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RESEARCH ARTICLE

Systematic Search for Drought-Resilient Provenances in Bavaria, Germany

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ABSTRACT

Repeated droughts have led to a decline in vitality and the death of entire populations of European beech (*Fagus sylvatica* L.), particularly in Lower Franconia, over the last decade. In order to identify suitable seed sources for future forest conversion measures, seed stands are being sought that remain resistant even under hot and dry conditions. This article presents a concept for a systematic method for identifying climate-resilient beech populations in Bavaria. Data from forest damage surveys, climate models, and site data have been merged for the first time in this context. The pilot study demonstrated a significant correlation between the modelled climatic marginality and the reported drought damage. The method of stratification using niche models and forest damage survey data thus proved to be a good starting point for identifying endangered forest sites and stands. The approach enables a targeted search for phenotypically healthy trees and forest stand that show little drought symptoms even under high site-related vulnerability (e.g., marginal sites, low plant available water capacity [AWC]). These stands, showing an apparently high phenotypic plasticity, are observational classified and hypothesised as particularly drought-resilient. Hence, carrying out these data analyses for the identification of more drought resilient beech in a first step effectively narrows the search area for field work and genetically analysis of potential seed stands.

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Terminology

Resilience is the capacity of a tree or forest system to recover its structure and function after a disturbance. It reflects the speed and degree of return to pre-disturbance growth, vitality, or population structure (DeRose & Long, 2014; Holling, 1973).

Resistance is the capacity of a tree (or population) to withstand a disturbance or stress event (e.g., drought, frost, pests) with little or no reduction in performance (e.g., growth, survival, physiological function) (DeRose & Long, 2014).

Vitality refers to the overall physiological vigor and functional performance of a tree, typically reflected in growth rate, crown condition, reproductive output, carbohydrate

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reserves, and ability to maintain metabolic processes under prevailing environmental conditions (Dobbertin, 2005; Roloff, 1991).

1. Introduction

Over the past decade, there have been repeated extreme drought events in northern Bavarian forests, especially in Lower Franconia. These weather conditions have affected the water supply and thus the growth of trees. Second, they also reduced the forest's resistance to abiotic damages and pests. Tree species that were once considered robust and vital, such as the European beech (*Fagus sylvatica* L.), showed signs of severe drought stress at many forest sites, especially in Lower Franconia. These ranged from premature leaf fall and crown damage to increased mortality (Figure 1).

Figure 1. Vitality loss of beech trees in Lower Franconia. Photos: Yves-Daniel Hoffmann (Bavarian Office for Forest Genetics), Andreas Hahn (Bavarian State Institute of Forestry)

This abiotic damage underscores the urgency of adapting to climate change in order to strengthen the resilience of forest stands. The search for resilient populations and their use in "assisted migration" (Fady et al., 2016) would be an important measure to increase the resilience of forests. However, moving a species within or even outside its range may disrupt ecological relationships and expose species to novel stresses. There is also the risk that introduced populations could become invasive, hybridize with local genotypes, alter community structure, or reduce local biodiversity (Aitken et al., 2013). We show, using the example of European beech, how forest damage survey data and precise observations on viability, vitality and water and nutrient supply can enhance the identification of resilient populations. This work was carried out as part of the sensFORnative project.

Field observations show that – contrary to most individuals of a population – some individual trees and specific groups of trees can maintain their vitality even under adverse environmental conditions. The influence of site-related factors on tree vitality is frequently observed and is considered ecophysiologically plausible. The search for suitable seed stocks base on visually and externally recognizable healthy tree populations, i.e. those that are apparently phenotypically resilient. It is obvious that observed resilience in populations could also be based on many factors other than genetic causes. Therefore, the search scheme focuses on genetically resilient populations by excluding other causes for the apparent resilience as far as possible, e.g. by taking site conditions into account (a high AWC is a key to bridge the water supply to trees during periods of drought; Marano et al., 2025). We demonstrate this here using a simple initial approach with a few parameters observed by us in this small preliminary study. This simple search scheme is based on comparing the intensity of vitality loss and their vulnerability, which is determined by climate at the large scale and local site conditions at the small scale. The relationship between vitality loss and vulnerability can be represented graphically (Figure 2). Those forest stands or individuals that show only minor damage even during a drought period despite high site-related damage susceptibility can be expected to be particularly suitable under climate change conditions (Figure 2, green dots).

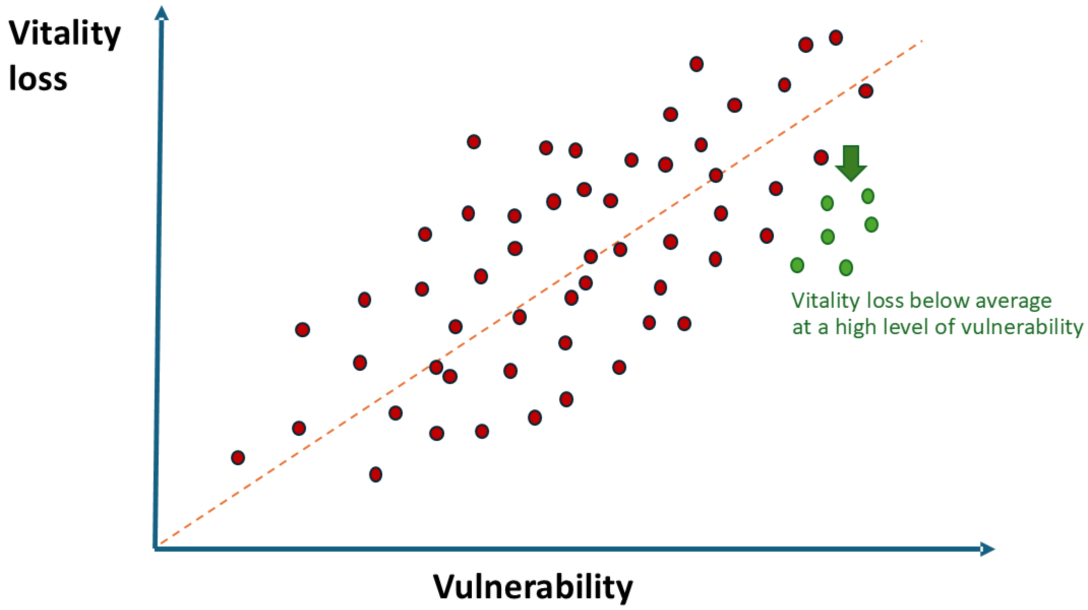

Figure 2. Schematic representation of the relationship between vitality loss (observed damage) and potential site-related vulnerability/susceptibility to damage. The interaction of site characteristics such as water, nutrient supply and the local climate determine the potential susceptibility to damage of a site. Some forest stands may show below-average symptoms despite high susceptibility (green points below the red regression line).

2. Materials and Methods

2.1. Survey on Regional Level

Vitality loss and drought symptoms in beech are reported within the forest damage survey of the Bavarian Forest Administration (WSM reports). Data used for this study was noted every six months between 2018 and 2021 for the total forest area (Schißlbauer et al., 2022). The forest damage survey includes all stands in a forest district this means both damaged and non-damaged stands were considered. Beech stands had to show noticeable signs of dieback in the upper crown to be recorded – but the beech trees did not have to be completely dead.

The potential vulnerability of seed crop stands was determined in the sensFORclim project as climatic marginality (CMI) on the basis of niche models (Mellert et al., 2023). The tree species distribution data were taken from the Bayerische Landesanstalt für Wald und Forstwirtschaft (2020) dataset. In order to fully exploit the climatic potential of a tree species, beech was already considered present if it occurred within a 16 x 16 km grid. WorldClim (Fick & Hijmans, 2017) was used as climate data. The variables BIO6 (minimum temperatures in the coldest month), BIO10 (average summer temperatures), and BIO18 (summer precipitation) for the climate period from 1970 to 2000 were used as proxies for the limitation caused by chilliness and frost (BIO6) as well as for summer heat (BIO10) and drought (BIO18) (Mellert et al., 2015). For the large-scale representation of vulnerability, climate data for Bavaria was taken, assuming a climate warming of +2.5 °C. This incremental scenario was used because such elevated temperatures have already been observed in Bavaria in recent years. The resulting forecast of marginality (CMI) was mapped and classified with the threshold values (CMI < 0.4 = marginal; CMI 0.4–0.7 = intermediate; CMI > 0.7 = optimal) for vulnerability (1-CMI). On this basis the CMI of European beech was mapped.

We checked whether the classes of climatic vulnerability provide a meaningful classification. Further, we examined whether there is a relationship between the CMI as a measure for potential vulnerability and the damage reports according to the concept described in Figure 2 by nonparametric correlation analysis with Kendall's tau.

2.2. Survey on Stand Level

The data for the local site conditions includes the defoliation rate of 332 trees situated in twelve European beech stands in northern Bavaria (Schmied et al., 2024). The data which was collected in the sensFORbeech project with a different objective (Schmied et al., 2024) are used here for an illustrative example how the search process at the stand level up to the plus tree could look like (for further details, Materials and Methods section and Schmied et al., 2024). Therefore, the identification of "drought-resilient" populations relies only on visual interpretation of deviations from the regression line. No statistical criteria were applied to identify significant outliers.

The potential vulnerability of stands was described by the available water capacity (AWC) as a main driver for the small-scale vulnerability (Marano et al., 2025; Mellert et al., 2018, 2023). This allows us to show the relationship according to the concept described in Figure 2 at the stand level, where AWC represents the potential vulnerability (x-axis) and the rate of defoliation represents vitality loss (y-axis).

3. Results and Discussion

3.1. Survey on Regional Level

The resulting area forecast of the CMI was divided into an optimal, intermediate, and marginal range in each case. A correlation between vulnerability and damage is plausible but cannot be expected with certainty. This is due to the fact that the niche models used are based on historical climate data (period 1970–2000) and a projected climate warming of +2.5 °C, while the WSM reports reflect the current annual damage. This analysis can therefore be seen as a proof of concept whether large-scale ecological parameters such as marginality or derived variables such as vulnerability are at all suitable as measures of potential susceptibility to damage.

As the map in Figure 3 shows, there is a correspondence between the CMI and the reported damage areas in the forest districts visible (Figure 4). Statistical analysis of the relationship between the two parameters provides more detailed information (Figure 4). The correlation between the two variables is significant (Kendall's tau = – 0.2; $p < 0.001$). The lower the CMI, i.e. the more marginal the stand, the greater the damage. The scatter plot in Figure 5 shows that the greatest damage occurs in forest districts in Lower Franconia – a climatically highly vulnerable area (marginal area: CMI < 0.4). In the optimal area, on the other hand, less damage occurs (see Figure 3). These results suggest that the stratification method based on niche models is fundamentally suitable for assessing the climatic vulnerability of populations.

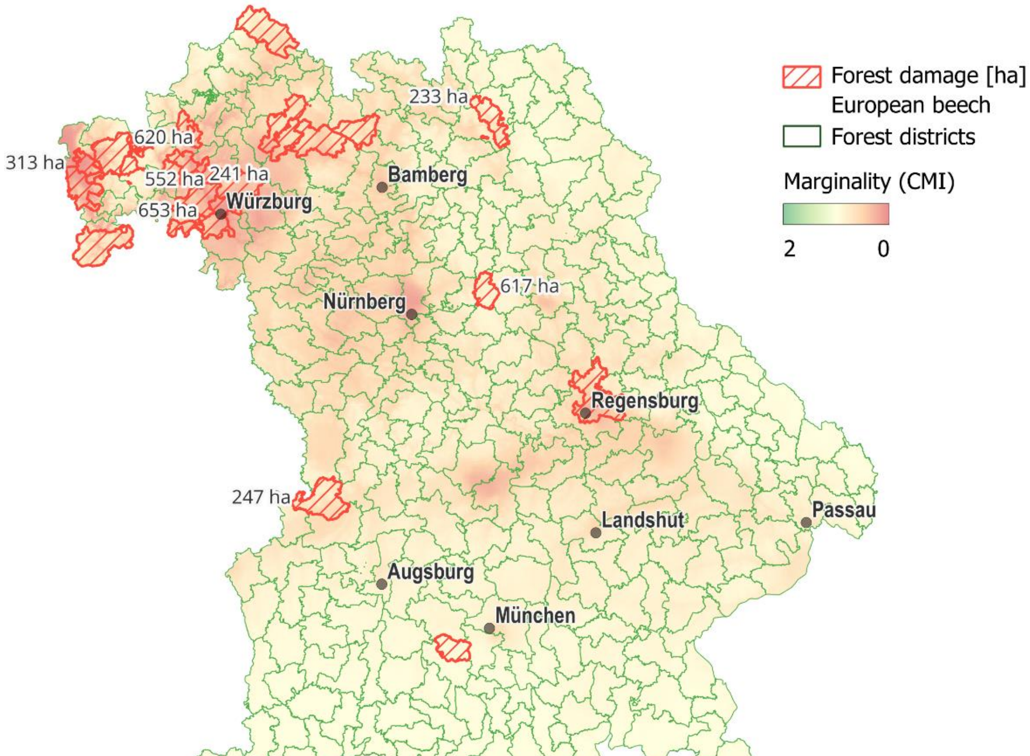

Figure 3. Marginality of European beech in Bavaria (CMI) overlayed by the damaged areas reported for the forest districts of the Bavarian Forest Administration (regional offices for food, agriculture, and forestry) for the years 2018–2021 (hatched polygons).

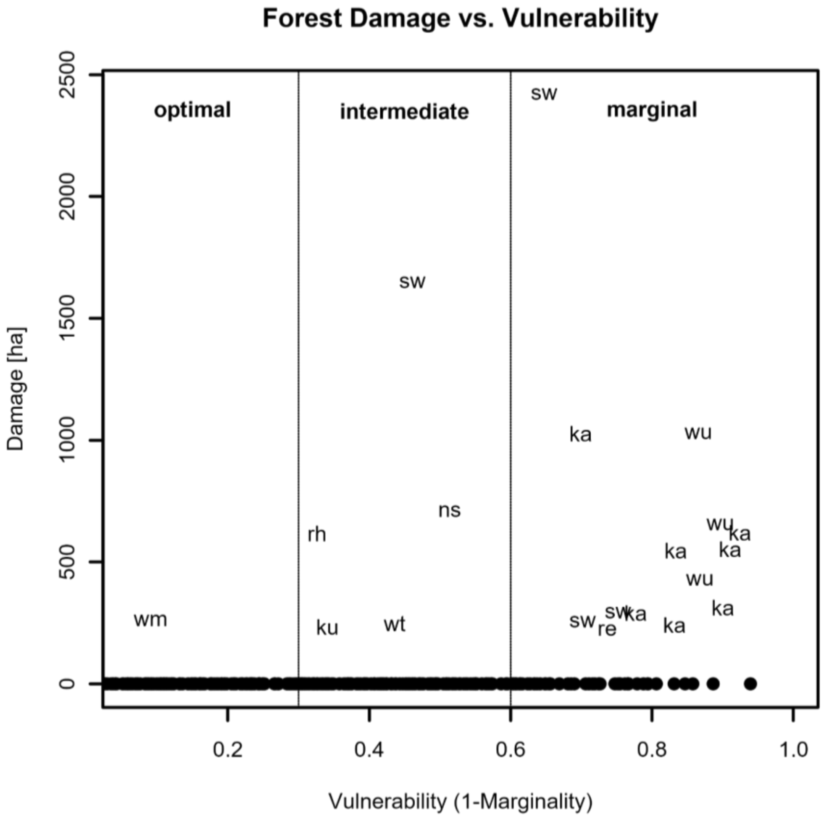

Figure 4. Reported forest area with drought damage to European beech in Bavaria stratified according to vulnerability classes (V). Forest districts of the regional offices of the Bavarian Forest Administration with reported damages are represented by abbreviations. Particularly noteworthy are the forest districts of regional offices in Lower Franconia with high levels of damage (ka=Karlstadt, sw=Schweinfurt, wu=Würzburg; see Figure 3). V < 0,3 = optimal; V 0,3 – 0,6 = intermediate; V > 0,6 = marginal.

3.2. Survey on Stand Level

The scatter plot in Figure 5 represents the effect of AWC as a driver for the vulnerability at small scale on the vitality loss (defoliation rate). Error bars in Figure 5 visualize the variation of individual trees within a forest stand. Increased climate plasticity is assumed in cases of below-average damage (stands below the dashed grey regression line). Promising trees or stands are present when high vulnerability is accompanied by only minor damage (highlighted error bars in shades of green).

According to our assessment scheme, three of the twelve tree populations stand out from the average trend, symbolized by the highlighted greenish error bars in Figure 5. These populations could therefore contain drought-resilient genotypes. We expressly formulate this conclusion as a hypothesis for further testing. It is obvious that an observed deviation from the expected damage does not in itself prove a genetic adaptation process. Therefore, the stocks identified in this way should be tested in further studies and practical cultivation trials. The propagation material from stocks tested in this way would be a valuable contribution to increasing the resilience and stability of forests.

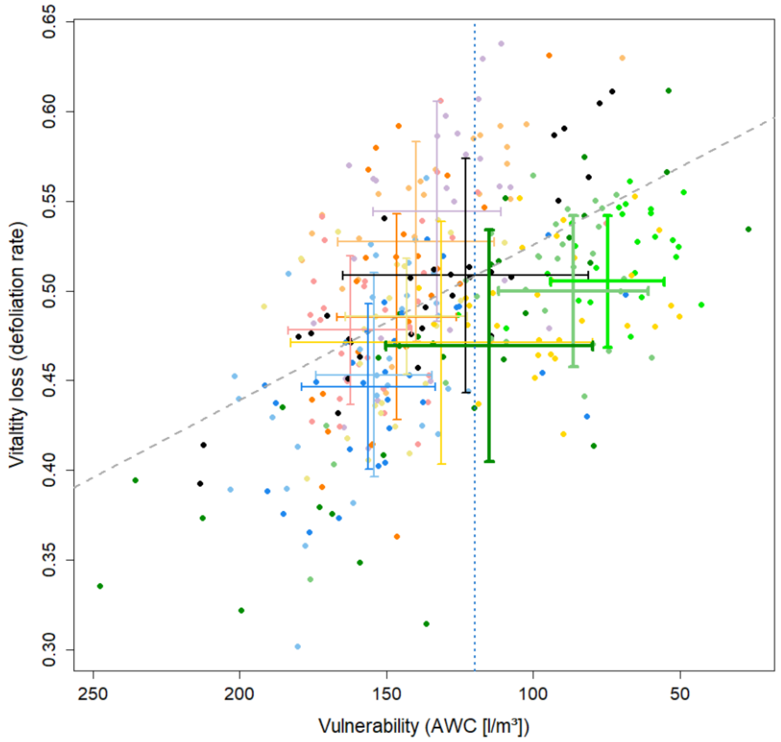

Figure 5. Example for the identification of drought-resilient trees (N=332) within stands (N=12): Vitality loss (estimated degree of defoliation of individual European beeches in August 2022) vs. small-scale vulnerability represented by AWC in declining order versus increasing vulnerability (vertical dotted blue line: AWC = 120 l/m²).

3.3. Operational Procedure Despite Unresolved Issues

After the severe drought events in recent years, the resistance and resilience of European beech was doubted for large amounts of forest sites (Klemmt et al., 2023). It was questioned, how these symptoms should be interpreted: Can the vitality loss and the dieback of European beech be assessed as an individual adaptation to new environmental conditions? Or is a reassessment of the suitable site requirements for European beech needed?

However, recent research in Bavaria points to a complex response of trees to drought impacts on a variety of environmental conditions - varying with spatial scales such as climate (Mellert et al., 2018), soil chemistry (Schmied et al., 2023), soil water storage (Schmied et al., 2024), and tree neighbourhood composition and structure (Rieder et al., 2026).

As we could show, concluding data on potential vulnerability information (Mellert et al., 2023) and forest damages (Schißlbauer et al., 2022) are already available and can be used for a systematic search for climate-resilient provenances in Bavaria, although the underlying processes for forest damage are not fully understood.

Nevertheless, the searching procedure described here have to be further developed with more comprehensive data: Future application-oriented research should include, forest protection data (data from all types of forest ownerships, longer time series), data from the forest condition survey, updated site data (Mette et al., 2025), but also high-resolution recording of damage symptoms using remote sensing data. Initial studies certainly give cause for optimism (Pfenninger et al., 2025).

4. Conclusion

Damage surveys at the forest district level provide a good overview on the dispersion of biotic and abiotic damages to forest stands; hot spot regions can be identified. The correlation between forest damage and climatic marginality, which serves as a criterion for the regional susceptibility of forests to damage, highlights the important role of macroclimatic drought risks. The climatic marginality can therefore be a starting point for a systematic search for drought-resilient populations. Stands with little or no vitality loss in such problem areas could indicate more resilient stands. Such phenotypically promising candidates derived from observational classification can be included in a systematic testing procedure. In particular, site-specific causes for (apparently) increased resistance of the populations should be excluded as far as possible. A tree population with increased resilience identified in this way could, after further intense testing in accordance with the German Forest Reproductive Material Act (BLE, 2003) – e.g., with regard to its quality and genetic adaptability – be designated as a seed stand for drought-resilient propagation material.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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