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Sustainability of Forest Cover under Climate Change on the Temperate-Continental Xeric Limits

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Abstract: Climate change particularly threatens the xeric limits of temperate-continental forests. In Hungary, annual temperatures have increased by 1.2 °C–1.8 °C in the last 30 years and the frequency of extreme droughts has grown. With the aim to gain stand-level prospects of sustainability, we have used local forest site variables to identify and project effects of recent and expected changes of climate. We have used a climatic descriptor (FAI index) to compare trends estimated from forest datasets with climatological projections; this is likely for the first time such a comparison has been made. Four independent approaches confirmed the near-linear decline of growth and vitality with increasing hot droughts in summer, using sessile oak as model species. The correlation between droughts and the expansion of pest and disease damages was also found to be significant. Projections of expected changes of main site factors predict a dramatic rise of future drought frequency and, consequently, a substantial shift of forest climate classes, especially at low elevation. Excess water-dependent lowland forests may lose supply from groundwater, which may change vegetation cover and soil development processes. The overall change of site conditions not only causes economic losses, but also challenges long-term sustainability of forest cover at the xeric limits.

Keywords: trailing limits; site potential change; growth decline; drought stress; pests and diseases; mortality; adaptation; decision support system; adaptive forestry; sessile oak

1. Introduction: Contrasting Opinions on Climate Impacts in Forests

Recent analyses demonstrate that terrestrial ecosystems will be severely impacted by climate change [1,2]. These impacts are manifold and can ultimately affect global biodiversity, the terrestrial carbon cycle and human well-being [3,4]. Regarding forests, symptoms of growth rate and vitality decline, insect calamities, as well as species abundance shifts in forest ecosystems are reported from various parts of the world, from Europe to North America, and from Amazonia to Siberia (e.g., [5–13]). Nevertheless, some studies postulate that forests may benefit from higher temperatures due to manifold compensating effects such as fertilization through rising atmospheric CO_2 concentration and N deposition, or improving water use efficiency [9,14]. In a review of the forestry literature of past decades, Boisvenue and Running [15] found that in the majority of ecosystems that are not water limited, growth trends are on the rise due to climate change. In a recent, detailed literature survey,

Allen et al. [16] thoroughly analyzed contrasting opinions and evidences. They concluded that it seems impossible to attain explicit inferences on a global level, currently due to the complex character of ecological processes and the necessarily incomplete and disparate data coverage of investigated case studies.

Analyzing assembled observation data with a widely different ecological background contributes to a high level of unexplained variance. Large-scale assessments typically do not consider compensating local effects such as the water holding capacity of soil or microclimate, and often miss restrictive components [12,17]. Despite attempts to quantitatively define generally valid rules for expected responses of forests to climatic stress in forest ecology [18] and in genetics [19], high uncertainty remains. This emphasizes the importance of focusing on regional and local ecological conditions to perceive site potential as understood by forestry: An *inseparable factor complex of climate, soil and hydrology.*

Threats to forest ecosystems are especially critical at the borders of distribution determined by droughts, i.e., at the *xeric limits*. The limiting effects of summer moisture deficit (drought events) are the climatic causes delineating the receding distribution borders of tree species in the temperate zone. Differing from the migration history-related term of trailing limits, the term xeric limit has been introduced to emphasize the role of rapidly changing climate in shaping distribution boundaries of species, which leaves little space for migration [20]. In water-limited ecosystems at the xeric limit, higher temperatures coupled with droughts are leading to declining growth and high rates of mortality, mostly due to hydraulic failure [21–23]. Thus, tree decline and mortality appears at xeric limits often *in absence of competitive pressure*. On the contrary, a serious problem at the xeric limit of closed forests is the *lack of competitive (native) species* to take over the role of the species going extinct locally.

Xeric limits are often fuzzy, especially on plains where species distribution patterns are mosaic-like and follow small-scale topographic, water regime and soil variation. Xeric limits are, therefore, determined by more complex factors on plains than on mountain slopes. Impacts of intense land use (including forestry), biotic interactions, and hindrances to forest regeneration are usually stronger on plain landscapes [22,24,25]. For these reasons, the drought-prone, temperate-continental xeric limit of forests has up to now largely escaped the attention of international research, in spite of its global importance [16,26]. This transition zone, bordering on open grassland (steppe) extends across Eurasia [13,26], from Hungary to North China and also across North America, from the prairies of Canada to the arid lands of Northern Mexico [5]. The ecological, economic, and geophysical importance of this transition zone is obvious, while local awareness of threats and proactive adaptive strategies needs to be developed in many countries [26].

2. Aims and Outlines of the Study

Due to the complexity of factors triggering responses of forest trees at low-latitude, low-altitude peripheries of distribution, causes and impacts have to be analyzed in more detail. We believe that *focusing on climate alone as the determining factor is insufficient* to understand climate impacts in water-limited regions at the xeric limits of forest cover [22]. *Stand-level site traits*, such as those related to soil and water supply might significantly modify the response of forest vegetation to changing conditions. We hypothesize that involving other site factors into modeling increases the reliability of projections of forest ecosystem responses.

We investigate recent and projected site condition changes and their impacts on forest trees at the xeric limits in Hungary to highlight the potential of assessing and modeling *from a forestry perspective, on a regional, site-oriented scale.*

Therefore, we aim at:

- Identifying the extent of recent and expected changes of main abiotic site factors (climate, hydrology, soil) on fine scale, i.e., on stand level

- Analyzing recent and projected growth and health responses of forest tree species related to site condition changes (based on available forest databases and observations), in order to achieve *better projections of site potential on stand level and to support adaptive forest management*
- Envisaging their effect on future forest management and sustainability

The fastest shift of temperature conditions is expected on plains because the geographic distance between isotherms is drastically higher by latitude than by altitude, reaching differences as high as three magnitudes [25]. At the xeric limits, this may lead to local extinctions or even closed forest cover loss on flat terrains. Hungary, a country devoid of large altitudinal variation, may therefore serve as a good case study for highly exposed xeric limits. Concurrently, the study of climatic impacts on plains may serve as a "time acceleration laboratory" for mountainous regions.

In this study, we deal only with climate change impacts on growth, health, and mortality, utilizing primarily local forestry data. Data from forestry databanks and from field monitoring are combined with climate model projections to assess growth trends. Disturbances such as wildfires or storms are not considered, as their frequency is unpredictable at present. Impacts are modeled based mostly on climate means as proxies for extreme events (droughts) as the standardized analysis of the latter is still unsolved [18]. We discuss projections predominantly until mid-century, i.e., approximately until 1/3 of the felling age of broadleaves (see [10]), because of higher uncertainties for the periods beyond.

The purpose of the analyses is to contribute to forest growth and vitality predictions on stand level and to the design of decision support systems on a local scale and, ultimately, to support adaptive forest management in conditions endangered by climate change. The results may provide general information on the long-term sustainability of forests and forestry at the xeric limits under climate change.

3. Recent and Projected Changes of Forest Site Potential in Hungary

3.1. Changes of Climate in the Recent Past and Projections for the Future (E. Führer–B. Gálos)

The climate of the Carpathian Basin follows the general trends in Europe. Since the 1980s, droughts tend to occur more frequently during the growing season. Annual temperature in Hungary increased by 1.2 °C–1.8 °C in the last 30 years, and the frequency of extreme dry and hot periods in consecutive years has increased as well [27,28]. This has led to the reduction of the macroclimatically suitable zone for beech- and oak-dominated forest types requiring higher precipitation, primarily at their lower, xeric distributional limit [20,28,29]. Drought-induced damage symptoms such as health status decline, declining growth and vitality, increasing mortality, as well as simultaneously increasing virulence, pest and disease invasions have been observed and reported in the past decades [30–34]; for details, see following chapters.

Regarding future prospects, regional climate projections for all of Europe largely agree upon a significant warming tendency until the end of the 21st century. Annual precipitation is expected to increase in the northern regions of Europe and decrease in the southern regions [35,36]. In the Carpathian Basin, which is located in the transition zone, the projected annual precipitation change is statistically insignificant; however, some increase in precipitation may be expected in winter, whereas in summer the reverse may be expected [28,37]. The latter can exceed 25% in the southern part of Carpathian Basin until the end of the century. Together with more than a 3.5 °C temperature increase of the summer mean (relative to the reference period 1981–2010), this may result in a further increase in the probability and severity of droughts. Forecasts indicate that more than half of the years in the 30-year period spanning 2071–2100 may be extremely dry (see Figure 1; [38]). Consequently, the probability and severity of already observable climate impacts and damages in forests are likely to increase considerably.
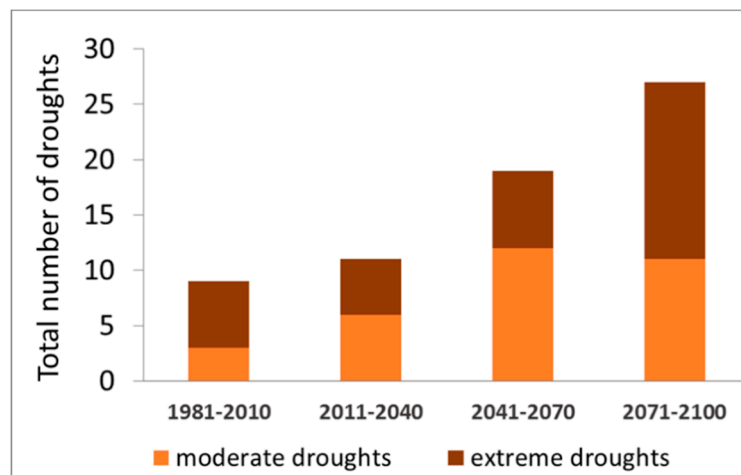
Figure 1. Total number of moderate and extreme summer drought years (May to August) for 30-year periods in Southwest Hungary. 1981–2010: Observed data; future periods: Observed data adjusted with changes based on the mean of projections of 12 regional climate simulations, assuming the A1B emission scenario (adapted from Gálos et al. [38]). Drought definition is based on [39]. (See also Figure 5).

In the absence of sufficient meteorological time series until the 1960s, Hungarian forest ecologists classified forest climate into four classes based on air moisture stress in July. In practice, the presence of the main climate indicator tree species, respectively community types, were used as proxies to identify the classes in the field; these were beech, hornbeam–oak, sessile oak–Turkey oak, and forest steppe. The latter is the warmest and driest category with no indicator tree species [41].

To macroclimatically characterize the classes noted above, the Forestry Aridity Index (FAI) has been developed [40,42]. The FAI is based on monthly temperature and precipitation data since these variables are the most readily available from observed records and climate model outputs. The FAI equation is as follows:

$$FAI = \frac{T_{July-August}}{P_{May-June-(2 \times July)-August}} \times 100 \tag{1}$$

The calculation and interpretation of FAI is described in Appendix A.2. Table 1 shows the FAI threshold values from cool/moist to warm/dry climates.

Table 1. Forest Aridity Index (FAI) limits of climate classes and the corresponding precipitation sum of the main growing period ($P_{May–Augst}$) and temperature mean of the critical months ($T_{July–August}$). The latter are averages for Hungary [40].

Climate Class	Low Limit	High Limit	$P_{May–August}$ (mm)	$T_{July–August}$ (°C)
beech	-	<4.75	332	18.2
hornbeam-oak	4.75	<6.00	288	19.4
sessile/Turkey oak	6.00	<7.25	245	20.2
forest steppe	7.25	<8.50	228	20.6
grass steppe *	8.50	-	undefined	Undefined

* Newly introduced, projected climate class.

Climate class is the prime classification descriptor of site types, i.e., of site potential in Hungary. The determination of FAI limits of climate classes has permitted the direct translation of downscaled climate data as forest site descriptors, and the conversion of projected climatic trends into shifts of forest vegetation zones.

Primarily due to the drastic increase of the summer mean temperature in recent decades, the total area of beech and hornbeam-oak climate class sites has shrunk significantly, whereas that of the drier sessile oak–Turkey oak and of the forest steppe climates have increased (Figure 2).
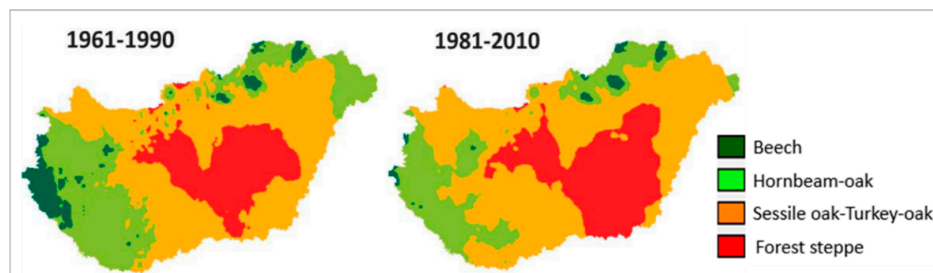

Figure 2. Recent shift of macroclimate classes in Hungary, defined by the Forestry Aridity Index (original by B. Gálos, see also [40]). For explanations see text and Appendix A.2.

In light of the projected warming and decrease of available water in the main growing period [38], the macroclimatically most favorable zone, the beech climate class, may all but disappear from Hungary in the near future (2021–2050; Figure 3). The largest macroclimatic site potential shift will take place in the lowlands where drier site conditions (forest steppe climate class) are expected to expand and cover more than 50% of the country. Not only will this result in the decline of forest site and yield potential [29], but also in novel combinations of site factors that have not existed in Hungary before. Consequently, climate simulations project the appearance of sites with FAI values exceeding an 8.50 value, indicating a grass steppe climate, by the middle of the century. These projections have prompted the introduction of this climate class into the site assessment system (Tables 1 and 2). According to the mean projections, the steppe climate class may reach 11% of the country's territory. In absence of surplus water, these sites will become unsuitable for managed forests (Figure 3). (Details of climate sources and assessment methods are described in Appendix A.1).
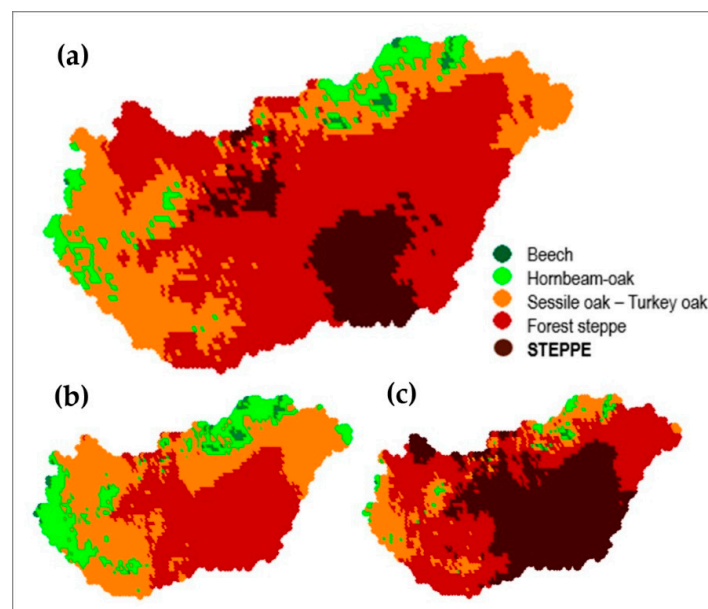

Figure 3. Projected area of macroclimate classes in Hungary for 2021–2050 based on Forestry Aridity Index (FAI) limits. Notice the appearance of grass steppe climate at FAI > 8.50. (**a**) Ensemble mean of the projections. (**b**,**c**) 66% range of the simulation results (emission scenario: A1B, source: B. Gálos, original; compare to Figure 2).

3.2. Role of Hydrologic Conditions and Their Changes under Shifting Climate Factors (Z. Gribovszki)

In the forest steppe zone, forest ecosystems largely depend on locally accessible excess water such as groundwater. Evapotranspiration (ET) of forests (both transpiration and interception) is generally higher in the forest steppe zone than in neighboring grasslands because of the higher leaf area index and the higher root depth of woody vegetation. This difference is especially true on the Great Plain, where precipitation is generally inadequate to support forests of higher water consumption; trees survive drought periods by utilizing groundwater resources [22]. The presence of a reachable groundwater table can draw roots deeper to tap the capillary rise; root elongation following sinking water levels has been observed [43]. Average annual ET of forests in groundwater discharge areas of the Great Plain (calculated using the complementary relationship-based evapotranspiration mapping (CREMAP) technique) was estimated at 620 mm year^{-1}, which was about 80 mm more than the local annual precipitation ([44]; Figure 4).
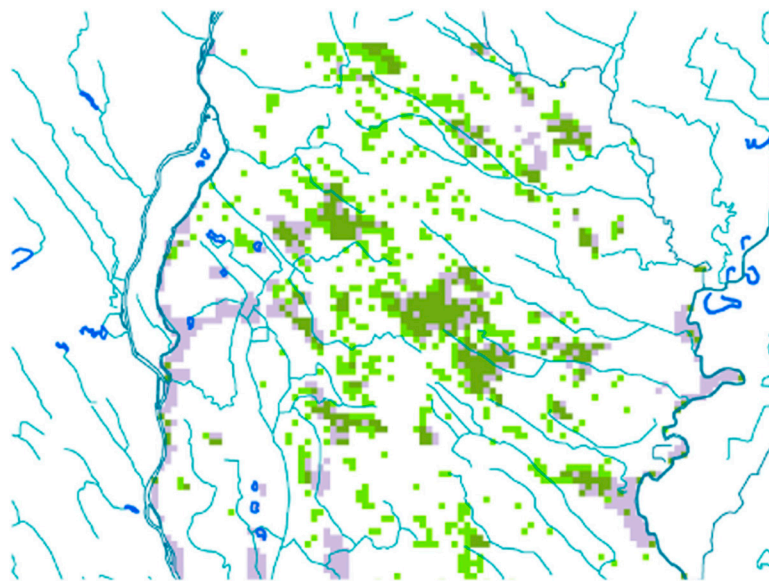

Figure 4. Groundwater discharge (i.e., estimated negative recharge) areas on the Sand Plateau of the Hungarian Great Plain. The map shows the frequent overlap of groundwater discharge areas (magenta) and of forest cover (light green). Overlapping areas are dark green. Rivers and ponds are marked dark blue (adapted from [44]).

Throughout the year, the groundwater table under forests (if trees are able to reach it) is detected at levels deeper (by 0.4–0.6 m) than under grassland and under agricultural land, with higher differences during the growing season [45]. The lower water table under forests causes local depressions in the groundwater level, which again induces groundwater flow.

Analyzing 20 groundwater well data with different vegetation cover, Csáfordi et al. [46] found differentiated groundwater uptake during extended dry periods on the Hungarian Great Plain. Comparing vegetation covers, low values of ETgw (groundwater evapotranspiration) were detected for black locust (*Robinia pseudoacacia* L.) (mean 0.4 mm day^{-1}), higher values for Euramerican poplar (*Populus x euramericana* (Dode) Guinier) (mean 1.7–6.0 mm day^{-1}), while the highest rates of ETgw were found for pedunculate oak (*Quercus robur* L.) (mean 8.2 mm day^{-1}). There were no or negligible traces of ETgw on the control grass plots, indicating the low groundwater consumption of herbaceous vegetation. Gribovszki et al. [45] found similar ranks of groundwater uptake.

Móricz et al. [47] compared the water balance of a pedunculate oak forest and of a neighboring grassland and also found that the forest had 30% higher ET, but the difference in groundwater use was

much higher (235 versus 85 mm). Groundwater consumption was 40% less in a wet growing season than in a drier growing season, although the groundwater level was deeper during the dry period.

Deeper rooting and higher water uptake of forests induce not only water table drop but also subsurface salt accumulation, which indicates long-term water use. Tóth et al. [48] evaluated the soil and groundwater data of 31 pairs of forest and control plots on the Great Plain. Tree biomass was positively correlated with soil salinization, but the rates were different by species (poplar > pedunculate oak > black locust). Salt accumulation under the monitored forest stands was much lower (far from being a threat to the trees) than that found on clayey sites of Hungary and Argentina.

Gribovszki et al. [45] also compared the salt accumulation of oak-, poplar- and grass-covered plots. Salt accumulation was slightly higher for poplar in both the vadose zone (the unsaturated part of the soil horizon above the groundwater, where the water is retained by adhesion and capillary force) and groundwater. Thus, hybrid poplars, which are preferred for afforestation, are a less favorable choice due to their salinization effect.

Driven by rising temperatures, increasing transpiration demand in the future will likely induce an enhanced groundwater uptake by plant communities. Eventually this may lead to the further lowering of the groundwater table and, probably, to more significant salt accumulation. If this occurs, the regeneration of groundwater-dependent forest communities in these areas will be questionable since the root system of young trees will be unable to reach the excess water source.

Expected climatic changes may also lead to runoff changes that affect catchments and the water balance. Using precipitation and temperature results of regional climate model simulations as input data (Appendix A.1), Csáki et al. [49] calculated projections of main components of the water balance for the Zala River catchment in Western Hungary. Increasing temperature (3.5 °C) in the 21st century is projected to cause a slight increase (4%) in evapotranspiration, but a substantial reduction (53%) of long-term runoff. The decreasing runoff/recharge may limit extractable groundwater resources, and could lead to serious consequences; e.g., the Zala River is the main tributary of Lake Balaton and its adjoining wetlands.

3.3. Changes in Soil Conditions (A. Bidló)

Projected higher frequencies of extreme precipitation events may have direct and indirect effects on soils by increasing erosion and deflation damages, leading to the decrease of fertility, a worsening soil texture and water balance, and the exposure of calcareous parent rock (loess, marl) [50]. Deflation-threatened sandy soils are frequent on the Great Plain, which is often devoid of closed vegetation cover. If climate turns drier, sand movement may start again despite the large-scale stabilization efforts in previous centuries.

Climate change also has an indirect effect on soils, primarily on their water balance. Increasing evapotranspiration decreases soil leaching; this is unfavorable for plants on sites with calcareous bedrock, which is frequent in Hungary. Although we reckon with the general decline of forest biomass production, it is expected that the organic content of soils will increase due to so-called double blocking: Fast decomposition of organic material in the topsoil is blocked both by low winter temperatures and by dryness in summer [51].

The transformation process of soda soils has significantly accelerated in the recent past. In a semiarid climate, the salty groundwater close to the surface is the most important factor for the development of these soils. According to present data, the area of soda soils will partly increase and partly decrease (for the latter case, in regions with a significant decline of the groundwater level, such as on the interfluvial Sand Plateau), which may also affect the forest cover. The lowering of the groundwater table may lead to the transformation of soil organic material, respective to the modification of soil development processes, due to changes in forest cover [52].

4. Observations of Yield Potential, Vitality and Health Condition Change of Forests

4.1. Negative Health Trends in the Hungarian Forests Triggered by Climate Change (G. Csóka–A. Hirka)

4.1.1. Abiotic Damages (Droughts)

The vast majority of the Hungarian forests grow on exclusively rainfed sites; i.e., without groundwater influence. Any unfavorable change in the amount or in the temporal pattern of precipitation may have significant effects on forest health. Analyzing long-term datasets of beech and sessile oak stands, it is evident that weather (more precisely, the lack of precipitation) is the main factor influencing forest health changes in Hungary [53]. During and after longer periods (2–3 consecutive years) of drought, mortality of trees increases significantly, even among dominant and codominant trees (see also Appendix A.6).

The increasing trends of the abiotic damages [32] clearly reflect the growing frequency of extreme weather events (drought, late frost, heavy storms, etc.). On top of their direct effects, abiotic calamities may create favorable conditions for pathogens or insects. Thus, even pests/pathogens commonly considered less virulent may cause severe damage. Compared to earlier years, the annual extent of drought damage reported from Hungarian forests shows significantly increased values in the previous two decades. Pálfai's drought index (PAI) was applied instead of FAI for the analysis of the impact of weather conditions, as PAI usually has higher explanatory power for forest health data (for both insect and drought damages). The index is based on the ratio of monthly temperature and precipitation data in the considered time periods:

$$PAI = \frac{T_{IV-VIII}}{P_{X-VIII}} \times 100 \qquad (2)$$

where $T_{IV-VIII}$ = average temperature of the period from April to August (°C); P_{X-VIII} = precipitation sum between the previous October and current year's August (mm).

Figure 5 shows the frequency shift of droughts between two recent time periods (see also Figure 2), while Figure 6 displays the close correlation between PAI drought index and reported damaged area. While direct drought damage was earlier reported mainly from younger stands and regeneration sites of the plains, it is becoming increasingly frequent in older aged stands even at higher elevations (e.g., in montane beech forests in the Mátra Mts.).
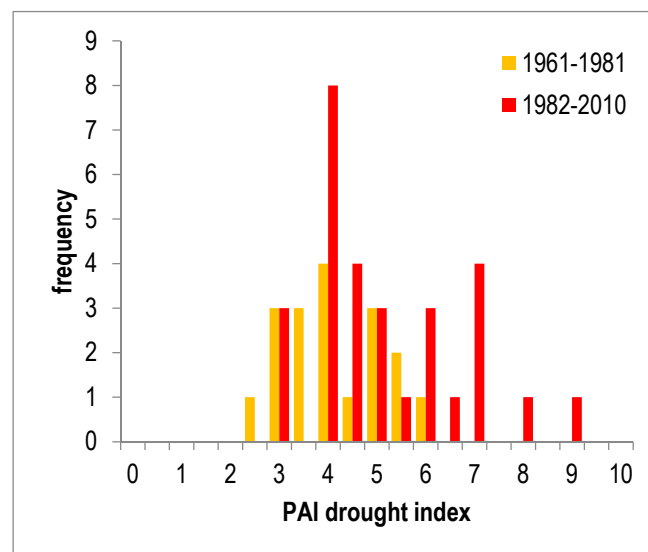

Figure 5. Frequency shift of the annual average values of Pálfai's drought index (PAI) for two 20-year time periods (1961–1981 and 1982–2010) defined by breakpoint analysis, see also [32].
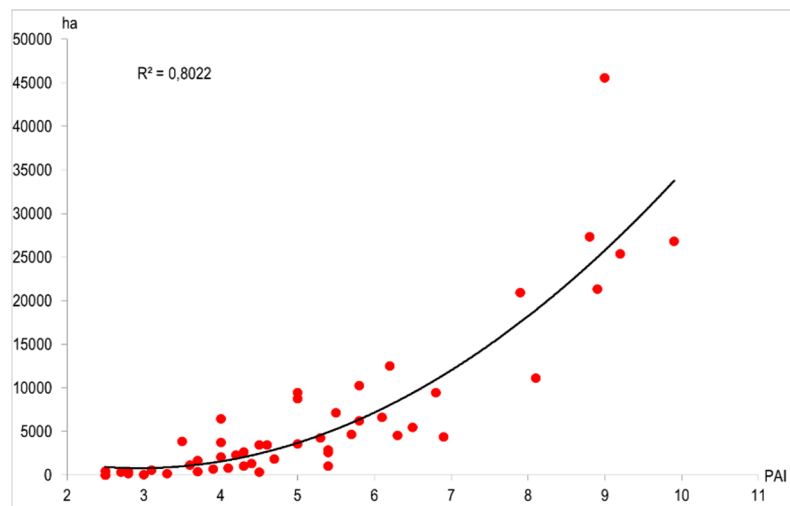
Figure 6. Correlation of the Pálfai's drought index (PAI) and the annual forest drought damage area (ha). Source of data: Forest damage database of the Forest Research Institute; see also [32].

4.1.2. Biotic Damages

The area damaged by biotic agents also shows an increasing trend in the last 50 years even when the permanently increasing forest area of Hungary is taken into account. This is true for both insects and pathogens. The triggering effect of droughts is statistically proven for many insect pests [54–57], and is also evident for fungal diseases such as the recent damages caused by pine decline (*Cenangium ferruginosum*), maple decline (*Armillaria* spp.), and charcoal disease (*Biscogniauxia mediterranea*) of Turkey oak.

The damage caused by previously unknown antagonists (pests and pathogens) is increasing year by year in drought-stressed forests. For instance, the gall wasp (*Pseudoneuroterus saliens*) killing the 2nd year acorns of Turkey oak is already severely obstructing the regeneration of the tree species in some regions. An earlier unprecedented outbreak of *Agrilus viridis*, causing mass mortality in beech stands, was triggered by extreme droughts in the first two years of the new millennium [58]. More frequent and severe outbreaks of this species are predicted, particularly in stands growing at lower elevations in SW Hungary.

4.1.3. Future Outlooks

The damage area of some other pests and diseases may also significantly expand because of climate change [59]. For instance, until 2003, charcoal disease was known to cause considerable damage in Tuscany. In 2003, severe damage was reported in Slovenia, and in the last decade also in Hungary, even in North Hungary. The area damaged by some insect pests may also expand vertically, causing considerable damage at higher elevations as reported for gypsy moth, *Lymantria dispar* [31,60,61].

Parallel to global trends, new alien species (insects/pathogens/plants) are being recorded in Hungarian forests at an alarmingly accelerating rate [62,63]. More newly immigrated non-native insect species feeding on woody plants have been recorded in the last two and a half decades than in the previous 110 years (Figure 7) [62]. The main reason for this is certainly the increasing volume of international trade (particularly of living plant material), but mild winters, i.e., climatic change, likely facilitate the establishment of immigrant insects. At the same time, drought-stressed trees with decreased resistance are suitable hosts to be attacked.
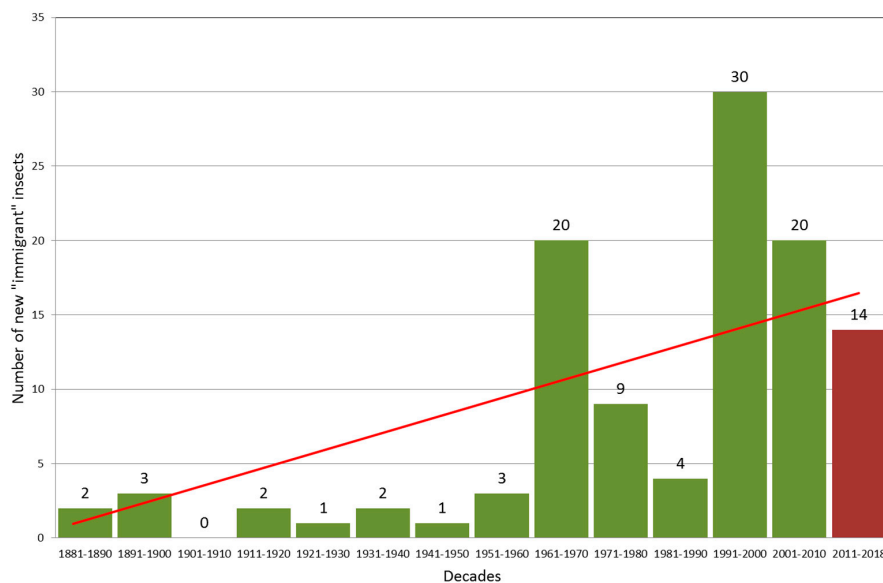
Figure 7. Newly recorded immigrant insects on woody plants by decades in Hungary between 1881 and 2018 (updated from Csóka et al. [62]).

Not all alien pests/pathogens become invasive, but some might be significantly aided by increased climate stress. The fungus *Chalara fraxinea* was first recorded in Hungary in 2008, and the widespread and severe mass mortality of ash stands appeared recently, following frequent dry years. The tropical/subtropical migratory noctuid, *Helicoverpa armigera* had been very rare in Hungary until 1986. In the last three decades, it became increasingly abundant causing considerable damage both to agriculture and forestry. The oak lace bug (*Corythucha arcuata*) was first recorded in Hungary in 2013 [64] and its recent outbreaks in Hungary and in other SE European countries (Bulgaria, Croatia, Romania, Ukraine, Serbia), were likely triggered by several consecutive mild winters [65]. It is assumed that it will spread further and have significant damage potential influencing growth, health, and even acorn crop. Biotic impacts may play a major role in the long-term destabilization of forests. The increasing virulence and high mobility of antagonists however make predictions of biotic damages uncertain.

4.2. Approaches to Estimate Yield Potential and Vitality Changes, Using Sessile Oak as Model Species

The combination of site descriptors and yield data accessible in forest inventory databases, interpreted as false time series, lend themselves to model the effect of climate on the growth, vitality, and health of tree species. Change of site potential will occur mostly in the lifetime of already existing stands or of stands regenerated in the near future. To estimate growth and yield trends driven by a rapid, large-scale shift of site potential, different approaches are compared. For this purpose, sessile oak (*Quercus petraea* Liebl.), a characteristic species serving as a climate indicator for moderate and low aridity forest climate classes, has been selected. The species' distribution limits reach the xeric limits of closed forests, making sessile oak well suited for the assessment of resilience to climate change effects.

Four approaches using sessile oak as model species are presented: (1) Machine learning-aided growth trend approximation using expert estimations of site potential and yield data; (2) analyzing forest inventory data; (3) assessing the impact of climatic stress on stand density (mortality); and (4) analyzing the response of identic populations to site changes in a provenance test network. In all approaches, the index FAI was used to characterize macroclimate and its change (FAI values were translated from respective climate data as described in Section 3.1 and Appendix A.2).

The assessments directly or indirectly use tree height as an indicator of site productivity. We interpreted the stand data of different sites (with different climates) as false time series, allowing for

the effects of soil traits and hydrology. In the case of the provenance tests, the height data of identical sessile oak populations planted at different locations were used.

The loss of half of the growth potential or the mortality of half of the stems in a stand is a significant risk and may be considered as the limit for economic forest management. Therefore, for the comparison of the rather disparate assessments, the threshold value of "50% loss of best performance" was applied as reference. To express the change of climatic conditions to reach the decline of reference, we used the ecological (or climatic transfer) distance (*ecodistance* [66]); i.e., the climatic change expressed as difference of FAI values (ΔFAI) along the site transect, or between the test site and seed origin in the case of provenance tests.

(1) Machine learning-aided growth trend approximation using expert estimations of site potential and yield data of sessile oak (K. Czimber)

An obvious option for the modeling of expected yield in Hungary is deriving information from the Manual of Target Stands [67], which contains the estimated yield potential of recommended species for typified site conditions, built on expert estimations (Appendixs A.2 and A.3). As site classification is based on climate classes (for details see Section 3.1), a growth trend approximation may be reached by analyzing the relation between site type variables (including climate), and estimated yield. This analysis has been performed for all economically important species. Only the results for sessile oak are presented here [68].

We have chosen a machine learning-based regression analysis for the evaluation, considering every entry of the Manual, i.e., all the site variables, and the estimated growth rates. The method searches the nearest site types in the 5-dimensional site space (of five quantified site descriptors) and weighs them by distance kernels (for details, see Appendix A.4).

The modeling procedure is illustrated in Figure 8 for one site descriptor–climate. Outside of the space of typified site conditions recommended for the species, the growth rate was considered zero. For this reason, we adjusted the generated 5-dimensional surface with another distance kernel (k, purple) so that the corrected surface (green) provides zero growth outside of valid occurrences.
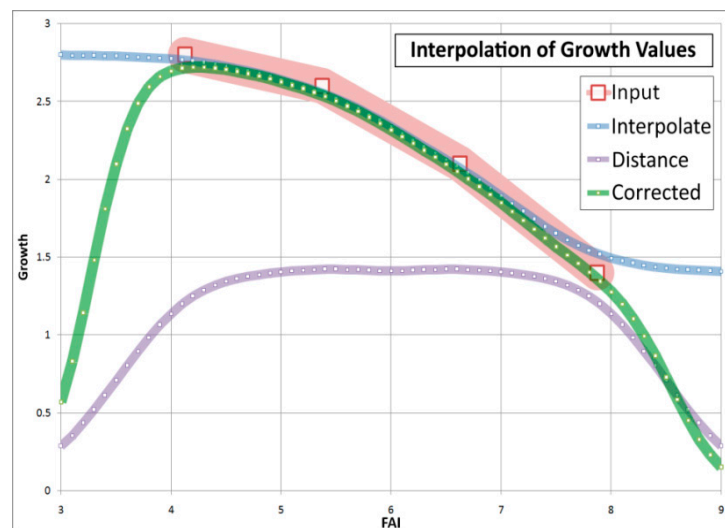

Figure 8. Interpolation of approximated growth rate of sessile oak with distance kernels, for a single site descriptor, climate, characterized by FAI values. Explanations in the text and in Appendix A.4 (Czimber, original).

The method generates a spreadsheet that comprises every potential site, and considers future climatic shifts. Each row indicates the nearest (maximum 5) tree species and their approximated growth rate (3.0: maximum) for the five forest climate classes (including the new class, grass steppe) (Table 2).

Table 2. Results of the machine learning-based analysis: Two sample rows of the spreadsheet differing only in soil texture, indicating recommended species and their estimated growth rate (first number), with number of analyzed entries (second number). Excerpt from the output of the machine learning method, validated by expert assessment. All data, except the field validations, are based on the Manual of Target Stands [67].

Hydrology	Genetic Soil Type	Soil Depth	Soil Texture	Recommended Tree Species *, Expected Yield (Decimal) and Number of Entries Climate Classes					
				Beech	Hornbeam-Oak	Sessile-Turkey OAK	Forest Steppe (Woodland)	Steppe (Extrapolated Model Data)	Steppe (Validated by Field Expertise)
rain-fed site	sandy brown forest soil	medium	Coarse sand	TU 1.6 2 PE 1.4 3 SC 2.5 2 BE 1.9 2	TU 2.3 11 RO 2.3 11 PE 1.9 7 SC 2.6 7 WH 2.0 7	TU 2.1 16 RO 2.2 15 PE 1.9 7 SC 2.2 11 WH 1.7 13	TU 1.9 14 RO 2.1 12 SC 1.9 10 WH 1.4 1 PE 1.7 4	TU 1.8 6 RO 2.0 5 SC 1.8 6 WH 1.3 7	AU 1.2 WH 1.2
rain-fed site	sandy brown forest soil	medium	sand	PE 2.0 5 TU 2.4 4 SC 2.9 4 BE 2.4 4	TU 2.3 12 PE 1.9 9 RO 2.3 11 SC 2.7 8 RE 2.9 6	TU 2.2 20 RO 2.3 18 PE 1.9 11 SC 2.3 13 WH 1.8 14	TU 2.0 17 RO 2.2 15 SC 2.0 12 WH 1.6 12 PE 1.8 6	TU 1.9 8 RO 2.1 7 SC 1.9 7 WH 1.4 8	AU 1.4 SC 1.4 WH 1.4

* Abbreviations: PE: sessile oak, TU: Turkey oak, BE: beech, RE: red oak, RO: black locust (*Robinia*), WH: White poplar, SC: Scots pine, AU: Austrian pine.

We developed the algorithm in several phases and improved it after each phase by analyzing the output. Growth data of novel, non-analog site variable combinations produced by the climatic shift require a review and validation procedure by silvicultural experts possessing extensive field experience (see last column, Table 2). A crosscut of the regression surface for one descriptor is shown in Figure 8. The simulated response function to changing climate is close to linear and does not suggest acceptable growth for sessile oak in the steppe zone. At 50% of growth rate, i.e., at value 2.0, the FAI value changes from 4.0 (maximum) to 6.7, which stands for a climatic change of +2.7 ΔFAI difference (the values are taken from the function in the respective figure (here Figure 8), similarly in the following other approaches).

(2)   Analyzing forest inventory data of sessile oak (G. Illés)

For the stochastic simulation of climate effects on growth (yield class), data of pure stands of sessile oak were selected from the National Forestry Database. We selected records of stands that were planted or regenerated before or within the climate reference period of 1961–1990. The climate of the reference period was determined from the Climate EU database in order to utilize bioclimatic variables (https://sites.ualberta.ca/~ahamann/data/climateeu.html) [69]. Forestry data were split up into sub-samples, consecutively and randomly selecting 10%, 25%, 33% and 50% of sample plots resulting in partially overlapping sample sets. We kept the whole sample (100%) for one model calibration.

A GIS framework involving bioclimatic [70] and soil variables (soil type, depth, texture [71]) was set up to characterize the main variables for growing conditions in the reference period. We developed Random Forest models for yield class predictions, and separately trained the algorithm with every single subsample using climatic and soil variables as predictors. The statistics of prediction sequences were used to assess the probability of each yield class in a spatiotemporal context. We followed the principles of Fournier [72] during the whole process. The results revealed that the severity of the impact of climate extremes strongly depends on the quality of other site factors, probably first on water holding capacity. Figure 9 shows two groups of stands, which we separated based on soil type and quality. The low site potential group contains shallow soils—lithomorphic or skeletal soils, or eroded, sandy brown forest soils with very shallow to medium-deep rooting horizons (max. 40–60 cm). Well developed, deep soils of sandy brown forest soils or clay illuviated forest soils with medium deep to very deep fertile horizons (min. 60–90 cm) were grouped into high site potential soils. The envelope curve of yield class of poorer sites drops more rapidly with warming and drying climate than that of the richer sites. This underlines the need for a flexible, site dependent forestry strategy to mitigate the effects of climatic extremes. (The stratification of dots around integer yield class values is due to the agreement of the models on predicted values. If the majority of the models predict the same yield class for a certain location, then the average of predictions will be positioned closer to the most frequently predicted class value).

Considering yield class 3.5 as 50% of maximum yield, respective FAI values for low and high potential sites are approximately 6.5 and 7.5, setting the ΔFAI difference value at +2.5 and +3.5.
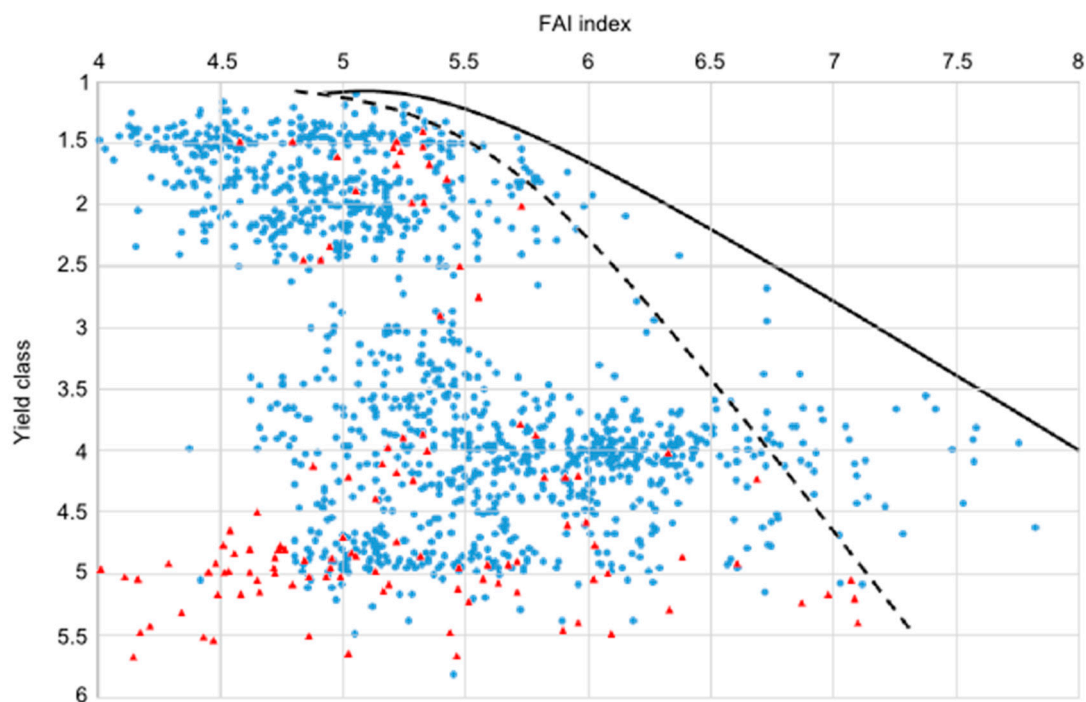
Figure 9. Envelope curves of forest inventory data indicate the role of soil conditions in limiting the presence of sessile oak under changing climate. Climate characterized by FAI values is set against yield class of stands on shallow soils (red triangles and dashed line), and on deeply rooted soils (blue circles with solid line). X-axis: Forest Aridity Index from humid (4) to dry (8) sites; Y-axis: Yield classes from the best (1) to the worst (6) class (G. Illés, original).

(3)   Assessing the impact of climatic stress on sessile oak stand density (mortality) (I. Berki)

Since the early 1980s, severe dry periods have triggered the growth decline and mass mortality of stand-forming forest tree species, including sessile oak [32]. A visible symptom of climate stress—stand density decline—is understood as tree mortality above the normal natural thinning rate. Analyzing the decrease in stand density due to climate-induced mortality requires the selection of specific stands in zonal position—on rainfed sites and with soils of high water holding capacity—without major confounding topographic or hydrologic factors changing the effect of macroclimate. It also requires a reference standard of normal density for comparison.

This principle was applied in selecting proper sample stands. We have investigated the decrease in stand density in 32 sessile oak stands along a climatic transect from the semi-humid region in Southwest Hungary to the continental semi-arid region in Northeast Hungary. We have selected stands that had no forest intervention during the last 30 years and showed no signs of abiotic or biotic damages. The 70-to-110-year-old sessile oak stands fulfil the requirements for climate-dependent, zonal conditions. The soils have fertile, deeply rooted horizons on all sites; the texture is loam.

Quadrats of 50 × 50 m were sampled to compare actual stand density with fully stocked density. To determine the latter, we have applied yield tables for 100% closure of sessile oak [73]. The tables were constructed in the 1960s, before the onset of significant climatic changes.

Relative stand density as the indicator of tree mortality due to drought events ranged from 55% to 112% in the studied quadrats along the climatic gradient. Despite a strong scatter of data, a significant density decrease towards the semiarid xeric limits of distribution was detected by regression analysis (Figure 10); the effect of climate in the variance of data was 48% ($R^2 = 0.48$; $P = 0.01$; for original data, see Appendix A.9). (The significant correlation with climatic stress does not exclude the role of antagonist organisms attacking trees and contributing to tree vitality loss and mortality.) Summer drought stress, expressed by FAI, increased from 4.5 to 7.3 along the transect. The vitality decline along the transect has

led to an average stem number loss of 40%. The volume loss is less due to relatively higher diameters in the thinned-out stands. However, it is interesting to note that the health status of the stands did not worsen with increasing summer moisture stress. The probable reason for the acceptable condition of the surviving trees was the greater availability of water and nutrients due to increased growing space and less crown interception following tree mortality [34]. None of the sampled stands has reached 50% mortality. To approximate the critical ecological distance with 50% density loss, the regression had to be extrapolated. The extrapolation reaches the threshold at 8.0 FAI value, which determines a difference of +3.5 ΔFAI (Figure 10).
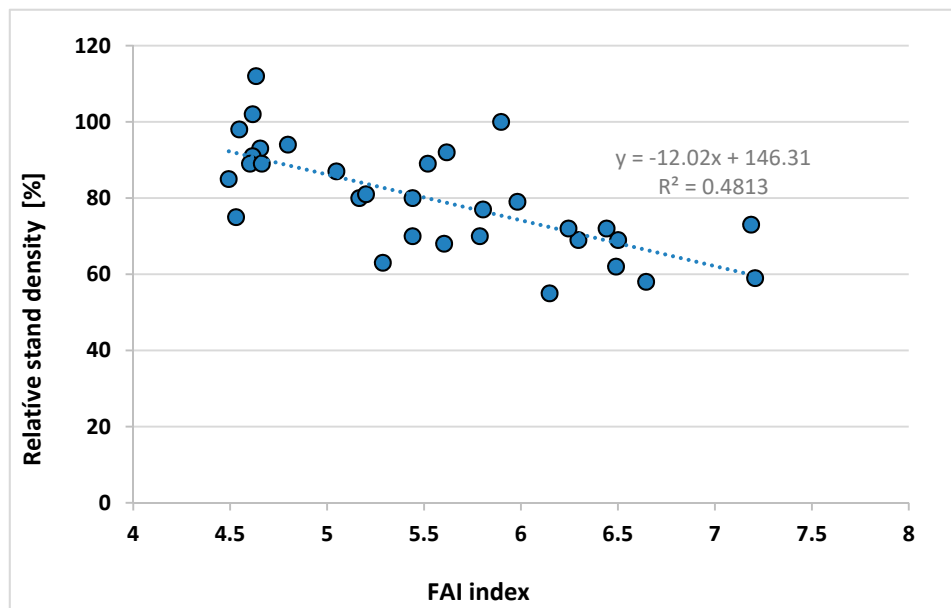

Figure 10. Regression of relative stand density of sessile oak stands vs. the FAI values of the selected locations (I. Berki, original).

(4)　　Response of identic sessile oak populations to site changes in a provenance test network (C. Mátyás)

Provenance trials or common gardens are suitable not only for exploring genetic diversity, but also for predicting the species-specific response of populations to climate (site) change, mimicked by transferring identical populations to sites with different climates [74]. The test sites provide an environmental transect, along which the phenotypic response is expressed by the reaction norm. Reaction norms are regressions describing the change of phenotype (e.g., height growth) in interface between inherited trait and environment. Publications on the results of the international provenance test network of sessile oak coordinated by A. Kremer [75,76] contain results suitable to assess the sensitivity of the species to changed climate. The mean heights per site of selected 13 populations measured at 22 locations were analyzed (Appendix A.5).

We have calculated reaction norm regressions between 10-year mean height of provenances and ecodistance [77]. The reaction norm of the pooled data shows the decline of height of identical populations with increasing climate change, i.e., with growing transfer distance to warmer/drier test sites, indicated by positive ΔFAI values (Figure 11).

The regression equations of the phenotypic response were linear; the expected second-order component was not significant. The significant genetic differences between populations have contributed to the high scatter of data, while the uneven distribution of data points is caused by the site potential differences of the experimental locations. Taking the mean height at origin (at 0 transfer distance) as reference (298.4 cm), "50% decline" (149 cm) appears at +7.7 ΔFAI difference (Figure 11). The regression was calculated with ΔFAI values. FAI values for maximum and 50% performance

cannot be determined; the populations were originating from very different climatic environments. Interpretation of the results are in the next section.
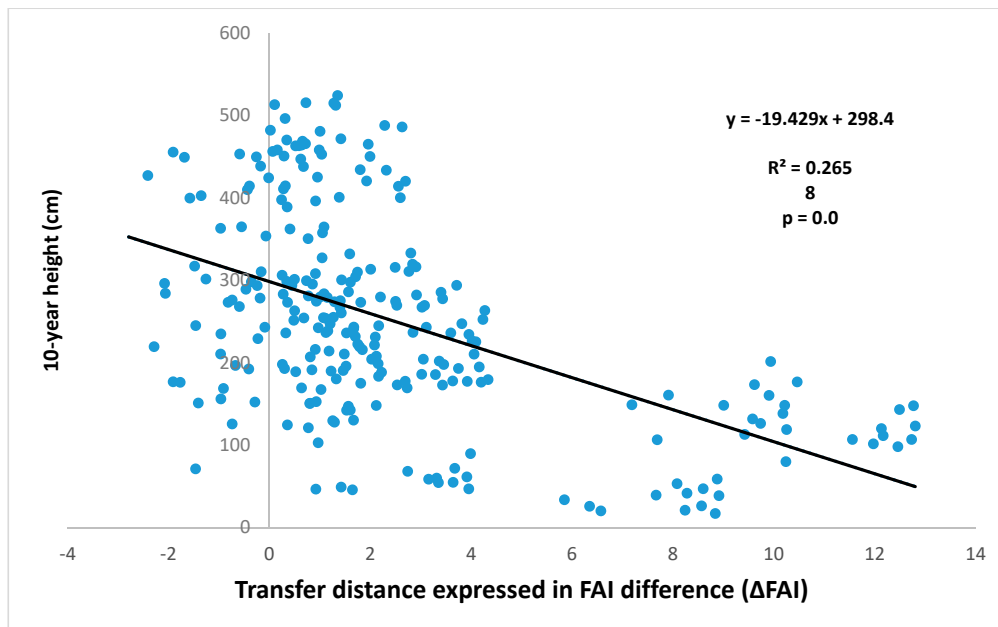

Figure 11. Regression of 10-year mean heights of 13 European populations of sessile oak vs. climatic transfer distance (ecodistance), expressed in FAI index difference (ΔFAI) (design by Kóczán-Horváth see also [77]).

4.3. Comparison of Four Assessments of Modelled Growth Decline trends for Sessile Oak (C. Mátyás)

In this section, results of independent forestry estimations are compared to climatological predictions to visualize uncertainties for projections at the xeric limits. Table 3 shows the results of the discussed four different approaches to estimate climatic change impacts from various datasets. As reference for comparison, the same estimated ecodistance between the climate at the maximum and at the threshold of 50% of performance (of growth, yield or survival) was selected. All calculations used FAI to express climate conditions of selected sites and its changes (ΔFAI). Low ecodistances for reaching the threshold signify a fast decline, while high values indicate a slower decline under future climatic change.

Table 3. Comparison of four approximations of effects of climatic change on growth and vitality of sessile oak, contrasted with recent and projected climatic changes in Hungary.

Approach (Data Used, Author)	Maximum Performance (FAI)	50% of Performance (FAI)	Ecodistance (Change) (ΔFAI)
Site descriptors vs. growth (Czimber)	4.0	6.7	2.7
Inventory data vs. low site potential (Illés)	4.0	6.5	2.5
Inventory data vs. high site potential (Illés)	4.0	7.5	3.5
Stand density vs. climate (Berki)	4.5	8.0 *	3.5 *
Provenance tests vs. climate (Mátyás)	- -	- -	7.7
Past climate shift 1961–1990 vs. 1981–2010 **			0.56
Projected change, 1981–2010 vs. 2021–2050 **			1.01
Projected change, 1981–2010 vs. 2041–2070 **			1.62

* Extrapolated data; ** Digital surface data average for Zala County, West Hungary, B. Gálos, original.

The last three rows of projected ecodistances serve as a tentative scale to contrast the magnitude of estimated ecodistances for reaching the limit of sustainable forest management; for comparison, ΔFAI values of climatic change are given for three periods. Digital surface average data calculated by B. Gálos for Zala County show that both recent climatic change and projected climate change for the near future are considerably below the "50% threshold" values, which is positive. This is,

however, only valid for stands occupying sites with favorable climate. On sites closer to the xeric limit, the indicated changes may be destructive. Contemplating further into the future (2041–2070), predictions indicate that shifts exceed the FAI limit of one climate class, which might lead to considerable stand decline.

To interpret the results in Table 3 correctly, it has to be clarified that the presented ecodistances were estimated in two different ways: Spatially and temporally. The spatial forestry approaches are the results of false time series, i.e., the spatial regressions of macroclimate vs. growth are interpreted as temporal changes. Thus, there is no "reference period" for the forestry results; the references are the maximum values for height or mortality identified in the respective analysis. The ΔFAI values for "true" temporal change (last three rows) are based on climate data; the ecodistances are differences between index values of observed data for reference periods and of observed/projected data for later/future periods, respectively.

Forestry estimates are relatively consistent, except for the result from provenance tests. Using expert estimations of typified site potential and expected yield data (K. Czimber), the decline to 50% of maximum yield was found at +2.7 ΔFAI ecodistance, while the analysis of forest inventory data (G. Illés) has brought similar results (ΔFAI: +2.5 and +3.5). This indicates that the expert assessment of growth and yield of forest stands correctly describes the actual conditions determined by forest inventory data. The similarity of the estimation based on stand density decline (mortality) is illustrative (ΔFAI: +3.5, I. Berki); it shows that the decline of growth potential along the site transect corresponds with mortality.

The provenance test results appear to be most optimistic compared to other false time assessments. However, in contrast to other estimates originating mostly from mature stands, the mean of +7.7 ΔFAI ecodistance for 50% height decline was achieved from data of juvenile, 10-year-old trees standing in experimental plots of test sites all over Europe (Appendix A.5). Considering climatic (drought) stress, small tree size transporting and transpiring smaller amounts of water probably partly offsets the disadvantage of less developed root systems compared to older trees. Although we admit that this does not provide a full explanation for ecodistances that are seemingly too high, nevertheless all forestry estimates are surprisingly high when compared to climate class differences (uniformly 1.25 FAI per class, Table 1). It has to be emphasized, however, that the ultimate purpose of FAI values is to orientate silviculturists about site potential in terms of climate classes, so as to be able to use site potential for supporting practical management decisions, e.g., about the preference of tree species for regeneration. However, FAI values do not necessarily match the concrete distribution of the indicator species. On the other hand, the provenance test results stand for the "real time" performance of populations transferred to sites that are warmer and drier than their original location, down to extreme sites in Northern Anatolia, Turkey.

Another effect compensating predicted impacts of climate factors was made visible for sessile oak: The observation of growth acceleration in young stands. I. Berki [78] measured top heights of zonal, mature (80–110 years old) sessile oak stands paired with neighboring young (25 to 35-year old) stands. Judged on the yield class of the mature trees, Berki has found significantly faster growth in young stands that have spent their whole lives under changed climatic conditions. Acceleration phenomena have been explained by raising atmospheric CO_2 concentration and N deposition, or by improving water use efficiency. Here, the explanation mentioned for the deviation of provenance test results should be adopted: At a younger age (and smaller size), extremes might be tolerated better (this opinion is not fully supported by forest protection observations, see Section 4.1.1).

The results of the sessile oak growth trend estimates bear many uncertainties; this demands the continuation of investigations and provides some likelihood for reviewing stern tree species survival predictions under climate change. The use of climatic descriptor (FAI index) values to confront estimated trends from forest datasets with climatological projections was performed likely for the first time for a model species. The result is surprising and bears hopes for unknown features of adaptation potential of forest trees that are not yet understood.

4.4. Generalizing Measured Trends of Growth and Vitality (C. Mátyás)

It is tempting to generalize the sessile oak trends for other species in the investigated region. In the absence of other reliable data on the differences in climate sensitivity of tree species in the field (outside of nurseries, greenhouses), we refer to recent provenance test data comparisons of two broadleaved and two conifer species [76]. Uniform response functions calculated for height vs. climatic transfer distance have shown significant differences in climate sensitivity between species. Sessile oak and European beech displayed low climatic response, indicating that their populations have a higher potential for resilience under future climate change in contrast to Norway spruce and Scots pine, which seem to be more sensitive to climatic change. These results are consistent with nursery measurements of A. Frank [79]. Interspecific differences may cause bias if projections of growth and productivity of forest ecosystems are generalized based on single species.

Projections contradicting the presented results may originate from climatic and site potential differences. For example, favorable precipitation and hydrology conditions allowing the increase of temperature may trigger growth acceleration to a certain limit. This might be a primary cause of the described acceleration phenomena [14] observed in Atlantic Western Europe. On the other hand, low water holding capacity of soils may exacerbate the negative effects of climatic change, as shown in the example of Figure 9.

Summing it up, the results on sessile oak are in accordance with findings of international research (e.g., [8,10,17,18,22,80]; for review: [16]) and, therefore, a cautious generalization can be made as sessile oak seems to be among the more resilient, phenotypically plastic species. The outcome confirms that future negative trends of climate change, exacerbated by the low water retention capacity of soils, lead most probably to further decline of the growth, yield, and vitality of forest species and ecosystems in regions under moisture stress. Vitality loss may lead to area decrease of both managed forests and of total forest cover. This is true first for regions where the respective species and communities are at their drought-determined ecological limits, i.e., at their xeric limits. Unexplained growth response modeling differences to climatic change and changes in antagonist pressure indicate that projections based on simplistic models may be biased manifold. Lindner et al. [81] rightly note that individual impact studies should be critically used to avoid possible shortcomings in system understanding, model accuracy, and other assumptions.

4.5. Long-Term Mortality and Carbon Balance: Grim Predictions (Z. Somogyi)

Increasingly arid climate conditions may lead to yet unexperienced drought risks for species and generally for forests by the end of the century [82]. To estimate potential carbon emissions from declining forests, we first modeled the mortality of beech from field data collected after a four-year drought period in Hungary ([33]; Figure A2; see Appendix A.6). The exponential model used for projection indicates that vitality changes of beech may become dramatic after the middle of the century.

The projection of carbon emissions from beech forests in Hungary until 2100, using the carbon accounting model CASMOFOR ([83,84], Appendix A.6), indicates, relative to the reference scenario assuming a stable climate, first a minor additional sink (considering the current age class distribution), but increasing emissions later on. Consistent with earlier findings [84–86], additional emissions (partly also due to the age class distribution) start to increase significantly in the second half of the century (Figure 12). The rate of the increase is alarming as it may amount to about one-fifth of the current total annual economy-wide emissions of the country (which amounts to 61.5 million t CO_2 equivalent; NIR data, Hungary 2018), even assuming a temperature increase of only 2.5 °C. If mortality hits forests in general at a rate similar to beech, countrywide emissions might completely offset the results of all mitigation efforts in the country and cause an extremely strong positive feedback, further enhancing climate change. The negligible differences between the harvesting scenarios (Appendix A.6) show that no meaningful mitigation might be achieved by changing harvest intensity.
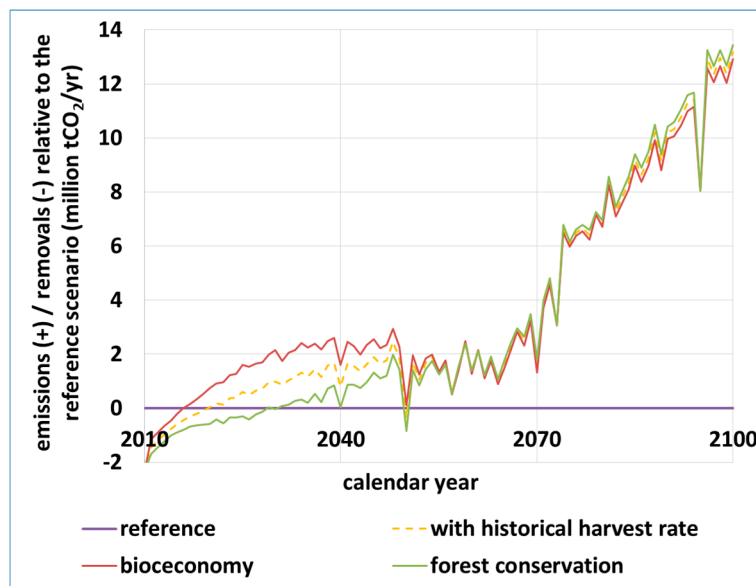
Figure 12. Balance of CO_2 emissions from declining beech forests (in million t CO_2) relative to the reference of stable climate, in three harvest rate scenarios (see Appendix A.6), assuming a 2.5 °C temperature increase by 2100 and that only a fraction of the diseased trees can be salvaged (Somogyi, original).

5. Discussion: Role of Forest Management in Mitigating the Effects of Site and Yield Potential Shifts

During the past several decades, the Earth system has changed significantly, affecting all life forms. The vulnerability of different organisms depends strongly on their inherited adaptability, life cycle length, and migration ability. In this respect, forest tree species are among the heavily threatened land organisms due to their low migration rate and extremely long life cycle [2]. The projected large-scale shifts of site potential assign new tasks to forest managers and question the validity of sustainable forestry in its original content. Sustainability ("Nachhaltigkeit"), a concept developed in forestry over three centuries ago by Carlovitz [87] with the aim of securing continuous timber harvest and—progressively refined—of maintaining ecosystem function and services, has been challenged in the past by manifold civilizational impacts, but probably the most by the expected climatic changes. Shifts of site potential advance faster at low elevations due to the "magnifying effect" of plains [25] and problems of sustainability are increasingly visible on low elevation landscapes in southeastern continental Europe, which is a special "risk zone" at the lower (xeric) limits of the closed forest belt.

The presented facts on ongoing and projected changes of growth, vitality, and mortality illustrate the urgency of reviewing the present, rigidly regulated Central European systems aimed at maintaining forest cover and its productivity, i.e., sustainability. Expected dramatic changes at the xeric limits require a more elastic approach and long-term planning in forest management.

A recent case study in Hungary [29] exemplifies the potential difficulties encountered in an economic respect. To evaluate the expected economic impacts of climate change, a pilot area with relatively favorable site conditions was selected, managed by Bakonyerdő State Forest Ltd., Veszprém, Hungary. The authors projected changes of forest yield and revenues for the mid-21st century (2050) according to the applied climate scenario A1B. Yield decline was calculated according to currently published trends, disregarding extreme events. The expected economic effect of climate change has been estimated based on revenues from actual and future harvestable yields. The added costs of stand regeneration due to ecological changes and effects of extreme drought years and other extreme events have been disregarded. Based on the rather optimistic analysis of the four most important tree species, a mean annual revenue loss of 9.4% was calculated until 2050. Thus, the forest company might expect a mean annual decline of revenues of approx. 240 billion HUF (1.1 million USD), quoted at

the current market prices at the time of the study. Beyond the ecological effects on the local forest stands, the loss raises doubts about the profitability of the company and, unsurprisingly, about the sustainability of "business as usual" forest management [29]. Unconsidered extreme events may overturn forest planning and long-term sustainability much sooner. An example of consequences of a single drought period in a forest district of the company is presented in Appendix A.8. In the peak year of salvation felling over three years, a volume three times higher than the annual allowable cut had to be removed [88]. Present projections forecast the increasing frequency and extent of similar events. Out of the numerous emerging implications, we point out the problems of nature conservation and the decline of ecological services. This brings about the rethinking of the principles and aims of forest management, traditional concepts of gene, ecosystem, or nature conservation, as well as the alternative view of concepts such as autochthony, assisted migration, etc. (Appendix A.7).

The forestry sector is highly dependent on the difficult-to-influence natural potential of biomass production and is exposed to its changes. Decline of vitality, mass mortality, insect pest outbreaks, or extensive fires cause long lasting disturbances in timber markets and endanger both proper regeneration and long-term planning of yields. Century-long forest use has also reduced the spontaneous adaptation capacity of ecosystems to changes (e.g., limited species and genetic diversity, low abundance of less productive, but drought-tolerant species, etc.). On the other hand, vast ranges of temperate forest cover have been included in planned forest management for centuries, especially in Europe. Long-term operation plans, a routine introduced to maintain sustainable management, are relevant means to introduce strategy and measures of adaptation, and mitigate climatic change impacts.

Thus, through its well-organized monitoring, planning and execution system, forest management may provide valuable assistance in amplifying spontaneous adaptation processes such as the dispersion, regeneration, competition, and migration of forest species. Large-scale inventory and monitoring systems, specialized networks and political structures (e.g., ICP Forests (International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests), EUFORGEN, Forests Europe) operating on the international level provide both the opportunity and the basis for planning and realizing interventions to develop more resilient and sustainable forest ecosystems. To decrease the vulnerability of managed forests and to improve adaptation capacity in forestry, more regional assessments and the development of guidelines and decision support systems are required [10,68,89]. Planned adaptive silviculture may become a prime factor in supporting forest ecosystems to adapt to rapid changes overtaking the natural potential of adjustment. Still, the majority of projections handle species distribution shifts typically as spontaneous phenomena (e.g., [90]), without including the large potential of forest management to support adaptive processes.

More effective alleviation of projected future impacts also requires the adjustment of mitigation and adaptation policies under the Paris Agreement and the implementation of these policies, forest management reference levels [91,92], forest carbon sink projections and greenhouse gas inventories under the UNFCCC. Results of investigations similar to the present one may support this process.

6. Conclusions

Recent and projected site condition changes and their impacts and consequences on forests at the xeric limits in Hungary have been investigated from a forestry perspective, with the following conclusions.

(1) Projections of expected changes of main abiotic site factors (climate, hydrology, soil) indicate a general decline of site conditions. In continuation of recent, significant climatic changes, further shifts of forest climate classes are expected in the next decades. The largest shift of macroclimatic zones will take place in the lowlands where the appearance of grass steppe climate is predicted. Future climate prospects until the end of the century are critical: More than half of the years may be extreme drought years.

Regarding the hydrologic conditions of lowlands, it has been proven that many lowland forests use considerably more water than that available from precipitation due to their high evapotranspiration demand. Higher water uptake from groundwater induces not only water table drop, but also subsurface salt accumulation. The further lowering of the groundwater table will inhibit the regeneration of groundwater-dependent species (e.g., *Quercus robur* L., pedunculate oak) since the root system of young trees will be unable to reach the excess water source.

Besides salt accumulation, soils in the lowlands face increasing erosion and deflation damages due to the higher frequency of extreme events. The lowering of the groundwater table may also lead to the modification of soil development processes.

(2) Growth and health responses of forest trees follow the changes of site conditions. Using sessile oak as a model species, four independent approaches confirmed the near-linear decline of growth and vitality with increasing summer heat and dryness. The use of a climatic descriptor (FAI index) to link and compare estimated trends from forest datasets with climatological projections was performed likely for the first time.

The decisive, instigating effect of droughts has been proven both for reported abiotic damages and for pests and diseases. The increasing virulence and high mobility (immigration) of antagonists make predictions of biotic damages uncertain. Escalating tree mortality and less forest management leads to higher emissions of forests and may significantly influence the national carbon balance in the second half of the century.

Comparing independent sessile oak growth projections to each other and with climate projections illustrates the uncertainties in predictions and the unknowns in the adaptive potential of trees. These ambiguities, combined with large-scale biotic effects, differences in climate sensitivity between species, and other compensating or curtailing site factors, emphasize the high necessity of field monitoring to validate model projections.

(3) The change of site conditions seriously challenges the substance of sustainability at the xeric limits. Analyses indicate that the decline of growth and vitality cause not only economic losses, but may also overturn forest planning and, ultimately, sustainability. Forest area loss and the increase of proportion of non-managed forests below the economic threshold are to be expected. The main constituents of longer-term forest management have become uncertain and "business as usual" cannot be continued at the xeric limits. Objectives of forest management must change considerably. The maintenance of forest cover and ecosystem services appear as new priorities. Management-oriented decision support systems based on regional projections are needed.

(4) The results indicate that in addition to the use of climatic data, the consideration of compensating or curtailing stand-level site factors (soil traits, hydrology, etc.) may contribute to the better projection of expected site conditions at the xeric limits and support adaptive management on the local scale.

The analysis of site and yield potential shifts at the xeric limit in Hungary may draw attention to specific issues of projected changes at a lesser known but globally represented zone of the temperate-continental forests. The presented results are expected to contribute to the development of a new positioning towards forest sustainability in drought-stricken regions. For less extreme climate zones, the analyses provide a "time acceleration laboratory"; the observed trends at the low-elevation xeric limits offers a glance into the future.

Appendix A.

Appendix A.1. Sources of Climate Information and Methods of Assessments (E. Führer–B. Gálos)

Observed changes of the climate conditions (1961–2010) were determined using the gridded monthly time series of temperature and precipitation from the Hungarian Meteorological Service [93,94] in 0.1° × 0.1° horizontal resolution. Displayed climate projections until 2100 are based on the results of 12 regional climate model simulations (spatial resolution: 0.22° × 0.22°; [95]) assuming the SRES A1B scenario of the IPCC [96,97].

Expected changes of the climate defined by the Forestry Aridity Index (FAI) were analyzed for the 30-year means of the periods 2021–2050, 2041–2070 and 2071–2100, relative to the reference period 1981–2010. In addition to the ensemble mean, the scatter of the projections, the "likely" range of the possible changes was determined using 66% of all changes projected by the various models [98].

Projections for the new RCP4.5 and RCP8.5 scenario of the IPCC [97] for Hungary show that in contrast to the robust drying tendency of summers for the A1B scenario, the sign of the changes of precipitation projected by the RCP scenarios is rather unclear. In spite of these, all climate models agree upon a significant increase of temperature (mean projection: 4 °C for A1B, 2.5 °C for RCP4.5 and 5 °C for RCP8.5) compared to the period 1971–2000 that will lead independently from scenarios to drastically arid climate conditions by the end of the century [82].

Appendix A.2. Climate Classes and the Forestry Aridity Index (FAI): An Integral Part of Site Qualification in Hungary (E. Führer)

Different from most Central European regions, the country is characterized by relatively low altitudinal variability but a high variation in moisture supply. A considerable part of the region is climatically barely suitable for maintaining productive forest cover. To integrate macroclimatic conditions into the assessment of forest site quality, forest ecologists categorized climate of sites into four forest climate classes: Beech (with the lowest temperatures and highest precipitation amount), Hornbeam–oak, Sessile oak–Turkey oak, and Forest steppe. The latter is the warmest and driest category where the macroclimate conditions are not suitable for closed forests. This class has no indicator (i.e., climate-dependent) tree species [41].

E. Führer has quantified the site classes with climatological descriptors. The Forestry Aridity Index (FAI) has been developed [40,42] based on monthly temperature and precipitation data, the easiest available from observed records and climate model outputs (for FAI values of site classes, see Table 1). Intended as proxy for summer drought conditions, the index was constructed based on ecophysiological considerations. According to observations of trees in Hungary, more than 80% of organic material is produced from May to August (main growing period; Figure A1). In this period, photosynthetic activity is the most intense and water use the highest. The critical months (July–August) are characterized by the highest temperatures that increase the evaporative demand. Water scarcity and extremely high temperatures in this period (the warmest month of the year is mostly July) enhance the drought risk and may severely impact vitality, growth and organic matter production of the trees.

Applying the ecophysiological approach shown in Figure A1, FAI is calculated from the sum of mean temperatures of the critical months (July–August) divided by the precipitation sum of the main growing period (May–August), where the hottest month (July) is weighted by 2:

$$FAI = \frac{T_{July-August}}{P_{May-June-(2 \times July)-August}} \times 100$$

FAI limits of the climate classes were determined from time series of the corresponding meteorological stations [40]. FAI characterizes the 30-year mean climate of critical periods in temperate-continental regions with similar temperature and precipitation distribution patterns as Hungary: With a main growing period between May and August, and with July or August as hottest months of the year. Figure 2 shows the extension of FAI-based climate classes in Hungary. It has to be emphasized, however, that the ultimate purpose of FAI values is to orientate silviculturists about site potential in terms of climate classes, so as to be able to use site potential for supporting practical management decisions, e.g., about the preference of tree species for regeneration. However, FAI values do not necessarily match the concrete distribution of the indicator species.
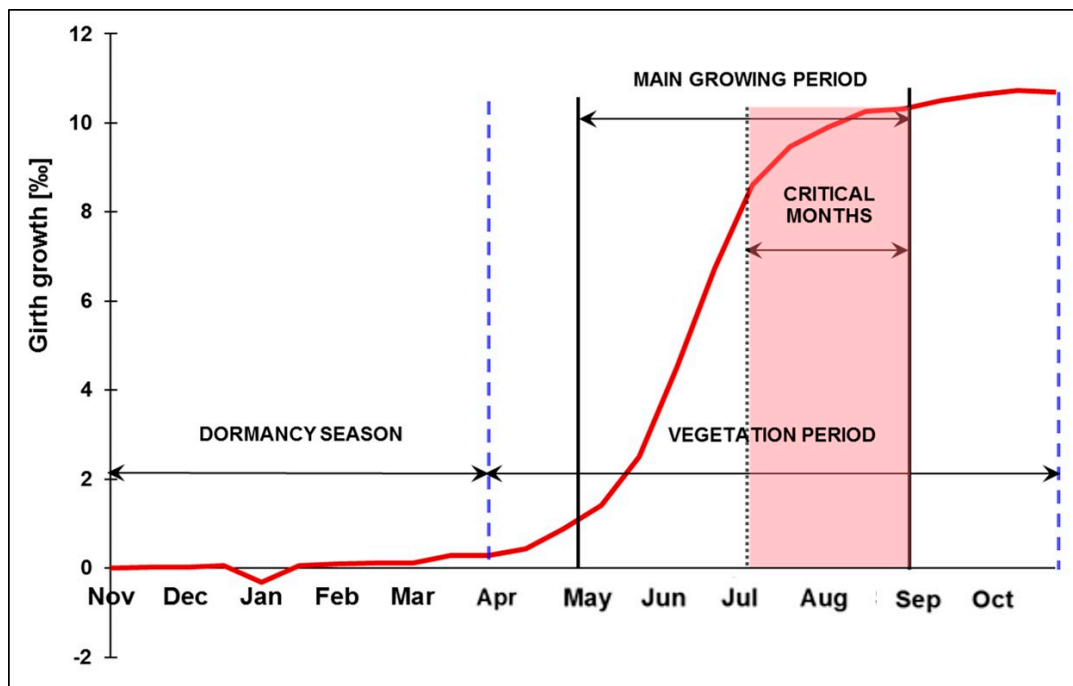

Figure A1. Mean annual cycle of girth increment of tree species in Hungary, on the example of beech (design by B. Gálos, see also [40,42]).

Appendix A.3. Typifying of Forest Sites and Their Yield Potential (A. Bidló)

Hungary went through a phase of intensive afforestation in the postwar period that doubled the percentage of forests (from 11% to 22%). In a region close to the xeric limits, with a high rate of afforestation sites of suboptimal productivity and considerable risk of silvicultural failures, this required a rather detailed site assessment scheme for planning and execution. The classification of site potential, the recommended tree species for regeneration and their expectable yield are the summary of several decades of Hungarian forestry practice and were developed by Z. Járó in the early sixties [41]. The site classification system has been improved several times and is still in use for site surveying and planning of forestations as "Manual of Target Stands" [67]. The Manual is not simply an ecological description of forest sites and of recommended, suitable tree species; the targeted species are selected on an economic, but also on forest policy basis (an example for the latter is the exclusion of invasive species). The site classification focuses on three main factors with the first being climate. Based on summer moisture supply, the country was divided into four zones, characterized by the presence of indicator tree species. With the help of the indicators, climate classes could be determined without locally available climate data, facilitating also the consideration of topographic exposure. The second factor is hydrology, accounting for excess water supply such as groundwater close to the surface. Its importance is especially high on the Great Plain (see Section 3.2). However, over 80% of the forest area in the country occupies exclusively rainfed sites,

utilizing only precipitation. The third pillar of site assessment is soil characteristics. Three aspects are taken in account: Genetic soil type, thickness of rooted soil horizon, and physical soil texture. These data, including some geographic features (altitude, topography, exposure, slope grade), are available in the National Forest Data Register for every compartment in the country. Examples for main data contained in the Register are shown in Table 2.

Appendix A.4. Developing the Model for Machine Learning-Based Regression Analysis (K. Czimber)

To calculate regressions, first, the site descriptors (climate class, hydrology, genetic soil type, soil thickness and texture) had to be quantified. Climate classes were replaced by respective FAI values (Table 1), soil depth categories with metric values, soil texture with soil water storage capacity. We kept the genetic soil type categories separate. Values 3, 2 and 1 were assigned to estimated good–medium–weak growth rates, respectively.

We used kernel density based regression for growth calculation [99,100]. The method searches the nearest stand types in the 5-dimensional site space (5 quantified site descriptors) and weighs them by distance kernels (w):

$$f_c(T) = \sum_{i=1}^{p} \sum_{t=1}^{5} n_{ci} e^{q_t(T_t - J_{cit})}, \ w_c(T) = \sum_{i=1}^{p} \sum_{t=1}^{5} e^{q_t(T_t - J_{cit})}, \ k_c(T) = \frac{f_c(T)}{w_c(T)} \left(1 - e^{r f_c(T) w_c(T)^2} \right)$$

where: T: site vector; c: stand type; i,t: indices; n: growth rate; p, q, r: constants; J: Manual data.

Gauss kernel was used as the distance kernel. The selection of the nearest stands is based on normalized distances; if the distance is larger than a given threshold, the stand is excluded from weighting.

The distance kernel-based interpolation and adjustment is also able to extrapolate the growth rates for the new climate class, the grass steppe. If the extrapolation results in a value lower than a selected threshold (<1), or the normalized distance is too large, then the method does not suggest the site type for forestation.

We have used 50% of the entries of rainfed sites in the Manual for training and the rest for testing. The average difference between the reference and the calculated growth rate was +0.01 and its standard deviation was 0.35. Considering the interval of values (1; 3) and the input values (1; 2; 3), this is very acceptable.

Appendix A.5. The Experimental Material of the Oak Provenance Test (C. Mátyás)

An international provenance test network was initiated with the reproductive material of 116 European-Anatolian populations of sessile oak (*Quercus petraea*), under the coordination of A. Kremer (INRA, France) in the course of four years (1990–1993, 1996), on 23 sites across Europe. Measurements of heights were performed at different time intervals (at 2, 5, 7, 8, 11, 15 and 20 years of age); therefore, growth data were standardized for age 10. Due to the difficulties of collection and distribution of seedling material, populations unevenly represent the range of distribution of sessile oak; for understandable reasons, both the sampled populations and the test sites are concentrated in the northwestern, Atlantic part of the range. Still, the network of tests embodies the largest representative population genetic inventory of the species, and it is improbable that similar initiatives will be successful in the near future.

Climate data for the provenance's origin and test sites were obtained from the ClimateEU database (http://tinyurl.com/ClimateEU). For the calculation of reaction norms, FAI has been used to typify climates of origin and of the test sites [77]. Access to unpublished sessile oak provenance data was possible thanks to numerous organizations and people, see in detail in Saenz-Romero et al. [76]. Details of sites and provenance means are in the appendices of the same paper.

We have calculated a reaction norm regression between 10-year mean height of provenances at 22 locations, and ecodistance [77]. The reaction norm shows the decline of height growth of

identical populations with increasing climate change, i.e., with transfer to warmer test sites, indicated by positive ΔFAI values. Provenance test results show that maximum growth performance is not necessarily expressed under original site (climate) conditions (at 0 FAI value), but under somewhat cooler, more humid conditions; thus, linear regressions height vs. ΔFAI may extend to negative values (Figure 11) [77]. Similar results were obtained in other species as well (e.g., [101]).

Appendix A.6. Projecting Beech Mortality and Carbon Balance Calculations (Z. Somogyi)

Earlier simulation results already predicted that sites in Hungary appropriate for beech will disappear during the present century. To estimate future mortality rates due to warming, an exponential curve fitted on the field mortality observations by Rasztovits et al. [33] was used. An empirical relationship, this curve estimates for European beech area-based mortality caused by drought, characterized by the average of EQ_mod values over four consecutive years (EQ_mod_4, Figure A2) where EQ_mod is the modified Ellenberg index. These averages are assumed to increase from a historical value of about 54 (with zero mortality) to about 59 and 70 in two regional scenarios assuming a warming of 2.5 °C and 5 °C by 2100 relative to 1971–2000 (https://esgf-data.dkrz.de/search/esgf-dkrz/), respectively. Given that climate change advances as predicted, an increasing annual mortality can be expected in both climate change scenarios with very huge cumulative mortality. Under the 5 °C warming scenario, beech forests will completely disappear before the end of the century.
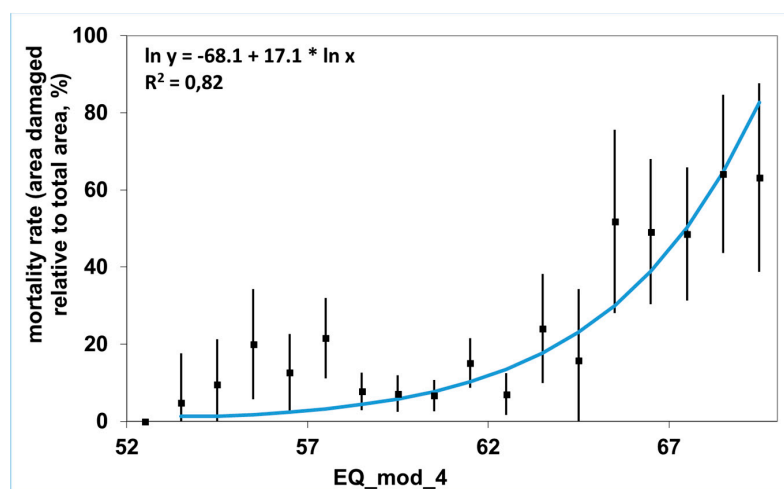

Figure A2. Relationship between drought (as measured by EQ_mod_4) and mortality by Rasztovits et al. [33], as well as the fitted function used for projections (Somogyi, original).

Considering the data above, the carbon balance of beech forests was projected until 2100 by using the carbon accounting model CASMOFOR. This MS Excel based model is able to calculate annual changes in all five carbon pools of IPCC (2006), i.e., aboveground and belowground biomass, deadwood, litter and soil, using a methodology that is fully compatible with that of the IPCC (2006) and the best data available in the country. For details of the model and its parameters, see www.scientia.hu/casmofor, Somogyi [83,84]. When running the model, we also tested how different harvesting scenarios might affect results. These scenarios were: (1) "business as usual" or reference scenario (which applied the silvicultural model included in CASMOFOR); (2) "bioeconomy" scenario (which assumed that harvest is increased by about 20% until 2030 and then kept constant, to model an increased use of harvested wood production and contribution of wood to energy production); (3) "forest conservation" scenario (with a decrease of about 20% until 2030 and then constant harvest level). The projection included the modeling of changes in mortality rates and tree growth due to the climate change scenarios studied.

Appendix A.7. Integrating New Concepts for Sustainability and Conservation into the Social and Legal Environment (C. Mátyás)

New social demands and pressures require the transition from current management paradigms in forestry. This postulate has reached a new dimension in view of projected significant changes of future climates [81,102]. From among novel management options, the ones requiring proactive intervention in structure and functioning of forest ecosystems, such as supporting gene flow and introduction of better adapted non-native species to future climatic conditions, have especially raised public controversy. Although sufficiently justified by evolutionary and other arguments (e.g., [103]), emerging initiatives encounter unexpected difficulties in practical implementation, especially in Europe.

The main impediment to applying adaptive management comes from the attitude-influenced public sector having very limited contacts with the forest supply domain. Many countries adhere to the principle of close-to-nature management as being a sufficient measure and apply a legal environment controlling forest management, e.g., the way forests are regenerated (e.g., Central Asian republics; [26]). Implementation of scientifically based adaptation and mitigation measures (e.g., [103,104]), are thus obstructed. For instance, although in most European countries the introduction of non-native, regionally non-autochthonous populations and species is in general allowed, as long as this is used for forestry purposes, certain other regulations inhibit these measures (e.g., [105]). Initiatives are supported only by the more highly-educated minority [106].

Appendix A.8. Extreme Drought Events May Overturn Forest Planning and Long-Term Sustainability (A. Jagicza)

The consequences of a single drought period 2011–2013 in the forest district Keszthely (Lake Balaton area, W. Hungary) are shown in Figure A3. In the three-year period, the average summer period (JJA) was only 1.3 °C higher than the 30-year average, but the average of precipitation (123 mm) was barely reaching 56% of the normal amount. On the shallow, lithomorphic soils of the limestone hills, Turkey oak (*Quercus cerris* L.) and Austrian pine (*Pinus nigra* Arn.) suffered heavy mortality, which changed the landscape. Compared to annual allowable cut, in the peak year of salvation felling, a three times higher volume was removed and second-order trees and shrubs took over [88]. Móricz et al. [107] recently published further details on Austrian (black) pine mortality.
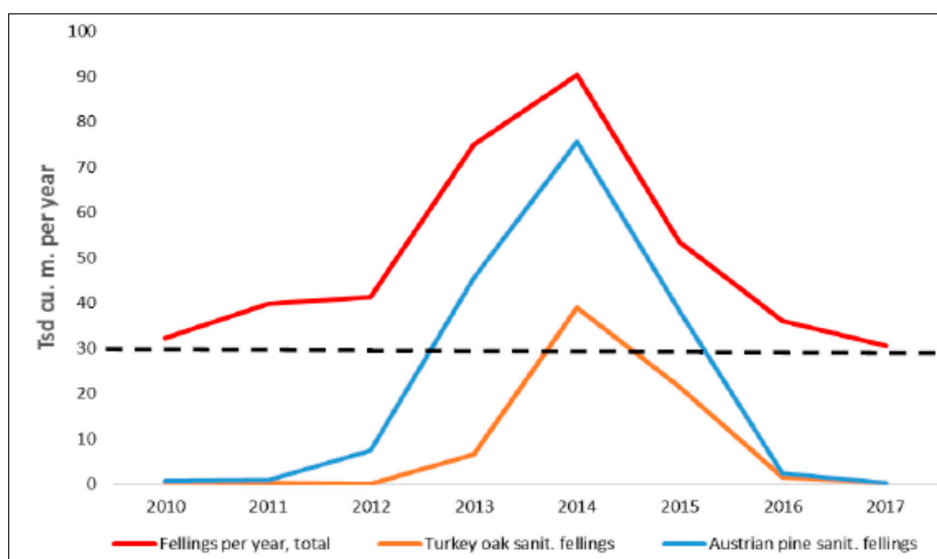

Figure A3. Total annual harvest (tsd. cu. m per year) including sanitary felling of two main tree species in the Keszthely forest district following a single drought event (2011–2013). Fellings surpassed the planned annual allowable cut (broken line; 30 tsd. cu.m per year) by three times the amount (data source: A. Jagicza, Bakonyerdő State Forest Ltd.).

Appendix A.9. Data of the Regression Stand Density vs. FAI of Locations in Figure 10 (I. Berki)

Table A1. Relative stand density of 32 zonal sessile oak stands and FAI values of their locations. FAI values were calculated from monthly means of the period 1961–2010.

Community, Compartment Nr.	Relative Stand Density %	P_{May}	P_{June}	P_{July}	P_{Aug}	T_{July}	T_{Aug}	FAI 1961–2010
Bak 4C	112	72.40	85.00	86.07	82.88	19.23	18.99	4.63
Bak 9A	102	72.23	85.24	86.41	83.22	19.23	18.95	4.62
Écs 1C	100	62.37	71.26	64.82	69.46	19.77	19.48	5.90
Felsőszterzsébet 21B	98	73.96	88.16	91.17	87.19	19.88	19.37	4.55
Daraboshegy 5D	94	71.09	85.49	85.93	82.10	19.92	19.48	4.80
Pusztamagyaród 9C	93	74.94	86.41	88.21	83.47	19.76	19.46	4.66
Almamellék 9A	92	66.08	83.86	68.75	71.00	20.35	19.92	5.62
Bodony 3C	91	75.47	86.43	75.30	70.99	17.76	17.64	4.62
Ispánk 1C	89	73.74	89.68	89.93	85.55	19.96	19.51	4.60
Hegyhátszentmárton 2F	89	73.43	88.96	88.97	84.07	20.00	19.59	4.66
Gősfa 2D	87	68.32	79.86	79.74	79.38	19.71	19.37	5.05
Aszaló 1B	79	65.45	76.32	68.31	60.09	20.44	20.06	5.98
Aggtelek 58B	75	76.93	90.55	84.08	71.98	18.61	18.33	4.53
Szemere 19A	70	68.32	83.52	84.51	66.24	21.26	20.87	5.44
Fulókércs 14B	80	68.24	83.20	80.53	64.85	20.74	20.32	5.44
Eger 83B	80	67.52	81.05	77.92	68.18	19.38	19.12	5.17
Sopron 80A	77	65.72	79.79	70.69	70.76	20.92	20.60	5.80
Balatonendréd 14B	69	57.68	73.51	62.43	71.24	20.84	20.37	6.30
Püspökszilágy 25A	69	60.02	73.03	61.69	56.38	20.53	20.14	6.50
Püspökszilágy 25B	62	59.99	72.93	61.65	56.39	20.50	20.09	6.49
Monok 17G	72	63.97	72.39	67.03	58.80	21.41	21.01	6.44
Kerecsend 1A	55	59.10	69.40	68.07	60.35	20.15	19.81	6.15
Gagyvendégi 4B	63	69.80	84.33	75.95	67.45	19.92	19.58	5.29
Herencsény 55A	68	66.30	82.10	67.14	61.31	19.41	19.14	5.60
Galgamácsa 68B	58	59.25	72.08	60.13	55.61	20.64	20.20	6.65
Füle 6B	59	54.90	67.39	53.48	60.25	21.11	20.62	7.21
Demjén 11F	72	59.24	70.13	67.02	61.41	20.46	20.11	6.25
Egervár 7E	81	67.98	78.88	78.02	78.39	20.06	19.60	5.20
Baktakék 17D	89	67.47	81.71	75.47	64.12	20.30	19.91	5.52
Biatorbágy 152E	73	56.59	65.32	53.76	54.74	20.65	20.20	7.19
Bajánsenye 5A	85	74.25	90.23	91.90	87.03	19.80	19.32	4.49
Buják 29A	70	65.41	82.12	64.37	58.75	19.54	19.24	5.79

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