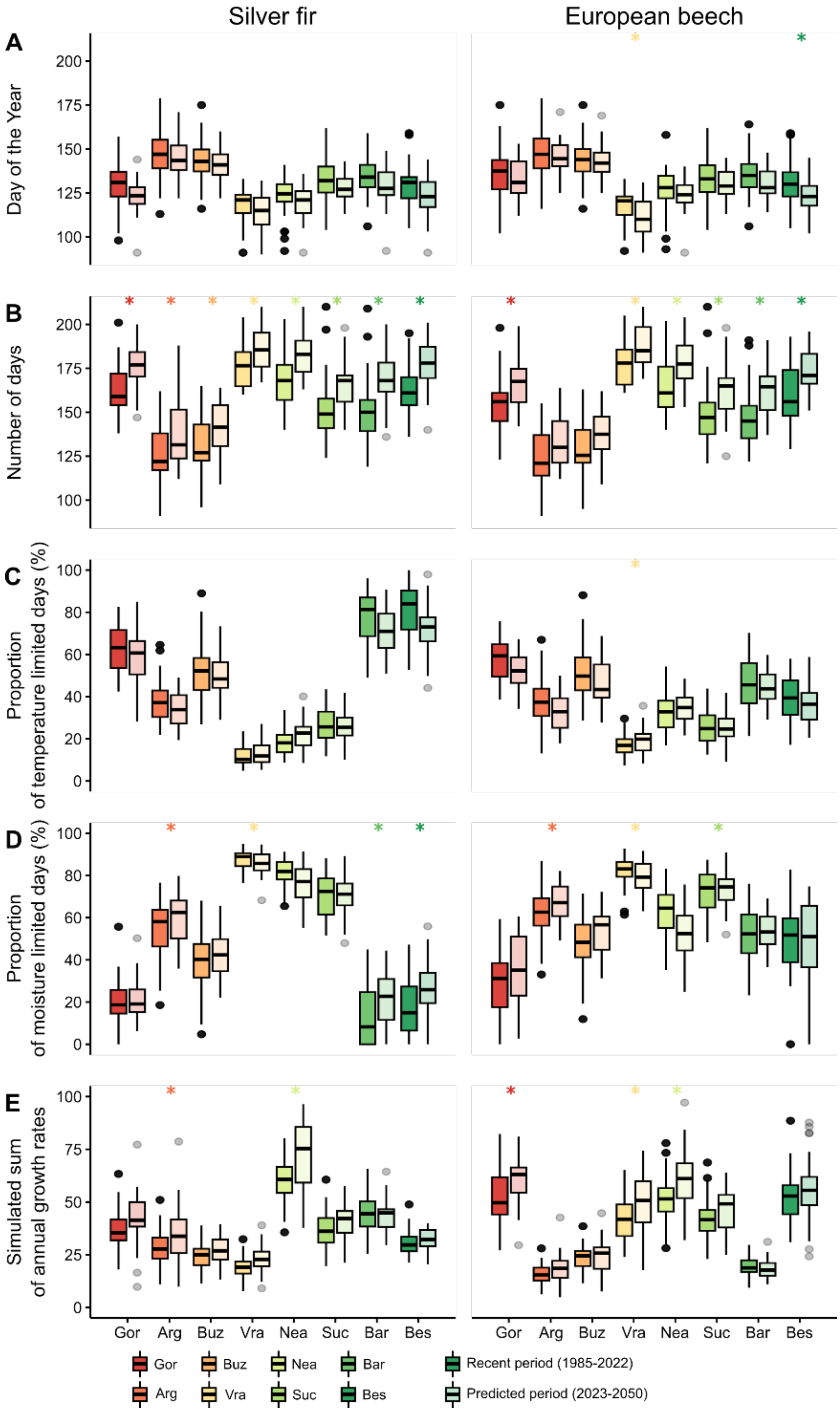

Fig. 2. *Growing season parameters and climate growth limitations at individual sites and tree species in the recent and predicted periods. A – start of the growing season; B – duration of the growing season; C – percentage of the growing season limited by temperatures; D – percentage of the growing season limited by moisture conditions; E – simulated growth rates. The boxplots denote 25th, 50th and 75th percentiles. Whiskers illustrate "reasonable" minimum and maximum, and dots represents outliers. For each site, the boxplot with the darker colour depicts the recent period (1985-2022) and the boxplot with the lighter colour the predicted period (2023-2050). Asterisks denote statistically significant differences ($p<0.05$) between recent and future periods.*

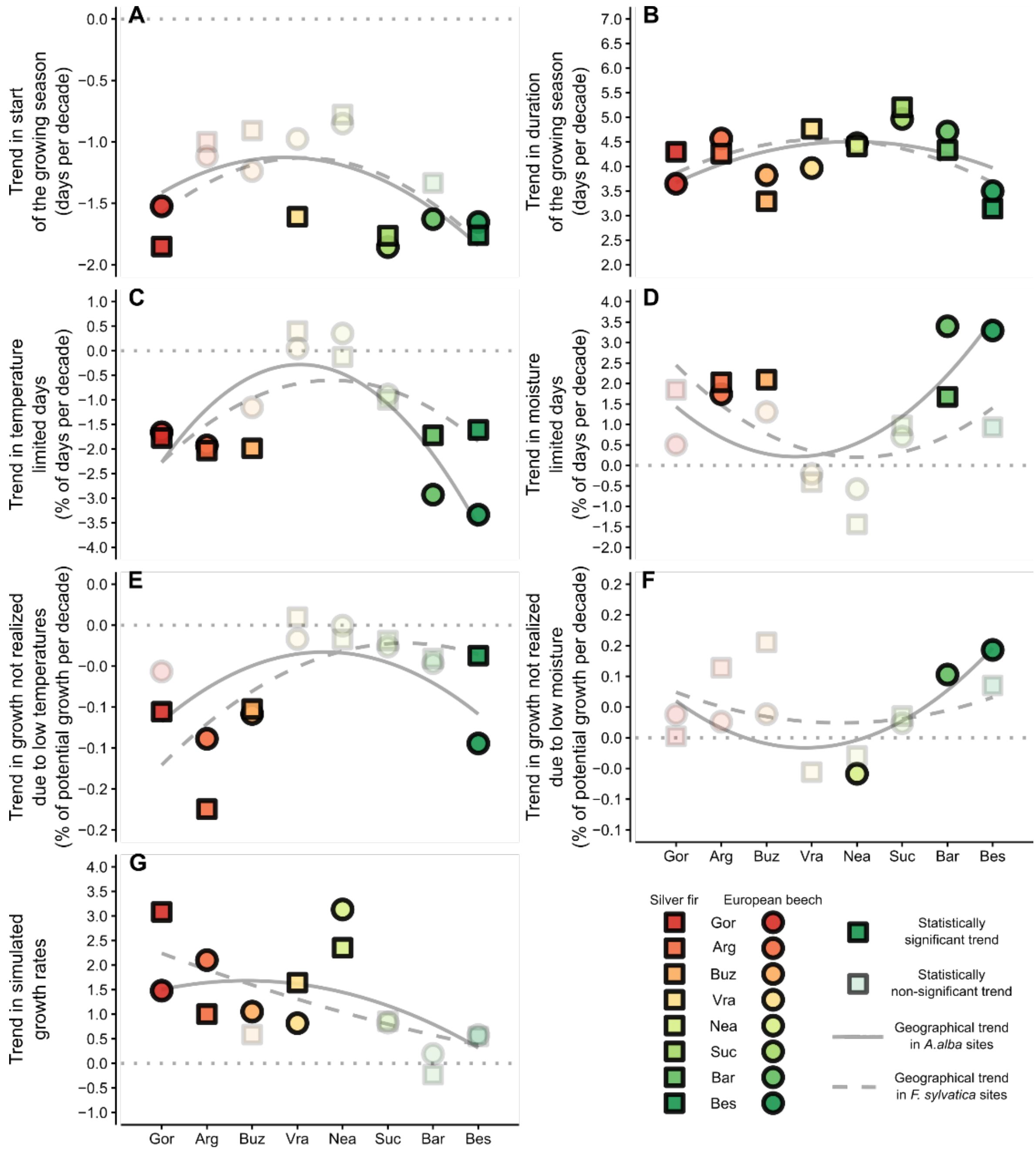

Fig. 3. Trends (slopes of linear regressions in the study period) in growing season parameters and climate-growth limitations of fir and beech at individual sites. A – start of the growing season; B – length of the growing season; C – proportion of the growing season limited by temperatures; D – proportion of the growing season limited by moisture; E – growth not realized due to temperature conditions; F – growth not realized due to moisture conditions; G – simulated growth rates.

Figure 3C). Conversely, limitations caused by insufficient moisture conditions showed a significant increase in the proportion of moisture-limited days (Figure 3D). Similar patterns were detected for growth not realized due to insufficient temperature (Figure 3E) and moisture (Figure 3D) conditions. The highest increase in simulated growth was observed at southern sites, with a gradual decrease towards the north (Figure 4G).

Based on the PCA, individual sites were clustered according to their common climate-growth limitations. For both species, we found (Figure 5A and A8): (i) sites mainly limited by low temperatures (for fir at the northern sites - Bes, Bar, plus Gor and for *F. sylvatica* Bes and Gor); (ii) sites mainly limited by low moisture (south-eastern sites - Suc, Nea, and Vra); and (iii) sites with mixed limitations (sites close to 0 at both PC axes; mainly southern sites; for fir Arg and Buz and for beech Arg, Buz and Bar. The results of the PCA also confirmed a gradual shift from temperature-limited growth towards limitation by low moisture at the expense of temperature limitation. Finally, the results of the PCA demonstrated that the period 2011-2020 was the driest in the recent period.

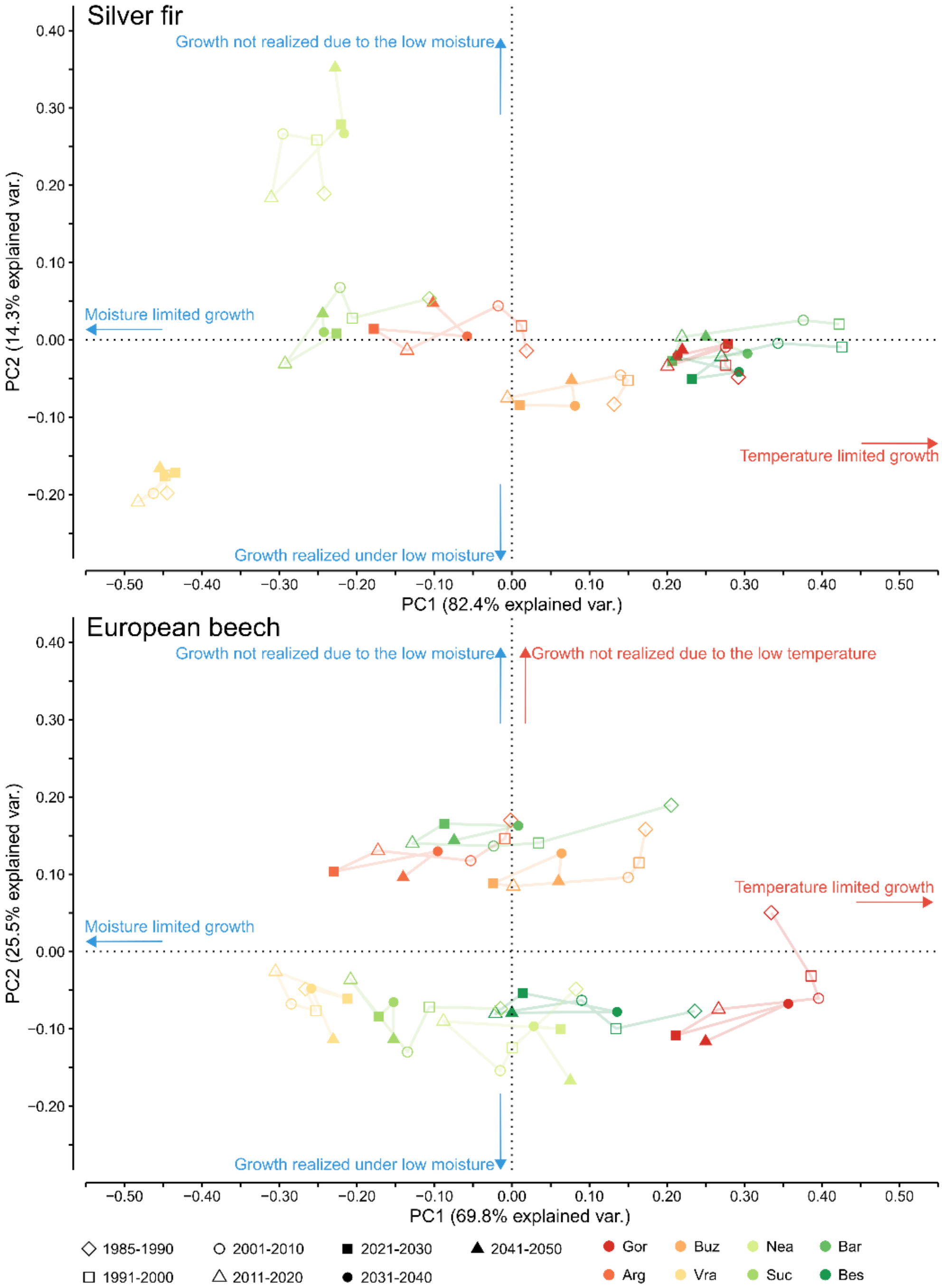

Fig. 4. Principal Component Analysis of growth limitations at investigated sites A – fir and B – beech.

Conclusions

In summary, our results confirmed three distinct regions in the Carpathians, with varying climate-growth limitations: the northern, south-western, and south-eastern areas (Adamič *et al.*, 2023). Northern sites are primarily limited by cold temperatures, southern sites by insufficient moisture, intensifying eastward. The gradual decrease in the main limiting factor results into increased growth rates, suggesting improved growth conditions of silver fir and European beech under RCP 4.5 scenario at elevations above 800 m (Klesse *et al.*, 2024). Nonetheless, under the RCP 4.5 scenario, distinctions among these clusters are anticipated to persist into the future. Our findings highlight site-specific variations in simulated annual growth between the recent and future periods beech consistently exhibited more pronounced moisture limitations across the entire Carpathian gradient (Zang *et al.*, 2014; Kašpar *et al.*, 2021), indicating a potentially heightened susceptibility to future droughts due to its limited growth plasticity compared to fir, which appears to show better adaptability to future conditions, particularly in the northern Carpathians.

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