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Modelling of forest production at climate change by growth model SIBYLA

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Abstract The paper presents methodology of climate change influence to forest stand production. The tree growth model SIBYLA is utilized for this purpose. The model has been developed at Department of Forest Management and Geodesy in Zvolen. The model is sensitive to climate factors (days of vegetation season, mean temperature during vegetation season, year temperature amplitude, and total precipitation during vegetation season). The climate factors modify height and diameter growth potential, and consequently tree increment. The climatic factors make influence to tree mortality model at the same time.

The methodology has been examined by examples of forest stand models. Stand models are created as typical stand structures of spruce (lower and mountain sites), fir, pine, beech, and oak. Typical stand mixtures are used at the same time (spruce-fir, spruce-beech-fir, beech-oak, pine-oak). Tree values have been generated by data of Slovak yield tables for middle site indices, 30 year, and critical stand density. The stands have been placed into typical forest vegetation zone, and typical forest eco-regions with appropriate elevation, aspect, and slope. Climate scenarios for 90 years period (with interval 1 year) have been prepared by research of National Forest Center, and Slovak Hydrometeorology Institute. Scenario for changed climate, and reference scenario without climate change have been prepared. Growth prognosis has been produced with natural development (only natural tree reduction). Results have been compared between different climate scenarios.

Key words: *growth modelling, growth potential, climatic value influence, climate regionalisation, climate scenario*

1 Introduction

In forestry well-developed European countries transition from stand models based on mean and area characteristics to tree models appears. The models are taking into account competition relations, mortality processes and different thinning concepts and they are closely knitted with site quality and climate values. The models have more detail modelling level and they are more flexible, mainly from usage versatility as the point of view. They offer possibility for modelling even-aged single species stands for static thinning concepts and site quality assessment, but they are highly applicable for mixed uneven-aged stands with dynamic thinning concepts and site quality description in the same time. The models include wide range of output values covered not only production aspect, but ecological and economical parameters of the stands also. This character of the models designate them as tool for strategic planning and multi-criteria decision support at risk management of forest ecosystems. The large amplitude of the inputs parameters and output values determines the models as the special computer programs. Hereby the software solution is induced by model complexity and involvement. This features of the models do not allow apply them only as system of mathematical equations or table outlines, but as structural computer programs. Rich tradition, powerful modelling background and sophisticated single tree growth simulators (SILVA, MOSES, PROGNAUS, BWIN, STAND) have been evident in German speaking countries and Scandinavian countries (Pretzsch 1992, Hasenauer 1994, Sterba 1995, Nagel 1996, Pukkala and Miina 1997, Sloboda and Pfreundt 1989).

The system of mathematical equation for modelling of tree values increments (diameter, height and eventually crown parameters) is necessary component of the individual tree growth models. Many of them are based on site quality definition directly through climate and soil factors. This approach is called as **ecological site classification**. The approach has big importance for increment sensitivity to different site factors. The current stand growth models like yield tables are not able to satisfy these modelling requirements. But phase of modelling development appears as disadvantage, because of great demands for expensive empirical material and complicated modelling techniques.

Objective of the paper is presentation of ecological site classification in frame of growth model SIBYLA and its utilisation for purposes of modelling of forest production at climate change. The model SIBYLA was developed on basis of research project of 5th framework programme of European Union called: „Implementing Tree Growth Models as Forest Management Tools“. One of the project objectives has been development of algorithm and software solution of growth simulator fully adopted to Slovak production and economical conditions. First necessary assumption is system of ecological site classification for main Slovak tree species (spruce, fir, pine, beech and oak). The mentioned system has never been existing in Slovakia before. In frame of indicated, the solutions of the following tasks have been arisen:

- derivation of main climate and soil factors, so-called *site values* (s_i) with count *n*, which have significant influence on diameter and height growth,
- quantification of individual factor influence (r_i) on diameter and height increment in form of *transformation functions*:

$$r_i = f(s_i); i = 1..n; r_i \in \langle 0,1 \rangle \quad (1)$$

- derivation of the complex influence of the factors s_i on basis of aggregation their individual influence r_i to total influence *r* by *aggregation functions*,
- derivation of the production ranges for diameter and height tree growth (minimal and maximal level at ecological optimum and pessimum),
- development of the model for regionalisation of climate and soil values as reference climate model and their derivation from current field forestry,
- development of software solution for ecological site classification and implementation in growth simulator SIBYLA.

Consequently we have utilised model for modelling of stand production change at climate change. In frame of indicated, following task have been solved:

- preparation of representative forest stand as sample of ecological and species amplitude,
- preparation of climatic scenarios for forest stand sample at climate change,
- growth prognosis and interpretation of production changes comparing influence of reference climate and climate in change.

2 Material

The modelling principle and algorithms of growth simulator SILVA 2.2 (Pretzsch 1992, Kahn 1994) represents mathematical background for Slovak ecological site classification. The growth simulator SILVA 2.2 was developed at the Technical University in Munich by team of German researchers (Pretzsch, Kahn, Biber, Pommerenning, Seifert). The choice is made on basis of the fact that the model is one of the detailed model in European area and fact that members of Slovak research team from Technical University in Zvolen (Ďurský, Fabrika) co-operated at its development. Some parts of the model have been fully undertaken from model SILVA 2.2 because of missing empirical data under Slovak conditions. The solution of first three tasks mentioned in previous chapter (choice of site values, derivation of transforming and aggregation functions) has these features. Other components of the model are based on empirical material and new algorithms are derived on principle of modelling by Kahn (1994).

Data background for derivation of model SIBYLA is composed from wide range of foreign and Slovak data:

1. The net of long-term Bavarian experimental plots of the Chair of Forest Yield Sciences in Munich is primary material for derivation of the functions of climate and soil factors to tree increment. At the same time, another experimental plots have been utilised for the model: plots in Rhein-Pfalz and Lower Saxony. The model is based on 404 experimental plots with 578 measuring time points and more than 150000 trees. These data sets are composed from information of breast height diameters, tree heights, heights of crown onsets, crown diameters regarding to different site conditions, growth position and tree vitality.
2. Yield tables (Halaj et al. 1987), mainly height and diameter growth curves, were used as the basis for ecological site classification of the SIBYLA model according to methodology of Kahn (1994) and were an important source for deriving height and diameter increments. The yield tables were based on material coming from experimental plots, which were founded in 1964 –1973. Additional the data come from permanent plots established in the past for various scientific purposes. Most of the plots were under the third or fourth cycle of measurement. The total number of measurements was 2199 for spruce, 436 for fir, 724 for pine, 1239 for beech and 746 for oak. Description of experimental data is published in (Halaj and Řehák 1979).
3. The next important source for the development of the SIBYLA model was data from inventory on the diameter and height structures of Slovak forests (Halaj 1957, 1978). This data was used for determining relations between maximal stand height (or maximal diameter) and dominant stand height (or mean diameter) in order to construct a model of ecological site classification. The diameter inventory was carried out on 740 stands of spruce, 370 stands of fir, 380 stands of pine, 420 stands of beech and 370 stands of oak. The height structure was based on 85 permanent plots of spruce, 57 plots of fir, 55 plots of oak and 75 plots of beech. The broad range of experimental material guarantees sufficient statistical research of diameter and height structures and was a very valuable source of data for constructing component algorithms of SIBYLA model.
4. The regionalisation of climate characteristics has been created by usage of published climatic data around all Slovakia. The mean data have been adopted from different time periods: 1901-1950, 1901-1970, 1931-1960, 1951-1980 and 1901-1980. All data have been transformed into reference period: 1951-1980 for temperature values and 1901-1980 for precipitation values. Data transformation has been performed through to reference weather-bureaus with the best quality of long-term observations and measurements. Final version of climatic database is composed from

522 weather-bureaus for precipitation measurements a 175 weather-bureaus for temperature measurements.

3 Methods

3.1 Selection of site values

Due to rich experimental material and detailed research, nine site values were been selected:

s_1 ... content of N_2O in air (ppb)

s_2 ... content of CO_2 in air (ppm)

s_3 ... content of nutriment in soil (relative value within interval 0 - 1)

s_4 ... number of vegetation days (days with mean daily temperature bigger than 10°C)

s_5 ... annual temperature amplitude (difference between minimal and maximal temperature during year in °C)

s_6 ... mean daily temperature in vegetation season in °C

s_7 ... soil moisture (relative value within interval 0 - 1)

s_8 ... summary of rainfalls in vegetation season in mm

s_9 ... index of aridity by DE MARTONE in mm.°C^{-1} derived by:

$$s_9 = \frac{s_8}{s_6 + 10} \tag{2}$$

3.2 Derivation of transformation functions

Transformation of site values s_i to relative values of their influence r_i is performed by transformation functions (Relation 1.). The functions have been created on analytical principles and they are based on *fuzzy sets* algorithms. The principle is shown in Figure 1. Ecological amplitude

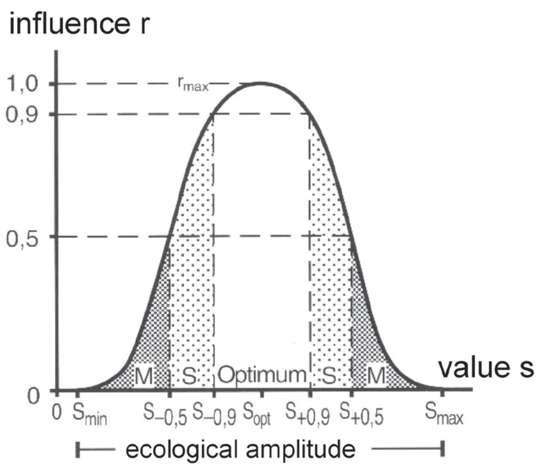

Figure 1 The principle of transformation function

of a value *s* is presented on the x-axis, it means range between minimal and maximal value for surviving of the tree species (for example range of mean temperatures in °C or total precipitation in mm). Transformed value *r* is presented on y-axis, it means range between 0 and 1. If site value *s* influences to species in range from 0,9 to 1,0 then species is under *optimal* conditions. Interval from 0,5 to 0,9 means *sub-optimal* conditions and interval from 0 to 0,5 means *minimal (pessimal)* conditions. The mentioned principle was applied for all tree species (spruce, fir, pine, beech and oak) and for all site values. The breakpoints (c_j) have been identified in each function and linear vectors have been created by:

$$r(s) = \begin{cases} (s \geq c_1) \wedge \left(s < c_1 + \frac{c_2 - c_1}{2}\right) \Rightarrow 2.\left(\frac{s - c_1}{c_2 - c_1}\right)^2 \\ \left(s \geq c_1 + \frac{c_2 - c_1}{2}\right) \wedge (s < c_2) \Rightarrow 1 - 2.\left(\frac{s - c_2}{c_2 - c_1}\right)^2 \\ (s \geq c_2) \wedge (s < c_3) \Rightarrow 1 \\ (s \geq c_3) \wedge \left(s < c_3 + \frac{c_4 - c_3}{2}\right) \Rightarrow 1 - 2.\left(\frac{s - c_3}{c_4 - c_3}\right)^2 \\ \left(s \geq c_3 + \frac{c_4 - c_3}{2}\right) \wedge (s < c_4) \Rightarrow 2.\left(\frac{s - c_4}{c_4 - c_3}\right)^2 \\ (s < c_1) \vee (s \geq c_4) \Rightarrow 0 \end{cases} \tag{3}$$

Described function is very flexible and able to shape various transformation functions with optimum in the middle, around the middle or at edge of the range $\langle s_{\min}; s_{\max} \rangle$. Flexibility is supplied by breakpoints c_1, c_2, c_3 and c_4. The breakpoints are defined by absolute values (°C, mm, ppb, ppm etc.). The values c_j are published by PRETZSCH and KAHN (1998).

3.3 Derivation of aggregation functions

Derivation of complex influence of individual site values is next step. Principle is based on aggregation functions. The function joints individual influence r_i into complex influence *r*. We have to reflect that some factors are limiting and some factors are co-operative. Limiting factors are jointed mainly by conjunction „and", it means all of them must be satisfied. Co-operative factors are mainly in relation „or", it means at least one of them must be satisfied. The most often intermediate relations somewhere between both extremes „and" versus „or" appear in reality. In accordance with mentioned, the aggregation by ZIMMERMAN and ZYSNO (1980) seems to be very flexible. The function has been applied in growth model SILVA 2.2 (KAHN 1994) and utilised for construction of Slovak ecological site classification. The algorithm is based on calculation of total **nutriment** (r_N), **thermal** (r_T) and **humidity** (r_H) effect:

$$r_N = \left(\prod_{i=1}^{3} r_i\right)^{1-\gamma_3} . \left(1 - \prod_{i=1}^{3} (1 - r_i)\right)^{\gamma_3} \tag{4}$$

$$r_T = \left(\prod_{i=4}^{6} r_i\right)^{1-\gamma_4} . \left(1-\prod_{i=4}^{6}(1-r_i)\right)^{\gamma_4} \quad (5)$$

$$r_H = \left(\prod_{i=7}^{9} r_i\right)^{1-\gamma_5} . \left(1-\prod_{i=7}^{9}(1-r_i)\right)^{\gamma_5} \quad (6)$$

The nutriment effect combines factors: content of N_2O and CO_2 in air and content of nutriments in soil. The thermal effect combines factors: number of vegetation days, temperature amplitude and mean temperature in vegetation season. The humidity effect combines factors: soil moisture, total precipitation and aridity index. The effects are aggregated into effect of asymptote reduction (r_A) and culmination age reduction (r_{tkulm}) for curve of tree height potential and reduction effect of increment of basal area (r_g):

$$r_A = (r_N.r_T.r_H)^{1-\gamma_1}.(1-(1-r_N)(1-r_T)(1-r_H))^{\gamma_1} \quad (7)$$

$$r_{tkulm} = (r_N.r_T.r_H)^{1-\gamma_2}.(1-(1-r_N)(1-r_T)(1-r_H))^{\gamma_2} \quad (8)$$

$$r_g = (r_N.r_6.r_8)^{1-\gamma}.(1-(1-r_N)(1-r_6)(1-r_8))^{\gamma} \quad (9)$$

In term of non-significant influence, only mean temperature in vegetation season (r_6) as thermal effect and total precipitation (r_8) as humidity effect is applied for calculation of r_g. The parameters γ have been derived by regression analysis from experimental data of research plots (Kahn 1994) and are published by Pretzsch and Kahn (1998).

3.4 Production ranges for derivation of tree increment

New production ranges was derived for diameter and height growth potential by methodology of Kahn (1994). Data from Slovak yield tables were utilised. Upper and lower height curves are results of the model. Curves are modelled by minimal and maximal asymptote and by minimal and maximal culmination age. The function by Korf has been adapted:

$$h_{\max} = c.A.e^{\frac{k}{(1-p).t^{p-1}}} \quad (10)$$

The function describes development of height potential (h_{max}) in dependence to age (t). The coefficients of the model (A, k, p) were derived from yield tables (Halaj et al. 1987) and coefficient c, which is describing relation between maximal and dominant height is derived from research of height structure of Slovak stands by Halaj (1978) on basis of analysis of height distribution functions. Potential of diameter increment (i_{dmax}) is second result of the model. Potential depends to tree diameter ($d_{1.3}$) by function:

$$i_{d\max} = d_{1.3}.\frac{k}{\left(\frac{-k}{\ln\left(\frac{d_{1.3}}{c.A}\right).(p-1)}\right)^{\frac{p}{p-1}}} \quad (11)$$

The coefficients of the model (A, k, p) were derived from yield tables (Halaj et al. 1987) and coefficient c, which is describing relation between maximal and mean diameter is derived from research of diameter structure of Slovak stands by (Halaj 1957) on basis of analysis of diameter distribution functions. Derived functions comparing to functions of SILVA model are presented in Figures 2. and 3.

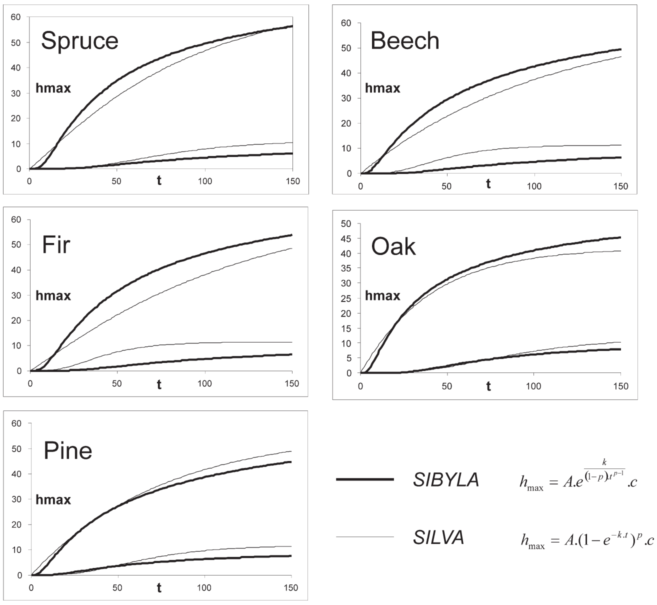

Figure 2 Development of maximal tree height for optimal and pessimal stand conditions - comparison of SIBYLA and SILVA model.

3.5 Model of Regionalisation of climate values

Ecological site classification is very flexible and very progressive for tree growth modelling. Besides great demands for construction of the model, very detailed inputs (climatic values) inhibits to wide-range implementing into field forestry. Climatic data are either inaccessible or expensive in the market. For all that, next logical step is derivation of general model for climatic values on basis of current forestry data from inventory, geography and type classification. Two tasks have arisen:

- to create detailed spatial model of climatic values by methods of regionalisation in GIS environment,
- to create general database-mathematical model for derivation of climatic values from current forestry information (forest eco-region, absolute altitude, aspect, slope),

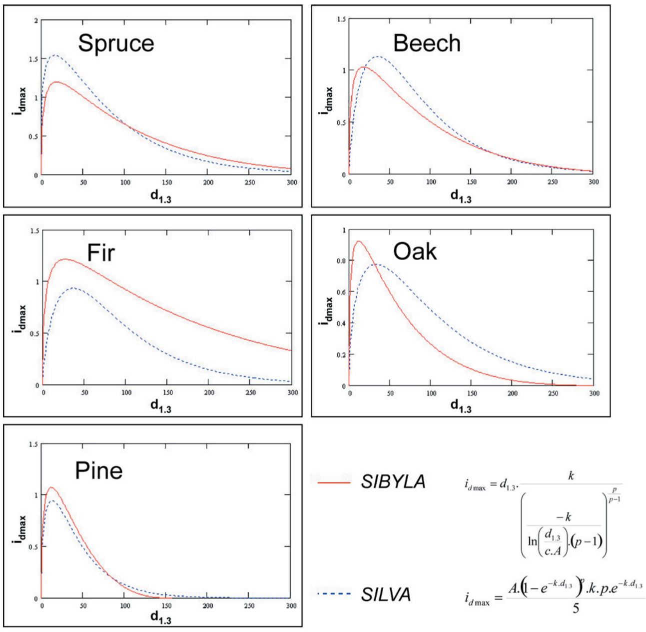

Figure 3 Development of maximal tree diameter increment at optimal stand conditions - comparison of SIBYLA and SILVA model.

At first, site values (S_i) have been calculated. Site values are necessary for ecological site classification and there are next values: number of days with mean daily temperature bigger than 10°C per year (S_4), annual temperature amplitude (S_5), mean temperature in period from April to September (S_6) and total precipitation in period from April to September (S_8). Methodology of World Meteorological Organisation (WMO) has been utilised. Regression functions have been derived. The functions describe dependence of climatic values ($\hat{s}_i$) and absolute altitude of weather-bureau (*Alt*). The functions are dedicated for regionalisation in GIS environment (Figure 4.):

$$\hat{s}_i = f(Alt) \tag{12}$$

Differences between real values (S_i) and modelled values ($\hat{s}_i$) have been calculated for each weather-bureau:

$$\Delta s_i = S_i - \hat{s}_i \tag{13}$$

Afterwards, climatic images have been derived by equation (12) in software IDRISI32. Analysis has been applied by map algebra over all pixels of digital terrain model (DTM) of Slovakia. Elevation image (GRID) has been derived from contour lines of topographic map in scale 1:50000 and by spatial interpolation. Derived image was utilised as DTM. Spatial resolution of the image is 90 by 90 m. Then layers of differences Δs have been generated by equation (13). Differences Δs have been spatial interpolated by reciprocal exponential function $1/x^2$, where „*x*" is distance to weather-bureau (data from 6 nearest stations have been considered). Finally, overlay operation has been applied as summary of climatic images and layers of differences:

$$s_i = \hat{s}_i + \Delta s_i \tag{14}$$

Corrected climatic images (Minďáš and Ďurský 2002) with spatial resolution 90 by 90 m are the results of the processing. The images are derived for all necessary climatic values.

Regionalised climatic values constitute background for ecological site classification. But they are applicable in field forestry with difficulties. Needs for GIS software and connection of the growth model with GIS is the reasons of barrier. Reasons lead to derivation of simplified model based on forest eco-region, absolute altitude, aspect and slope. The procedure for derivation has been done as follows:

1. Raster map of Slovak forest eco-regions has been created and individual terrain models for each eco-region have been extracted.
2. Lower and upper elevation rank has been extracted on basis of absolute altitude for each eco-region. Lower elevation rank is composed from pixels with altitude range $\langle \min; \min + 3 \rangle$ and upper elevation rank is composed from pixels with altitude range $\langle \max - 3; \max \rangle$.
3. Mean climatic values from regionalised climatic images have been extracted for upper and lower elevation ranks of all eco-regions in software IDRISI 32. The **table of climatic amplitude (TCA)** is the result.
4. Required climatic value is derived from TCA by forest eco-region and absolute altitude. Interpolation process is applied:

$$s' = s_{\downarrow} + \left(s_{\uparrow} - s_{\downarrow}\right)\frac{Alt - Alt_{\min}}{Alt_{\max} - Alt_{\min}} \tag{15}$$

where Alt_{min} and Alt_{max} are minimal and maximal absolute altitudes of used forest eco-region, $s_{\downarrow}$ and $s_{\uparrow}$ are site values at minimal and maximal absolute altitude and *Alt* is current absolute altitude of the stand.

5. Interpolated site values are modified. Modifiers by Kahn (1994) are applied:

$$s_4(DAYS) = s'_4 + \rho.10 \tag{16}$$

$$s_5(TAMPL) = s'_5 + \rho \tag{17}$$

$$s_6(TEMP) = s'_6 + \rho \tag{18}$$

$$s_8(PRECIP) = s'_8 + \rho.50 \tag{19}$$

where ρ is basic modifier depending to *slope* and *aspect*:

$$\rho = \sin(slope)(-\cos(aspect)) \tag{20}$$

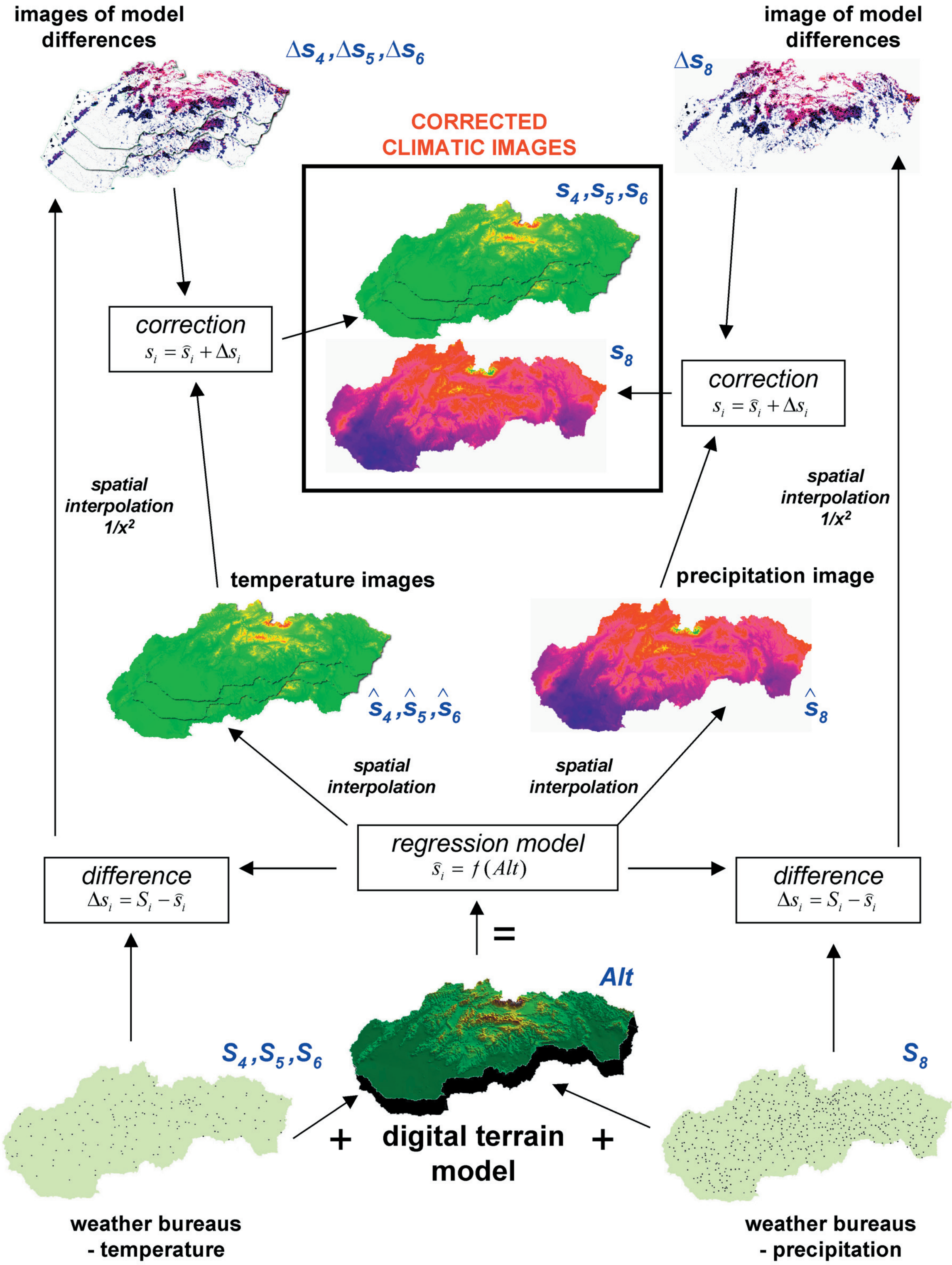

Figure 4 Regionalisation of climatic values in GIS environment.

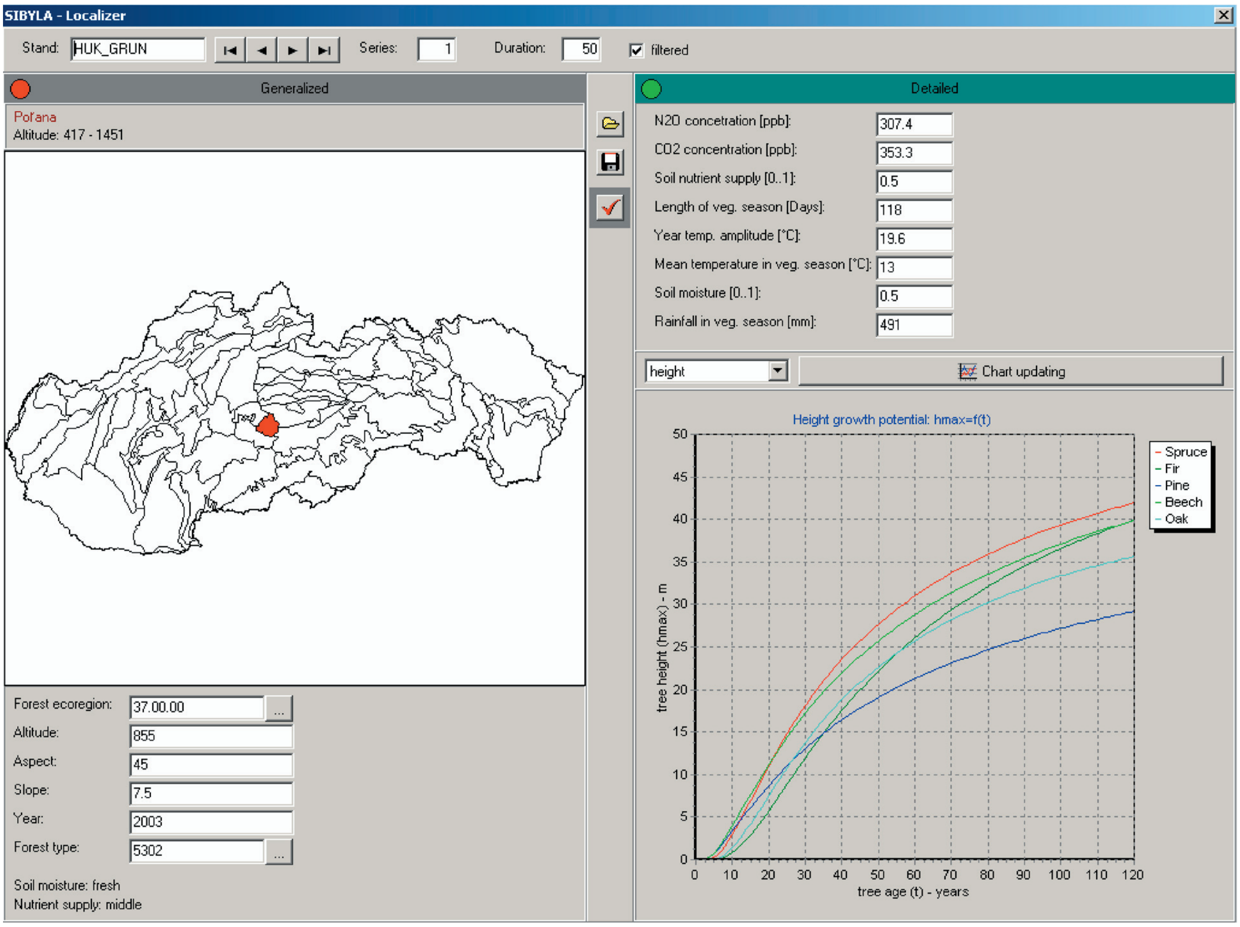

Figure 5 Dialog of the software unit SIBYLA Localizer

3.6 Software implementation

Described methods and derived algorithms for ecological site classification of tree species (spruce, fir, pine, beech and oak) have been converted into software unit called SIBYLA Localizer (Figure 5.) and have been integrated to software solution of growth simulator SIBYLA Suite. The software unit allows specify detailed or generalised input site values (climate, soil, air pollution) and performs modelling of production level of height and diameter increment on basis of input data. In case of known detailed site values (from s_1 to s_9) we can specify them directly in right site of the software window. If detailed site data is unknown we specify forest eco-region, absolute altitude, aspect, slope, year, and forest type in left part of the software window. We can specify forest eco-region and forest type directly from keyboard or select them from the list. Alternative way is selection of the forest eco-region from geographical map by mouse pointer. Then we can update chart of height potential or chart of maximal diameter increment for all modelled tree species (spruce, fir, pine, beech and oak). Chart is presented in the graphic form or tabular shape. Printout of algorithms (equations and coefficients) is possible as next variant. Mainly, the algorithmic part represents the most important benefit because of opportunity to utilise the equations for purposes of growth prognosis for example in other software. This direct publication of derived coefficients makes process of growth simulation more transparent and model is not like „*black box*", which is frequent problem of different models. Major advantage of the model is connection to structured Microsoft Access Database. The approach allows collect wide range of forest stands, eventually import them from other database tables. This solution together with connection to next units of software SIBYLA Suite makes the model as robust and sophisticated tool for growth prognosis. Therefore, the solution is able to be instrument of objective analysis of risk management of forest ecosystems under climate change. The most important fact is that solving of ecological site classification integrated into effective software tool for forest growth prognosis has not been existing in Slovakia before.

3.7 Represenative forest stands for climate change evaluation

Nine representative forest stands have been produced. The representative stands are prepared as stand models covering all important forest vegetation zones in Slovakia and their typical species compositions. Tree species spruce, fir, pine, beech and oak have been located in typical forest eco-regions and altitudes. List of representative forest models is presented in the Table 1. Mean site indices and mean yield levels by Slovak yield tables (Halaj et al. 1987) have been applied for each stand model. We used young stands 30 years old, besides the model 4 from mountain spruce with age 45 years. Critical stand density defined by Halaj (1985) was used in the stand models. Then SIBYLA forest structure generator (Fabrika 2005) has been applied for derivation of individual trees and their tree dimensions (diameter, height, crown dimensions, and co-ordinates). Following stand parameters derived from Slovak yield tables have been used for generator: growing stock per hectare, mean diameter, and mean height. Stand models have been placed on representative terrain models with required aspects and slopes. Each stand model has been reproduced 3 times, because of stochastic constitution of the stand generator.

Table 1 Forest stand models used for analysis of climate change influence to forest production

Stand model 1

forest eco-region	altitude	age	stand density	aspect	slope
37.00.00 - Poľana	900	30	0.9	south	20°

species	percentage	site index	yield level
spruce	100%	28	2.2

Stand model 2

forest eco-region	altitude	age	stand density	aspect	slope
17.01.00-Zvolenská pahorkatina	400	30	0.8	east	15°

species	percentage	site index	yield level
beech	100%	24	2.2

Stand model 3

forest eco-region	altitude	age	stand density	aspect	slope
12.00.00 - Košická kotlina	300	30	0.9	flat	0°

species	percentage	site index	yield level
oak	100%	24	2.2

Stand model 4

forest eco-region	altitude	age	stand density	aspect	slope
47.01.00 - Liptovské Tatry	1300	45	0.9	south-east	25°

species	percentage	site index	yield level
spruce	100%	20	2.2

Stand model 5

forest eco-region	altitude	age	stand density	aspect	slope
46.03.01 - Kráľová hoľa	1000	30	0.9	south-west	20°

species	percentage	site index	yield level
spruce	59%	28	2.2
beech	27%	24	2.2
fir	14%	26	2.2

Stand model 6

forest eco-region	altitude	age	stand density	aspect	slope
20.01.00 - Slanské vrchy	400	30	0.8	north-west	10°

species	percentage	site index	yield level
beech	61%	24	2.2
oak	39%	24	2.2

Stand model 7

forest eco-region	altitude	age	stand density	aspect	slope
35.00.00 - Veľká Fatra	800	30	0.8	east	15°

species	percentage	site index	yield level
beech	65%	24	2.2
fir	35%	26	2.2

Stand model 8

forest eco-region	altitude	age	stand density	aspect	slope
01.00.00 - Borská nížina	200	30	0.9	flat	0°

species	percentage	site index	yield level
pine	100%	20	2.9

Stand model 9

forest eco-region	altitude	age	stand density	aspect	slope
01.00.00 - Borská nížina	200	30	0.9	flat	0°

species	percentage	site index	yield level
pine	43%	20	2.9
oak	57%	24	2.2

3.8 Reference climate, climate change and growth prognosis

The climate scenarios at climate change have been prepared for all nine representative stand models. The climate scenarios includes development of all necessary climate and soil values mentioned in section 3.1 and have been prepared for period 90 years with annual interval. Scenarios have been prepared by National Forest Centre with co-operation of Slovak Hydro-meteorological Institute by Minďáš (2006). Example for mean daily temperature1 in vegetation season (°C) is presented in the Figure 6. Then growth prognosis for all representative stands have been executed and processed. Natural development of the stands has been chosen. It is development without thinning concept only with natural mortality processes. Prognosis has been performed for two variants: a) climate scenarios and b) reference climate. Reference climate is without climate change and it is described in the section 3.5. Then output parameters during prognosis of two variants have been calculated: mean diameter, mean height, growing stock per hectare, and total volume production. Growth prognosis has been performed three times for three generated structures of representative stands, because of stochastic principle of the model. It means 9 repeated cases have been produced. Furthermore arithmetic means and standard deviations have been calculated and used for statistical tests of differences between outputs values of climate scenario variants at the end of the prognosis period.

4 Results and discussion

Total volume production (TVP) as summary of growing stock ($m^3.ha^{-1}$) at the end of prognosis period and volumes of all dead trees during prognosis has been used as indicator of climate change. Total volume production has been compared between climate change and reference climate. Differences in absolute and relative value have been calculated and statistically tested (the Table 2.). Then tree species percentage comparing climate change and reference climate has been analysed (the Table 3.).

Spruce has natural appearance in two forest vegetation zones, nowadays: sixth and seventh. Spruce often growth in mixed stands in 6th forest vegetation zone (with beech and fir). The Model 5 represents this type of stands. Spruce also growth in pure stands in 6th and 7th forest vegetation zone. The Model 1 represents 6th zone (lower sites) and the Model 4 represents 7th zone (mountain sites). Climate change induces significant decreasing of spruce production in pure stands of 6th zone (-22%) and significant increasing of spruce production of mountain pure stands in 7th zone (+7%). Spruce production in mixed stands of 6th zone is decreased significantly (-4%) but less then production in pure stands in the same zone. Percentage of spruce is increased at the expense of fir, thanks to production change and change of natural mortality process.

Fir has natural appearance mainly in 5th forest vegetation zone as mixed stands with beech and 6th forest vegetation

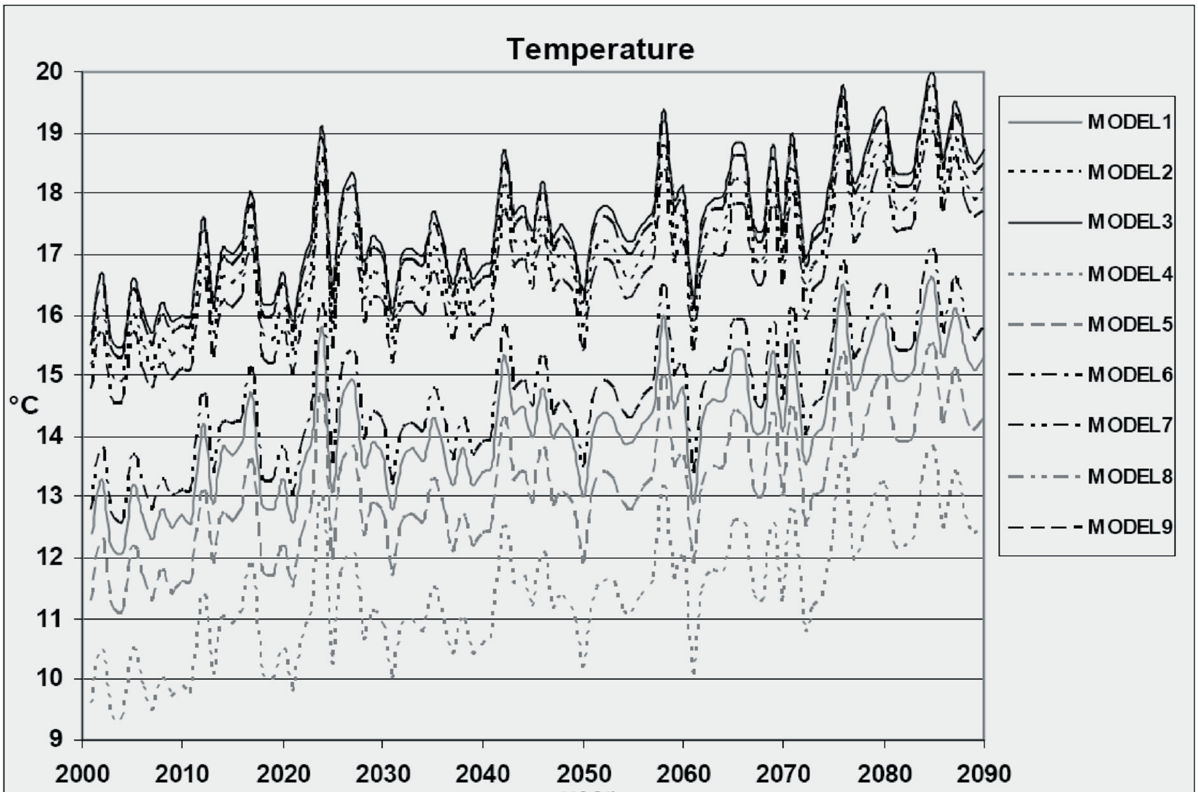

Figure 6 Scenario of mean daily temperature in vegetation season for all nine representative stand models

zone as mixed stands with spruce and beech. The Model 7 represents 5th zone and the Model 5 represents 6th zone. Production of fir is significantly reduced in both models under climate change, but more in 6th zone (-31%) than 5th zone (-13%). Percentage of fir is reduced in 6th zone but percentage in 5th zone has the same level for reference climate and climate change.

Pine has natural appearance almost in all vegetation zones (from 1st to 5th), but typical area is 1st and 2nd zone. Pine stands are often composed as pure stands (the Model 8) or mixed stands with oak (the Model 9). Production of pure stands is significantly reduced under climate change (-26%). This reduction is higher than reduction of production in mixture with oak (-14%). At the same time pine percentage is slightly increased at the expense of oak (+4%).

Beech has natural appearance in several vegetation zones and various compositions: pure stands and mixed stands. Typical are mixed stands with oak in 2nd and 3rd zone (the Model 6), pure stands in 4th zone (the Model 2, *fagetum typicum* and *pauper*), mixed stand with fir in 5th zone (the Model 7), and mixed stands with spruce and fir in 6th zone (the Model 5). Production of beech is significantly reduced in all vegetation zones under climate change except zone 6th where difference is not significant. Difference is bigger in lower zones than upper zones (2nd + 3rd zone = -20%, 4th zone = -17%, 6th zone = -8%). Percentage of beech is increased in zone 6th (the Model 5) and decreased in zone 2nd + 3rd (the Model 6). Percentage of beech in zone 5th (the Model 7) has the same level comparing climate change and reference climate.

Oak has natural appearance in lower vegetation zones (from 1st to 3rd). Typical is composition with pine (the Model 9) and pure stands (the Model 3) in 1st and 2nd zones, and mixed stands with beech in 3rd zone (the Model 6). Oak production in 1st zone in mixture with pine is significantly reduced (-19%), oak production in pure stands of 2nd zone is less significantly reduced (-10%), and oak production in 3rd zone in mixture with beech is not changed (difference -1% is not statistically significant). Oak percentage is increased in mixture with beech (the Model 6) and decreased in mixture with pine (the Model 9).

Table 2. Total volume production (TVP) at the end of the prognosis

stand model	tree species	TVP ($m^3.ha^{-1}$) climate change	TVP ($m^3.ha^{-1}$) reference climate	difference $m^3.ha^{-1}$ (%)	statistical significant
MODEL 1	spruce	1157	1488	-331 (-22%)	yes
MODEL 2	beech	942	1131	-189 (-17%)	yes
MODEL 3	oak	729	813	-84 (-10%)	yes
MODEL 4	spruce (mountain)	902	842	+60 (+7%)	yes
MODEL 5	spruce	468	490	-22 (-4%)	yes
	beech	445	470	-25 (-5%)	no
	fir	194	283	-89 (-31%)	yes
	total	1107	1243	-136 (-11%)	yes
MODEL 6	beech	693	866	-173 (-20%)	yes
	oak	185	186	-1 (-1%)	no
	total	878	1052	-174 (-17%)	yes
MODEL 7	beech	790	855	-65 (-8%)	yes
	fir	341	394	-53 (-13%)	yes
	total	1131	1249	-118 (-9%)	yes
MODEL 8	pine	712	967	-255 (-26%)	yes
MODEL 9	pine	164	190	-26 (-14%)	yes
	oak	478	592	-114 (-19%)	yes
	total	642	782	-140 (-18%)	yes

Table 3. Change of tree species percentage in mixed representative stands

stand model	tree species percentage (%) reference climate	tree species percentage (%) climate change
MODEL 5	SM 59, BK 27, JD 14 → SM 38, BK 37, JD 25	SM 59, BK 27, JD 14 → SM 41, BK 40, JD 19
MODEL 6	BK 61, DB 39 → BK 83, DB 17	BK 61, DB 39 → BK 77, DB 23
MODEL 7	BK 65, JD 35 → BK 70, JD 30	BK 65, JD 35 → BK 69, JD 31
MODEL 9	BO 43, DB 57 → BO 17, DB 83	BO 43, DB 57 → BO 22, DB 78

Note: SM – spruce, JD – fir, BO – pine, BK – beech, DB – oak

5 Conclusion

Growth prognosis by model SIBYLA comparing climate change and reference climate for all representative stands confirm following hypothesis:

1. If tree species have their amplitude of appearance in several vegetation zones, then optimum of tree production will be transferred from lower vegetation zones to upper vegetation zones during climate change.
2. Vulnerability of mixed stands is lower than pure stands, it means production of mixed stands will be less attacked than production of pure stands during climate change.
3. Mountain forests will have more optimal conditions for their production during climate change and top forest line will be shifted to higher altitude.

Presented work demonstrates that SIBYLA growth model is appropriate for climate change investigation. This experimental study has proved some hypothesis of forest research regarding to climate change. It is necessary to continue in future application of SIBYLA. Requirements of next application are following:

1. It is necessary to implement some model for natural disasters and damages (like wind-storm, snow-damages, bark miners, timber borers, etc.) in SIBYLA growth prognosis. These influences are significantly increasing during climate change and they bring higher tree mortality. Sub-model called SIBYLA Aggressor is in phase of testing nowadays and will be utilised in near future.
2. It is necessary to expand range of tested stands and use also not typical stand location. For example, we can shift current location of stands over upper limit of their appearance and investigate influence to forest production during climate change.
3. It is necessary to find out optimal forest management concepts for elimination of negative effect of climate change to tree production. This experimental study investigates only natural development of forest, but the SIBYLA model has big possibilities for application in field of forest management.

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