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# Application of a new aridity index in Hungarian forestry practice

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**Abstract—**The ecophysiological observations and the investigations of the weather dependent vital processes of the forests have clearly proved that the water supply in the main growing–main water consumption period (from May to July) as well as in the critical months (July and August) have crucial influence on the growth, vitality, and organic matter production of the forest. Evapotranspiration rate is higher in these periods; and forest ecosystems are most sensitive to the extreme weather conditions this time. Relationship between meteorological parameters and girth-growth of trees (proportional with organic matter production) can be characterized by a simplified forestry aridity index (FAI) for Hungarian conditions: $FAI = 100\ T_{VII-VIII}/(P_{V-VII} + P_{VII-VIII})$, where $T_{VII-VIII}$ is the average temperature in July and August (˚C), $P_{V-VII}$ is the precipitation sum (mm) of the period from May to July, and $P_{VII-VIII}$ is the precipitation sum (mm) of July and August. By this index, the average weather conditions of different climate categories applied in forestry practice can be described. *FAI* values representative for different species are beech: < 4.75; hornbeam–oak: 4.75 − 6.00; sessile oak and Turkey oak: 6.00 −7.25; forest-steppe: >7.25.

*Key-words:* forest ecosystem, climate change, productivity, forestry aridity index, forestry climate categories

## *1. Introduction*

The predicted climate change is one of the greatest challenges of the 21st century. In terms of Hungary's climate, warmer and drier weather circumstances will be expected (*Láng et al*., 2007). Main reasons for the increasing aridity in air and soil would be the decrease and change of seasonal distribution of precipitation as well as the significant increase of air temperature (*Führer*, 2010; *Führer* and *Járó*, 1992; *Várallyai*, 2002, 2010; *Várallyai* and *Farkas*, 2008). All these changes have impact on the productivity of forests influencing not only the structure and species composition of forests but also, indirectly, the organic matter production (*Führer*, 1995). For these reasons, the investigation of the effect of the possible climate change on forestry practice is important not only from the point of view of change of spreading and vitality of species (*Berki et al*., 2007, 2009; *Mátyás*, 2010; *Mátyás et al*., 2009), and the increase of biotic and abiotic damages (*Csóka et al*., 2007; *Molnár* and *Lakatos*, 2007). The detailed evaluation − from practical production biology approximation −, the climate effect on the growth properties of trees and stands will also be more and more necessary.

Aridity indices frequently used in agrometeorology are summarized in *Dunkel* (2009). Some of them take into account measured precipitation and temperature characteristics; others apply derived or complicated parameters as potential evapotranspiration, radiation balance, Bowen ratio, etc. The primary aim of this paper is to describe and specify the climatic-ecophysiological relationships and to propose a simple index based on meteorological parameters measured routinely and available all over the country.

## *2. Scientific background*

### *2.1. Seasonal variation of tree growth*

Regarding the annual tree growth, it is important to distinguish between the growing period and the vegetation period. On one hand, vegetation period is the season of the potential growth. In the temperate climate zone, this period ranges between the early and late frost (*Linderholm*, 2006). On the other hand, the growing period is a term when actual growing (shoot or thickness) or other physiological processes take place such as the formation of bud structure.

In Hungary, trunk thickness and growth-pattern observations have shown that more than 80% of organic material production takes place during the months from May to July in case of various tree species (*Szőnyi*, 1962; *Halupa*, 1967; *Járó* and *Tátraaljai*, 1984-85; *Führer*, 1994, 1995; *Manninger*, 2004). This means that in Hungary the low precipitation and high summer temperatures basically influence the intensity and magnitude of organic material production and they also have an impact on the ratio of spring and autumn tree rings.

Vegetation period out of main growing period and critical months only plays an important role when weather circumstances restrict the physiological processes leading to organic matter production. Such circumstances can be observed during the late May frost period or during April droughts.

*2.2. Water supply and girth-growth of tree*

Apart from the changing temperatures, the organic material production of trees is mostly influenced by the water supply. The growth of trees is restricted by the common water shortage in Hungary during warm months with high potential evapotranspiration rate. The annual water cycle of forests and the related organic matter production is based on three phases of water supply and water consumption, and three life cycles of growth (*Führer*, 1994, 1995, 2008, 2010; *Führer* and *Járó*, 2000; *Járó*, 1989). When evaluating the precipitation relations in different life-cycles, we have to take into consideration many dominating interdependent factors, both in time and space. These all may either strengthen or balance the effect of extreme weather circumstances.

From the point of view of water cycle, the winter season between November and April is the *storage period*, while regarding the growth it is the *dormant* and *initial growth* phase (*Fig. 1*). In this phase, most amount of precipitation, somewhat decreased by crown and litter interception infiltrates into the soil, and gradually fills it up. The physiological water consumption is negligible. During winter drought in storage period when precipitation deficit exceeds the 40% compared to regular years, the effect of water deficiency on the growth is difficult to define since transpiration process starts only later.

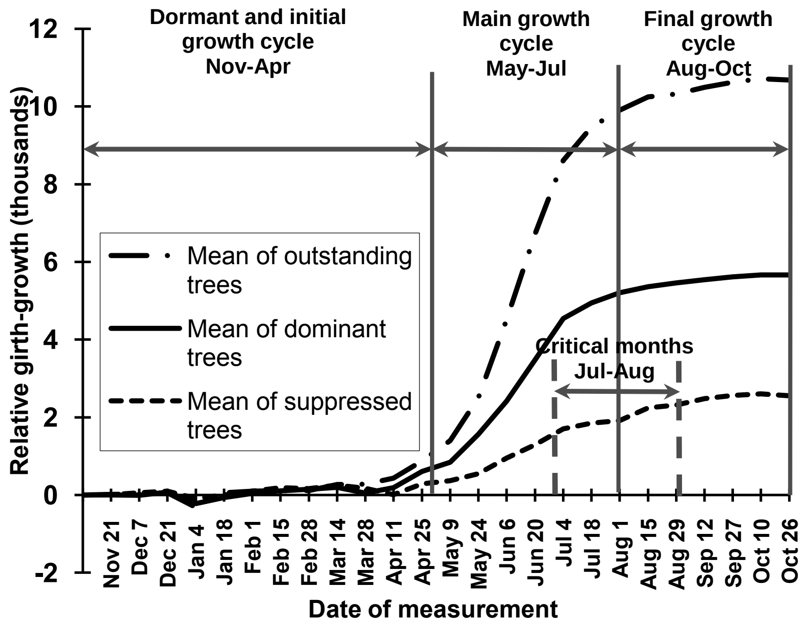


*Fig. 1.* Average annual girth-growth of a Brennbergbánya beech forest over five years in relative units (1988−1992) (*Führer*, 1994, 2010).

The period between May and July is called *main utilization phase* or *main growth cycle*. At this time, the precipitation decreased by crown and litter interception gets into only the upper layers of the soil. It is used later − together with the water left from the storage period – mostly for organic matter production and less for other physiological processes. In this cycle, 80% of the increment of the forest occurs, and this is why the extreme weather conditions, namely the effect of deficient precipitation can be more effective. This happens in case of increment decrease, i.e., in case of *partial aridity damage*.

The period between August and October is called *final growth phase*. At this time, the precipitation decreased by interception fills up only the upper layers of the soil recovering the amount of water used up during the main growth cycle; supplying the water demand of physiological processes apart from thickness growing (e.g., cropping). Low precipitation can only result in small increment decrease.

If significant deficit of precipitation in the main and final growth phase (May to October) is accompanied by extremely high temperatures in July and August (critical months), not only increment loss can be observed, but even organic matter production of trees can stop. This may happen because water is used for transpiration to keep the heat balance of trees during extreme circumstances. In extreme cases, the physiological debilitation of trees might result in decrease in trunk number of trees. This so-called total drought damage is mostly characteristic for hybrid poplars and spruces planted at marginal sites in Hungary.

## *3. Results*

### *3.1. Forestry aridity index (FAI)*

The principle of the further development of forest management shall be the ecosystem based evaluation of ecological (site) factors of forest management regions. In this system, climate has become a dynamically changing site factor. The ecophysiological observations and the investigation of the physiological processes of forests depending on weather have clearly proved that water supply in the *main growth cycle – main utilization cycle* (May to July) and in the *critical months* (July and August**)** essentially influences the growth and organic matter production of the forests. In this period, evapotranspiration is most intensive, therefore, forest reacts sensitively to the extreme weather conditions.

To describe the relationship between weather conditions and thickness growth of tree stands, we propose a simplified forestry aridity index applicable for Hungarian conditions. The index is based on meteorological parameters, namely on precipitation and temperature that have been measured extensively all over Hungary with adequate precision, so adaptation and up-scaling for the whole country can be surely done. In the formula, based on monthly temperature and precipitation averages, theoretical approximations of the aridity index for arable land proposed by *Pálfai* (2002, 2007, 2010) and the critical water supply index applied for dry forestry regions (*Führer* and *Járó*, 2000), appear together. Consequently, the *FAI* index takes into account the ratio of the average temperature of the critical months (July and August) and the precipitation sums in main growth cycle (May to July) plus the precipitation sums in the critical months (from July to August) (*Führer*, 2008, 2010):

$$FAI = 100\, T_{VII-VIII} / (P_{V-VII} + P_{VII-VIII}), \tag{1}$$

where $T_{VII-VIII}$ is the average temperature in July and August (˚C), $P_{V-VII}$ is the precipitation sum (mm) in the period from May to July, and $P_{VII-VIII}$ is the precipitation sum (mm) in July and August.

In the future, we aim to refine the *FAI* values with developing more exact relationships, i.e., we have to apply some correction factors taking into account: (i) the weather circumstances in dormant season (from November to March), (ii) especially in April, when weather conditions may influence the start of vegetation, (iii) the correct weighting in the formula for the magnitude of the role of different months in organic matter production, (iv) the exposure and slope circumstances.

With the help of the *FAI* we are able to classify the average climate of a spot or even a region from forestry viewpoint. On the other hand, we can characterize the expansion area of certain tree species, and we are also able to measure the impact of extreme weather conditions.

It clearly follows from Eq. (1) that increasing *FAI* means warmer and dryer weather in the main growth cycle and in the critical months and vice versa; decreasing *FAI* indicates cooler and wetter climate.

### *3.2. Relation between FAI and tree growth*

The adaptability of the forestry aridity index is tested by an experiment (*Führer* and *Jagodics*, 2009), where mass of organic material (dendromass) were measured above and below the ground of a beech, hornbeam-English oak, and Turkey oak ecosystem. The age of the investigated ecosystems is 50−70 years; the canopy density is between 95−100%. Stands are located on deep, brown forest soil, and the source of water is solely the precipitation infiltrating into the soil. The climate of stands differs. The total mass of organic matter of a stand at a given forest site is basically determined by the production capacity (ecological potential) of the site. Taking into account that production capacity strongly depends on the climate parameters, the mass of organic matter is less (191 tC ha$^{-1}$) where the forestry aridity index is higher (*FAI* = 5.50 as for Turkey oak) (*Fig. 2*). In contrast, in beech stand with cooler and wetter climate (*FAI* = 4.45) the mass of organic matter is high (292 tC ha$^{-1}$).

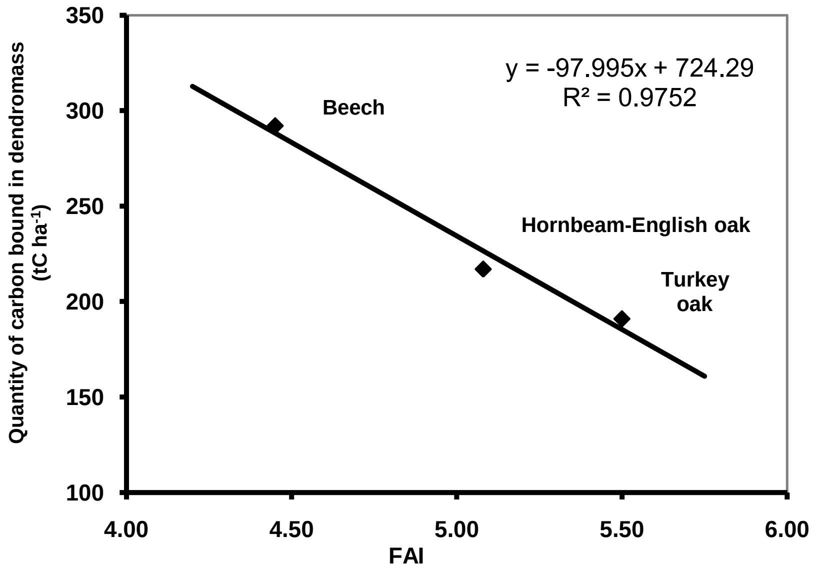


*Fig. 2.* Correlation between carbon bound in dendromass and *FAI* (*Führer* and *Jagodics,* 2009).

The applicability of *FAI* is also justified by another experiment evaluating the annual thickness (girth) growing of a hundred-year-old beech stand at Brennbergbánya research site. Increase of girth of trees was observed weekly by dendrometer bands located at stems of emergent, dominant, and suppressed trees. Basal area growth was calculated from girth-growth data. In *Fig. 3* we can see that variation of annual *FAI* values from average was always inverse in the examined 9 years (1999−2007) compared to the difference from the average basal area growth of beech. This means that warmer and drier years (represented by higher *FAI*) resulted in less of growth increment (*Fig. 4*).

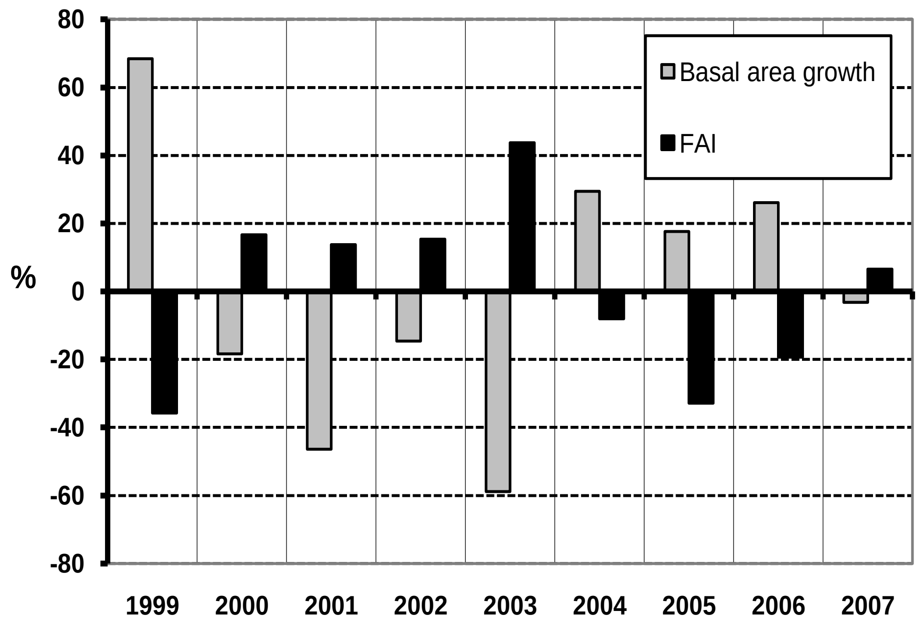


*Fig. 3*. Annual difference from average annual *FAI* values and basal area growth.

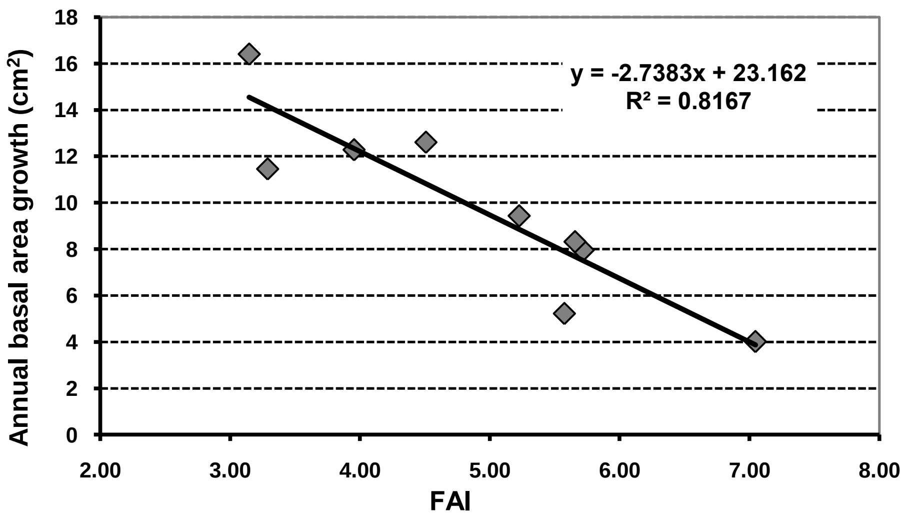


*Fig. 4.* Annual basal area growth as the function of *FAI*.

## *3.3. Calculation of FAI by means of meteorological data used at earlier forestry evaluations; characterization of forestry climate categories*

Current forestry climate classification in Hungary is based on air humidity circumstances, since water-loss of trees (transpiration) is strongly determined among others by the relative humidity.

On the basis of agrometeorological investigations, daily relative humidity at 2 p.m. in July seemed to be the most suitable index, because humidity is the function of the temperature of the warmest summer month and more or less of the precipitation needed for evaporation. From data of 62 meteorological stations, between 1901 and 1950 we can draw the following conclusion (*Führer* and *Járó*, 2000); when the mean relative air humidity in July, 2 p.m. is higher than 58%, the natural plant community is beech. Between 53−58% and 48−53%, the plant community hornbeam-oak and sessile oak / Turkey oak, respectively. When air humidity is lower than 48%, the area is originally treeless (forest-steppe climate). Beside July, low relative humidity can also be observed in August; sometimes it is even lower than in July, therefore, mean humidity of critical months (July−August) would represent better the weather of climate categories according to our newest knowledge. Unfortunately, the exact characterization by air temperature and precipitation data − according to the climate categories − of annual periods essential in the physiological processes of trees has not been realized yet. So far, in forestry practice, the climate categories have been determined according to occurrence of test species (beech, hornbeam, sessile oak, and Turkey oak) in Hungary.

However, *FAI* index takes into account the temperature and precipitation characteristics of the period when organic matter production is directly influenced by these parameters. According to this criterion, we evaluated the data of meteorological stations in the important growth periods, which were earlier taken into consideration in the characterization of forestry regions.

Using data of 94 meteorological stations between 1901 and 1950 covering the whole area of the country, on the basis of the *Járó-type* evaluation (*Führer* and *Járó*, 2000), there are 11 stations in the beech climate, 16 in the hornbeam−oak climate, 43 in the sessile oak / Turkey oak, while 24 stations of them belong to the forest-steppe climate. On the basis of the mean of 50-year long measurement record (*Table 1*), we can conclude that:

*Table 1*. Meteorological features of forestry climate categories (*Führer*, 2010)

| **Meteorological parameters** | | | **Forestry climate categories** | | | |
|---|---|---|---|---|---|---|
| | | | **Beech** (***FAI*** **<4.75**) | **Hornbeam–oak** (***FAI*****: 4.75−6.00**) | **Sessile oak–Turkey oak** (***FAI*****: 6.00−7.25**) | **Forest-steppe** (***FAI*** **>7.25**) |
| Precipitation (mm) | annual | mean | 752 | 663 | 598 | 546 |
| | | S.D. | 31.0 | 55.4 | 43.4 | 29.0 |
| | Nov−Apr | mean | 297 | 267 | 248 | 233 |
| | | S.D. | 25.9 | 36.5 | 26.1 | 18.7 |
| | May−Jul | mean | 259 | 218 | 192 | 174 |
| | | S.D. | 12.5 | 15.0 | 11.3 | 6.6 |
| | May−Oct | mean | 455 | 395 | 350 | 313 |
| | | S.D. | 22.0 | 25.5 | 22.7 | 13.0 |
| | Jul−Aug | mean | 167 | 139 | 118 | 101 |
| | | S.D. | 8.6 | 12.8 | 8.9 | 5.4 |
| Temperature (˚C) | annual | mean | 8.80 | 9.40 | 9.90 | 10.4 |
| | | S.D. | 0.87 | 0.73 | 0.61 | 0.29 |
| | Nov−Apr | mean | 2.30 | 2.70 | 3.00 | 3.40 |
| | | S.D. | 0.95 | 0.85 | 0.66 | 0.35 |
| | May−Jul | mean | 16.6 | 17.50 | 18.20 | 19.0 |
| | | S.D. | 0.84 | 0.80 | 0.66 | 0.33 |
| | May−Oct | mean | 15.2 | 16.20 | 16.80 | 17.5 |
| | | S.D. | 0.82 | 0.71 | 0.62 | 0.34 |
| | Jul−Aug | mean | 18.5 | 19.60 | 20.30 | 21.1 |
| | | S.D. | 0.79 | 0.74 | 0.67 | 0.39 |
| ***FAI*** | | **mean** | **4.36** | **5.51** | **6.56** | **7.65** |
| | | S.D. | 0.30 | 0.41 | 0.38 | 0.31 |

(a) In the *beech climate*, where the climate marker species is beech, the sum of annual average precipitation reaches the 750 mm. During winter (in the storage period, from November to April), the average precipitation is nearly 300 mm; in the main growth phase (from May to July) it is 260 mm, whilst in the critical months it is 170 mm. The annual average temperature ranges between 8.5 and 9.0 ˚C, and during the warmest, critical months it is 18.5 ˚C.

(b) In the *hornbeam−oak climate*, where the climate marker species is hornbeam, the annual average precipitation sum is higher than 660 mm, and in the water storage period it is nearly 270 mm. In the main growth phase and in the critical months, it reaches 225 and 140 mm, respectively. These values are about 10 −15% lower than in the beech climate. The annual average temperature is 9.4 ˚C, but in the critical months it is higher than 19.5 ˚C.

(c) In the *sessile oak −Turkey oak* climate, where the climate marker species depending on the acidity of the soil is either the sessile oak (acidic site) or the Turkey oak (alkaline site), the annual average precipitation is around 600 mm, and in the water storage period it hardly reaches 250 mm. In the main growth cycle and in the critical months it is 190 and 120 mm, respectively. These values are about 10% lower than in the hornbeam−oak climate. The annual average temperature can reach 10 ˚C, and in the critical months it is higher than 20 ˚C.

(d) The *forest-steppe* climate cannot be characterized by tree species since it is originally treeless area. The lowest annual average precipitation sum under 550 mm is found here. In the storage period it is 230 mm and in the main growth cycle it is 175 mm. In the critical months the value goes down to 100 mm. This climate is the warmest in Hungary, the annual average temperature is nearly 10.5 ˚C and the average temperature in the critical months is higher than 21.0 ˚C.

(e) The average data of the climate categories significantly differ from each other at the confidence level of 90%.

Average value of forestry aridity index in the beech climate is nearly 4.4. Lowest value in Hungary can be derived at the meteorological station of Kékestető ($FAI = 3.3$), Hungary's highest peak (1005 m above sea level). The average *FAI* value at the stations in the hornbeam−oak climate is 5.5. The average *FAI* value in the sessile oak−Turkey oak climate nearly reaches 6.6. At stations of the forest-steppe climate, the average *FAI* value is higher than 7.6. The highest value ($FAI = 8.3$) was calculated for Csongrád town, in the warmest and lowest area of the Great Hungarian Plain.

Although the spatial distribution of considered meteorological stations only partially agrees with the distribution of marker stands representing various climate categories, we can still draw – on the basis of calculated mean *FAI* values and its deviation − the borders of different forestry climate categories with sufficient reliability, and we can also specify the classification of meteorological stations taking into consideration in our evaluation.

This means that in the *beech climate* zone the *FAI* index is 4.75 or below. *Hornbeam−oak climate* can be characterized by *FAI* value between 4.75 and 6.00, while we have *sessile oak−Turkey oak climate* between the values of 6.00 and 7.25. The *forest-steppe climate* can be found over higher *FAI* values.

## *4. Application of forestry aridity index for future estimations*

On the basis of different climate scenarios during the summer months, the average temperature in Hungary increases, while precipitation will be less in this period (*Bartholy,* 2006). The *FAI* number allows us to model the expected impact of climate change on the basis of different scenarios, in other words, how the area of the certain climate categories will change.

In a simple way when we increase the mean temperature of critical months in calculation of *FAI* index with parallel decrease of precipitation according to the scenarios, we get the *FAI* representing the expected climate category in the future. Based on 30-year average meteorological data for 1961−1990, we have determined the distribution of the forestry climate categories. The distribution of categories in Transdanubian region will substantially be modified by a moderate temperature increase (1.0 ˚C) in summer (*Figs. 5* and *6*). Taking into account higher temperature increase (1.7 ˚C) and lower precipitation (8.2%) in summer (*Fig. 7*), 90% of the beech climate will disappear and the territory of the hornbeam-oak climate will decrease by 50%. The area ratio of the Turkey oak climate will remain the same, but it will be moved to the area of the today's hornbeam-oak climate. Expectedly, the area of the forest-steppe climate will be 4 times larger, and it will occupy the area of the current Turkey oak climate and partly in some extent that of hornbeam-oak climate.

The practical impact of this new situation (the change of areas of climate categories) is significant. It basically modifies the future forestry strategy of the country and the principle of forestry management from the point of view both of ecology aspects (species selection) and cultivation technology (regeneration, nursing sylvicultural treatment), as well as profitability.

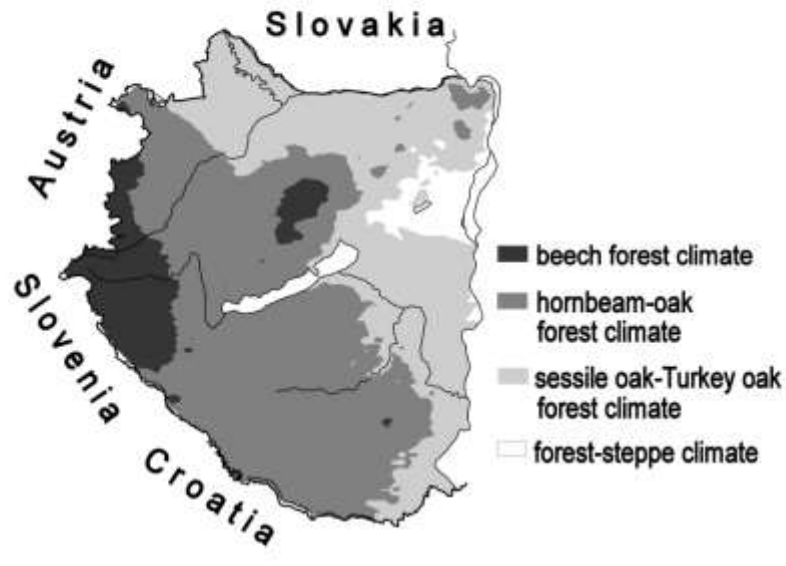


*Fig. 5.* Current distribution of climate categories in Transdanubian region according to today's weather conditions.

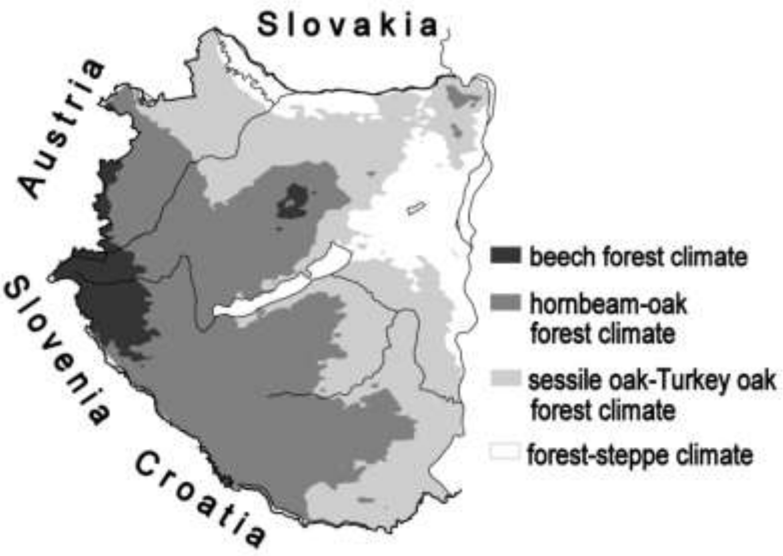


*Fig. 6.* Distribution of climate categories in Transdanubian region with a weak summer temperature (1.0 ˚C) increase scenario.

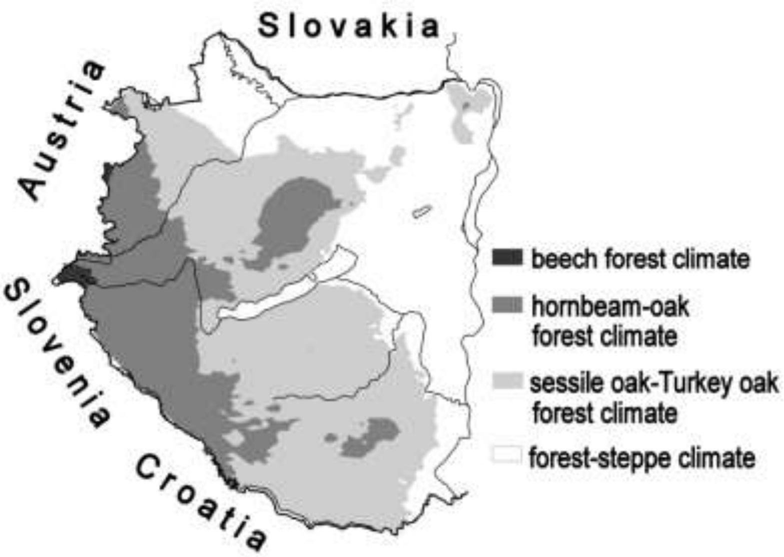


*Fig. 7.* Distribution of climate categories in Transdanubian region with a summer temperature increase of 1.7 ˚C and summer precipitation decrease of 8.2% scenario.

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