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*FELLOWSHIP FINAL REPORT*

# Global Tree-Ring Growth Evolution Neural Network (VS-GENN)

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REPORT INFO

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ABSTRACT

The project addresses a fundamental problem of forest reaction forecast to the climate change and increasing concentrations of greenhouse gases for the terrestrial ecosystems of the Earth.
The main target is to produce a retrospective assessment and a short-term forecast of annual tree-ring productivity (seasonal cell production) of the major conifer plant species in terrestrial forest ecosystems around Eurasia forced by climate and non-climatic factors. The analysis is based on an Interactive Information platform "Global Tree-Ring Growth Evolution Neural Network" (www.vs-genn.ru) and datasets available for the European and Asian dendroecological test-polygons. To achieve the goal of the project, we testified the Vaganov-Shaskin model and its parametrization, as a part of the developing IT system, based on direct long-term field observations for the tree-ring sites in Europe and Asia. As a result of the fellowship four papers were published in high impacted ISI journals. Moreover, a special issue of the ISI journal "Annals of Forest Science" is prepared.

## 1- Introduction

Climate appears to be changing and society needs to respond. Specifically, there is a need to know how tree growth will respond to changing climate and how to adapt the forest management. Mean Northern Hemisphere temperatures have increased over the last century and the rate of change has been higher in the last few decades (IPCC, 2008; 2013).

It is well known, that climate signals are detectable in tree-ring data from ecologically sensitive sites (Briffa et al., 1998; 2002; 2008; D'Arrigo et al., 2004; Corona et al., 2010; Guiot, Corona 2010; Hughes et al., 1999; Misson et al., 2004; Rathgeber et al., 2000; Shishov, 2000; Shishov et al., 2002; 2007; 2016; Sidorova et al., 2013; Touchan et al., 2012; 2014; Vaganov et al., 1999; 2006) and tree growth rates have been shown to vary over altitudinal and latitudinal transects. Recent tree-growth trends across northern Eurasia are unprecedented in the context of the last 2000 years (Briffa et al., 2008). The start and end dates of tree growing seasons have changed and spatial analysis of Normalized Difference Vegetation Index (NDVI) trends have revealed several regions with increasing primary productivity (Myneni et al., 1997; Zhou et al., 2001). Moreover, significant spatial correlation between trends in tree-ring growth and NDVI has been shown for recent decades at Eurasian high latitudes (Shishov et al., 2002; Burn et al., 2013).

Some complications exist in that a number of dendroclimatic studies have found an apparent change in the sensitivity of tree-ring growth response to climate forcing (Anchukaitis et al., 2006; Briffa et al., 1998; 2008; Evans et al., 2006; 2013; Jacoby and D'Arrigo, 1995; Hughes et al., 2011; Melvin, Briffa, 2008; Rathgeber et al., 2000; Sidorova et al., 2007; 2013; Shishov et al., 2007; 2016; Vaganov et al., 1999; 2006;) which may be climate related (e.g. an increase in moisture stress on temperature sensitive trees) but these identified changes have not, as yet, been satisfactorily explained. Dendroclimatic tree-growth indices are created as the average of series of annual measurements taken from individual trees which have progressed through the juvenile, adult and mature stages of growth and as such, represent a limited sample of the parameters needed to characterize forest growth at a site.

Vegetation models are generally used to predict forest growth but, because of their inherent complexity, the outputs of vegetation models are poorly constrained (Smith et al., 2001; Ni et al., 2006; Guiot et al., 2009). Tree-growth models use series of specified environmental conditions (climate) to predict the growth, development and mortality of individual trees at a site but also track soil development, nutrient and carbon exchanges, and competition providing a detailed description of forest development over time (Smith et al. 2001) and at a more detailed level can predict the annual cycle of tree ring development (Fritts et al., 1991; 1995; Vaganov et al., 2006). Forest growth is dynamic and measurements made in the modern era represent a snapshot of this dynamic growth rather than a description of the equilibrium state which, in conjunction with uncertainty in the estimation of climate in the centuries prior to the introduction of instrumental measurement, leads to uncertainty in the initialisation of vegetation and tree-growth models (Guiot et al., 2009).

Tree-ring growth and wood formation are strongly affected by climatic variations in boreal zones of the Northern Hemisphere. Often the formation of tree rings is defined as a linear function of local or regional precipitation and temperature with a set of coefficients that are temporally invariant. However, various researchers have stressed that tree-ring records are the result of multivariate, often nonlinear biological and physical processes. For example, tree-ring records may reflect nonclimatic influences, including age-dependent effects, specific local environmental conditions, fire disturbances, and insect outbreaks (Cook and Kairiukstis, 1990; Cuny et al., 2015; D'Arrigo et al., 2004; Shishov, 2000; Shishov et al., 2002; Touchan et al., 2014). The temporal nonstationarity of biological tree-ring response to climate may also be connected with local climatic variation itself (Fritts et al., 1991; 1995; Aykroyd et al., 2001; Briffa et al., 2008; Bunn et al., 2013; Cuny et al., 2015; Shishov, Il'in, 2009; Shishov, Vaganov, 2010; Vaganov et al., 2006; Touchan et al., 2012). The process-based tree-ring Vaganov-Shashkin model (VS-model) can be used to describe critical processes linking climate variables with tree-ring formation (Vaganov et al., 2006).

The VS-model is a nonlinear functional operator of daily temperature, precipitation and solar irradiance, which transforms a climatic signal to tree-ring growth rate, which is connected closely with seasonal cambial activity and cellular production of tree rings (Vaganov et al., 2006; Popkova et al., 2018).

Several publications have described the use of the model in different environmental conditions and for various conifer species. For example, the potential of the VS-model was used to simulate tree-ring growth of conifers in North America (Evans et al., 2006; 2013). A total of 190 tree-ring chronologies were adequately simulated in different parts of the United States in this first broad-scale application of the VS-model for simulating tree-ring width data used for statistical paleoclimatology. The obtained results showed that the analyzed broad-scale network of tree-ring chronologies can be used primarily as climate proxies for their further use in statistical paleoclimatic reconstructions.

Furthermore, Anchukaitis and others (2006) used the VS-model in a case study for the southeastern United States region to understand if tree-ring chronologies across the warm, mesic climate conditions could be simulated as a function of climate alone. They showed that there is a significant correlation between simulated and observed tree-ring width data (Anchukaitis et al., 2006). Moreover, application of the process-based model in the Mediterranean region demonstrates its ability to explain observed patterns of tree-growth variation in the past and to simulate tree-ring growth in extreme drought conditions (Touchan et al., 2012).

These results illustrate how nonlinear multivariate functions can provide realistic results, but the various authors noted that the same default sets of the model's parameters for different regions were used. Similarly, equally artificial results would be obtained if the process model's parameters were adjusted to obtain the best fit for each modeled tree-ring width chronology (Evans et al., 2006;; Tychkov et al., 2019). It means that the "optimal" values of model parameters could conflict with field observations of tree-ring growth due to unreal ecological interpretation of that values and natural observed process. Therefore, to parameterize the VS-model — estimation of the model's parameters to provide the best fit of initial tree-ring chronologies and a reasonable description of interaction between climate and tree-ring formation – is a real challenge for researchers.

The complexity of the described problems and labour-intensiveness of their resolution lead to the need of new methodological approaches in the analysis of spatial-distributed data sets (i.e. tree-ring time series, cell measurements and climatic data) as a whole or as a system of interrelated data. A Global Tree-Ring Growth Evolution Neural Network (VS-GENN) available on-line (http://www.vs-genn.ru/) is an example of such system where the VS-model and its modifications are considered as an important component to develop a corresponded neural network or meta-model able to estimate possible tree-ring growth (or even anatomical) response on future climate projections for terrestrial forest ecosystems in automatic mode.

Here we present examples of VS-GENN using for Eurasian forest ecosystems where tree-ring growth are strongly affected by climate (temperature, precipitation or mixed climate signal during growing season).

## 2- Materials and Methods

### 2.1 Concept of the VS-GENN

The research is based on a developing Interactive Information platform "Global Tree-Ring Growth Evolution Neural Network" (VS-GENN) and available datasets developed for the European and Asian dendroecological test-polygons.

The Global Tree-Ring Growth Evolution Neural Network is an intellectual parameterization system of different multidimensional process-based models (particularly, VS-model as a tested example) which combines three novel parallel process (Fig. 1):

- Direct parameterization based on optimization evolutional IT- algorithm;
- Proxy parameterization based on a metamodel (artificial neural network which operates as direct model but can produce simulation results much faster)
- Re-training of metamodel to reduce a discrepancy between simulations obtained by the direct and proxy parameterizations.

One of the principal project targets is to test a Global Tree-Ring Growth Evolution Neural Network (VS-GENN) as an information platform to simulate tree-ring growth of conifer species in automatic mode for the well-documented test-polygons in the Europe, Siberia and Latin America.

- The Data input block, in which observed temperature, precipitation and estimated solar irradiance are used as input data;

- The Basic block, in which an integral tree-ring

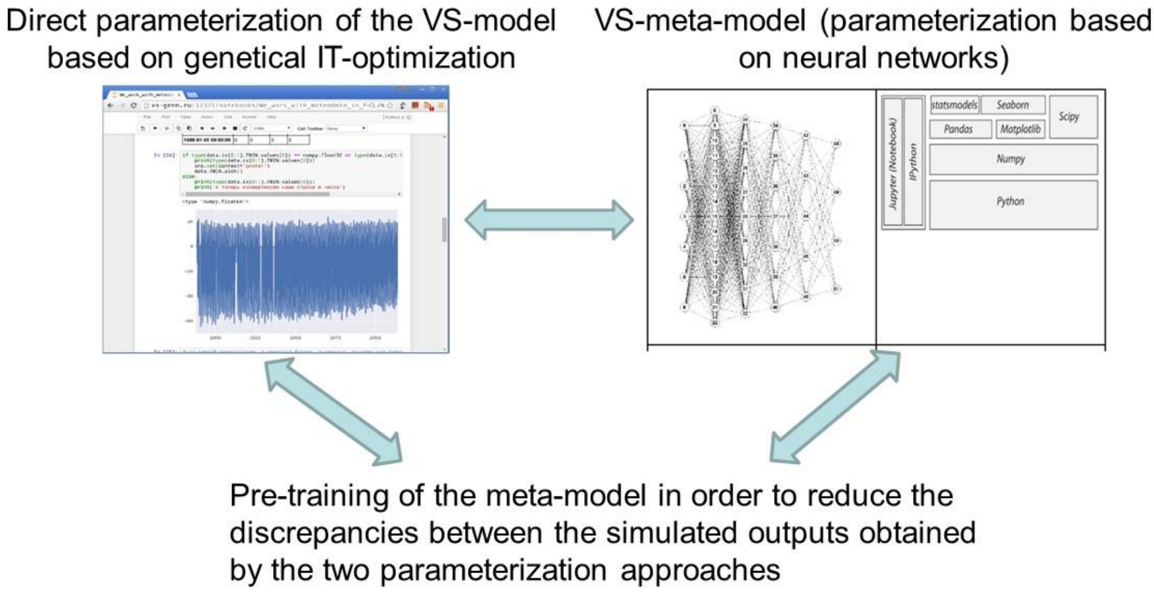


Figure 1. Principal structure of the developed VS_GENN

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Results should allow to estimate the long-term annual tree-ring productivity (cell production) of woody plants impacted by the principal climatic and non-climatic factors, and to predict tree-ring productivity in the short-term context for the research regions. VS-simulations based on direct long-term field observations for the well-documented tree-ring test-polygons in Europe, particularly in France, Asia and South America will be used as well as state-of-art techniques, including unique approaches developed by the authors.

### 2.2 Brief description of VS-model

Process-based Vaganov-Shashkin model of tree-ring growth simulations (VS-model) plays a crucial role in the research because all developed algorithmic approaches used in the VS-GENN are tested and integrated in the platform by the step-by-step VS-model application.

The basic algorithm of the model can be divided into four blocks (see Vaganov et al., 2006 for details):

$$Gr(t)=GrE(t)min\{GrT(t),GrW(t)\},$$

where $Gr(t)$ is an integral tree-ring growth rate, $GrE(t)$, $GrT(t)$, $GrW(t)$ are partial growth rates depended on daily solar irradiation $E$, temperature $T$ and soil moisture $W$, respectively;

- The Cambium block, where seasonal number of cells and cell sizes are estimated;

- The Data output block which provides seasonal cell profiles.

The model estimates a daily water balance based on accumulated precipitation into the soil (taking into account snow melting if needed), transpiration (dependent on temperature) and drainage. Daily solar irradiation from the upper atmosphere is determined by latitude, solar declination and day of the year.

Rate of cambial activity depends on the number of cells in the cambial zone and rate of their divisions, which linearly depends on the integral tree-ring growth rate in the model. Moreover, the integral tree-ring growth rate is used to estimate actual cell sizes during the enlargement stage and the phase of maturation (Vaganov et al., 2006). It was shown that the simulated integral growth rate can be transformed to tree-ring indices by specific procedures used in the Fortran code of the VS-model (Vaganov et al., 2006; Tychkov et al., 2012; Touchan et al., 2012; Shishov et al., 2016).

### 2.3 Model parameterization in semi-automatic mode

The principal goal of parameterization of the model is to obtain a best fit of the simulated tree-ring curves to the observed tree-ring chronologies by selection of certain parameter values of the model. At the same time, the selected values should not conflict with the biological principles of growth and field parameters, obtained for the different ecological conditions of analyzed forest stands. The solution of this task by direct mathematical optimization of multi-dimensional parameter space is problematic, taking into account a high probability to reach local optimum generating artificial decisions (Evans et al., 2006; Tolwinski-Ward, 2011; 2013). It is necessary to develop a parameterization tool, which allows the correct selection of parameter values in an interactive mode in complete accordance with the expert knowledge.

Two different techniques of parameterization were used in the proposal.

The VS-oscilloscope is a computer program with a graphical interface developed by the cross-platform integrated development environment - Lazarus – using the Free Pascal Compiler (Shishov et al., 2016). By definition, an oscilloscope (also known as a scope, CRO, DSO or an O-scope) is a type of electronic test instrument which allows observation and analysis of constantly varying signal voltages as a two-dimensional graph of one or more electrical potential differences using the Y-axis, plotted as a function of time on the X-axis. The oscilloscope is used to observe the change of an electrical signal over time, so that voltage and time describe a shape which is continuously graphed against a calibrated scale. Simple manipulation of amplitude, frequency, phase and other values allows simulation of an electrical signal of any complexity. Potentially any tree-ring chronology can be considered as an analogue of "electrical signal," in which case parameters of the VS-model play the role of manipulators that modify the "signal". By interactively changing the parameter values, we can observe the variation of climatic signal in a tree-ring chronology. Moreover, we can correct the selected values of parameters according to the direct observations and knowledge. Therefore, we named this new parameterization approach "VS-oscilloscope" (Shishov et al., 2016).

Such approach allows to control values of model parameters which should be not conflicted with the biological principles of tree-ring growth and field parameters (Tychkov et al., 2019).

The obtained "expert-controlled" VS-parameters can be used then as a training sets in the Global Tree-Ring Growth Evolution Neural Network.

### 2.4 Direct parametrization of the model in automatic mode.

In the research we used the R-code version of the VS-oscilloscope and specially developed robust estimation of 19 parameters of the model using the differential evolution (DE) approach (Storn, Price, 1997; Price et al., 2005) which was integrated in the VS-GENN and supercomputer facilities of the Siberian Federal University.

Optimal values of the 19th VS-parameters are considered as a set which provide significant positive Pearson correlations ($p<0.05$) on calibration and verification periods between simulated growth curve and initial tree-ring chronology obtained by the differential evolution (DE). DE is used to find optimal values for multidimensional real-valued functions or mathematical system of them. DE does not use the gradient of the problem being optimized, which means DE does not require the optimization problem to be differentiable, as is required by classic optimization methods such as gradient descent and quasi-Newton methods. Due the last definition the DE can be applied for wide class of the process-based tree-ring models.

## 3- Results and discussion

### 3.1- Key role of the model parameterization to explain tree-ring growth features

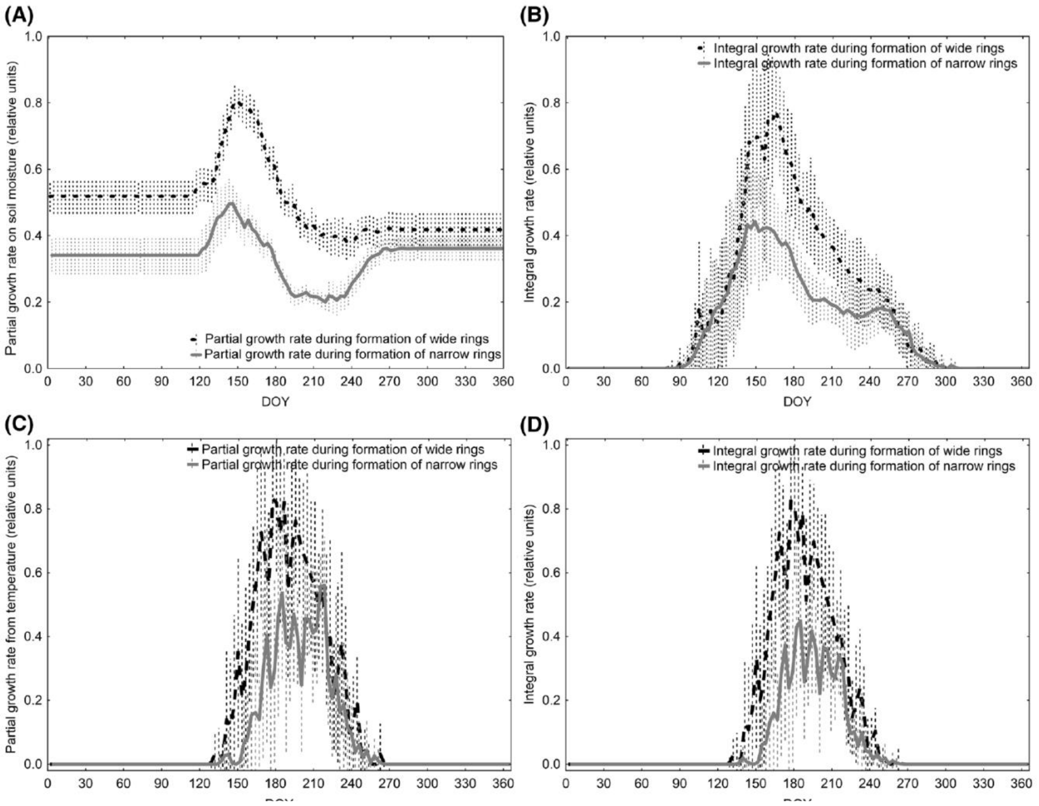


Figure 2. The mean kinetics of partial growth rate on soil moisture during seasons when the wide (black dashed curve)/narrow (grey solid curve) rings were being formed for MIN site (Pinus sylvestris) (**A**); the mean kinetics of integral growth rate during seasons when the wide (black dashed curve)/narrow (grey solid curve) rings were being formed (**B**) for MIN site; the mean kinetics of partial growth rate on temperature during seasons when the wide (black dashed curve)/narrow (grey solid curve) rings were being formed for PlatPO site (Picea obovata) (**C**); the mean kinetics of integral growth rate during seasons when the wide (black dashed

Tree-growth response to changing climate varies depending on tree species, forest type, and geographical region. Process-based models can help us better understand these outcomes.

To characterize growth sensitivity to different climate parameters, we applied the VS-Oscilloscope analytical package, as a precise visual parameterization tool of the Vaganov–Shashkin model, to two contrasting habitats: one with tree-ring growth limitation by soil moisture (in the southern part of central Siberia) and the other with temperature limitation (in the middle part of central Siberia).

We speculate that specific parameter values of the Vaganov–Shashkin model and their variability under local conditions and species are the key to understand different physiological processes in conifers.

According to the simulation results for the temperature-limited site, wider rings of *Picea obovata* can result from a longer growing season (Fig. 2 C, D).

However, for the soil moisture-limited site, the final sizes of the tree rings of *Pinus sylvestris* were not affected by the length of the growing season but were primarily defined by the intra-seasonal variations in soil moisture, even under cold conditions (Fig. 2A, B). For the two sites, we obtained a 20-day difference between the two phenological dates, in which the early date could be associated with cambial initiation and the late date with the appearance of the first enlarging cell. In the case of central Siberia, the period was half that of the southern Siberia. Such differences could be explained by both geography and species-specific responses to phenology.

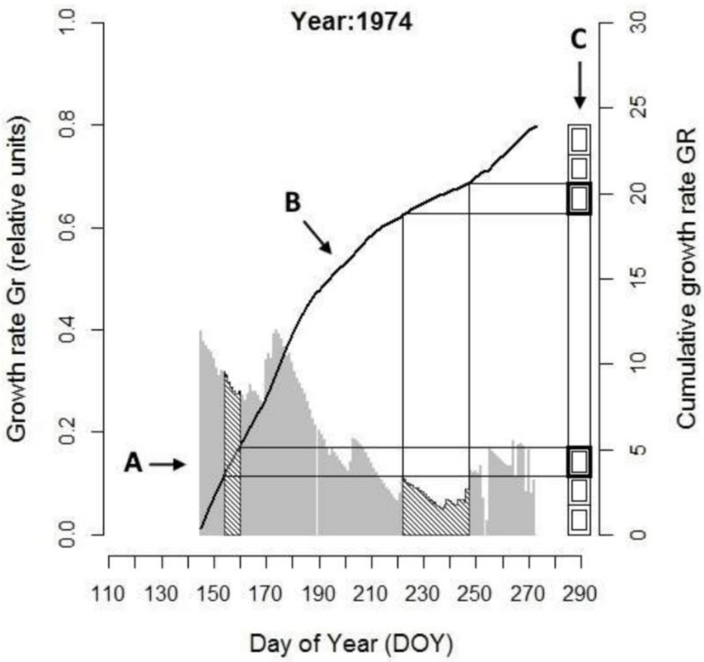


Figure 3. Daily integral growth rate Gr simulated for 1974 (A); cumulative growth rate Gr (B); actual cell profile (C). At the start of growing season the formation of bigger cell needs less time than smaller cell at the end due to different rates of cell formation.

In this study, we concentrated our attention on how the VS-parameter adjustment (parameterization) is important in the cases of two contrasting habitats. It was confirmed that the adjusted values of the model parameters depend not only on difference in local environmental conditions but also reflect the unique cambial phenology and physiology of different tree species (Tychkov et al., 2019). Moreover, the VS-model parameterization calculates year-to-year best-fitted variability of tree-ring width via calculations of the seasonal kinetics of tree-ring formation, and we have justification to consider the simulated kinetics of tree-ring seasonal growth to be an adequate representation of the actual kinetics of tree-ring seasonal growth and climate influence (Tychkov et al., 2019).

### 3.2- Timing procedure of cell production in tree rings

Main anatomical characteristics of tree ring structure, e.g. number of cells and radial cell size, are closely related to the kinetics of cell production. Therefore, timing of seasonal production is a fundamental aspect of plant development and functioning (Popkova et al., 2018). To better assess the impact of specific climatic events to the timing and dynamic of growth, a process-based modeling can be a very useful tool.

The Vaganov-Shashkin model was proved to provide reliable estimates of tree growth under strong limited conditions.

Based on the assumption that climate conditions are determining cell differentiation mostly in the cambial zone, the model computes daily growth rate and converts it into the rate of cell production. In this work, we present a two-steps approach combining the process-based VS-modeling and the timing procedure for cell production (Figure 3). An automatic method to identify the formation time of new cell transfer to the enlargement zone of tree ring was developed in R (Popkova et al., 2018).

The main advantage of a new approach was the ability to estimate daily values of growth rates and timing of cell formation in the forest-steppe zone in southern Siberia over a long period of direct climate observations without labour-intensive field measurements. The significant correlation between the original algorithm and its updated automatic version proves correctness and reliability of the new method.

### 3.3- VS-simulation and tree-ring phenology

The variability of tree stem phenology plays a critical role in determining the productivity of forest ecosystems. Therefore, we aim to identify the relationships between the timings of cambium phenology, and forest growth in terms of tree-ring width over a long-term scale (He et al., 2018; 2019). A meta-analysis was performed that combined the timings of xylem formation, which were calculated by VS- model and its parametrization over the period 1960–2014, and a tree-ring width series at 20 composite sites on the Tibetan Plateau (He et al., 2018).

Both the start and length of the growing season significantly affected the formation of wood at 70% of sites within the study region. A wider tree ring probably resulted from an earlier start and a longer duration of the growing season (He et al., 2018; 2019).

The influence of ending dates on tree-ring width was less evident, and more site-dependent. Weak relationships were identified between the start and end of the growing season at 85% of the composite sites (He et al., 2018).

Compared to the monitoring results, which could only detect the relationships between cambium phenology and xylem cell production from a limited number of trees and years, our long-term relationships deepened such connections, and therefore should be used to improve mechanism models for the accurate evaluating and predicting of wood production and carbon sequestration in forest ecosystems under current and future climate change (He et al., 2018).

### Conclusion

By itself, the Global Tree-Ring Growth Evolution Neural Network (VS-GENN) is an unique information technology platform which uses most modern design of mathematical algorithms and approaches applied in Dendroecology. Another significant part of VS-GENN is an expert knowledge in Dendrochronology, Tree Physiology as an Expert Data Base integrated in the IT-platform, which will be used for the machine learning of the neural network.

Developing VS-GENN can be a good visual example for young scientists from different countries (particularly, France and Russia) to use data in real ecological tasks based on modern information technologies. With this goal, we plan to develop several sources with step-by-step decision of different ecological tasks in the near future after project completion.

### 4- Perspectives of future collaborations with the host laboratory

The developed IT-system will facilitate the processing of complex spatial-temporal data sets for experts from many countries and lead to a reduction of the time taken for such processing.

The potential users of obtained results include palaeoclimate researchers, scientists studying and testing models and processes of sub-components of the climate system and a variety of climate change impacts researchers.

### 5- Articles published in the framework of the fellowship

- He M., Yang B, Bräuning A., Rossi S., Ljungqvist F.C., Shishov V., Grießinger J., Wang J., Liu J,, Qin C. 2019. Recent advances in dendroclimatology in China. Earth-Science Reviews. DOI: 10.1016/j.earscirev.2019.02.012
- Tychkov I.I., · Sviderskaya I.V., · Babushkina E.A., · Popkova M.I., · Vaganov E.A., Shishov V.V. 2019. How can the parameterization of a process-based model help us understand real tree-ring growth? Trees - Structure and Function. V. 33(2). P. 345-357 DOI: 10.1007/s00468-018-1780-2
- Popkova M.I., Vaganov E.A., Shishov V.V., Babushkina E.A., Rossi S., Fonti M.V., Fonti P. 2018. Modeled

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