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# Process based model sheds light on climate signal of mediterranean tree rings

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**BGD**

8, 11089–11105, 2011

## Process based model sheds light

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

We use the process-based VS (Vaganov-Shashkin) model to investigate whether a regional *Pinus halapensis* tree-ring chronology from Tunisia can be simulated as a function of climate alone by employing a biological model linking day length and daily temperature and precipitation (AD 1959–2004) from a climate station to ring-width variations. We use two periods to calibrate (1982–2004) and verify (1959–1981) the model. We have obtained highly significant positive correlation between the residual chronology and estimated growth curve ( $r = 0.76$   $p < 0.001$ ). The model shows that the average duration of the growing season is 191 days. On average, soil moisture limits tree-ring growth for 128 days and temperature for 63 days.

## 1 Introduction

Instrumental records such as precipitation and temperature can be extended back several centuries with proxy data in North Africa. The resulting records can provide estimates of the past frequency and severity of climatic anomalies, and these in turn may be used to help anticipate the probability of such events in the future. Long time series of tree-ring growth are one of the best sources of proxy data for reconstructing past records of precipitation, streamflow, and drought on interannual to centennial time scales during the late Holocene. Tree-ring records are annually resolved, well-replicated, and can be calibrated and validated against the instrumental record. Dendroclimatic studies have been performed in several North African countries, including Morocco (e.g., Till and Guiot, 1990; Chbouki et al., 1995; Glueck and Stockton, 2001; Esper et al., 2007; Touchan et al., 2008a,b, 2011), Algeria (Messaoudene and Tessier, 1997; Touchan et al., 2008a,b, 2011), and Tunisia (Aloui and Serre-Bachet, 1987; Tessier et al., 1994; Touchan, 2008a,b, 2011).

Generally these dendroclimatic studies assumed that annual tree-ring growth is practically determined by a linear function of local or regional precipitation and temperature

**BGD**

8, 11089–11105, 2011

## Process based model sheds light

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



with a set of coefficients that are temporally invariant. However, Fritts (1976) and Vaganov et al. (2006) reported that tree-ring records are the result of multivariate, often nonlinear biological and physical processes. There are nonclimatic influences on tree-ring records, including tree biology, size, age and the effects of localized forest dynamics (Cook and Kairiukstis, 1990). This represents a problem for both single-variable dendroclimatic reconstructions using linear statistical calibration of the tree-ring proxy data and for prediction of the effects of climate change scenarios on tree biology and forest ecology. Therefore, linear empirical-statistical analyses alone cannot be used to demonstrate a physical or biological mechanism for variability or change in the climate-tree growth relationship.

The process-based VS (Vaganov-Shashkin) model (Vaganov et al., 2006) was used to resolve the critical processes linking climate variables to proxy formation. Such modeling allows us to identify and account for such processes in developing better estimates of past climate. In this paper, we are investigating whether a regional *Pinus halapensis* tree-ring chronology from Tunisia can be simulated as a function of climate alone by employing a biological model linking day length and daily temperature and precipitation from a climate station to ring-width variations (Vaganov et al., 1999, 2006).

## 2 Methods

We used a tree ring chronology and a modeling approach to evaluate whether the tree ring chronology could be simulated as a function of climate alone. A regional tree-ring chronology of *Pinus halepensis* from Tunisia (Touchan et al., 2008) and daily precipitation and temperature data (AD 1959–2004) from the Jandouba weather station (36.48° N, 8.8° E) were used in the model.

The process-based VS (Vaganov-Shashkin) model (Vaganov et al., 2006) used here has two unique characteristics. First, it deals with rates of growth of cells as if their formation in the cambium is influenced entirely by the physical environment. Second, it deals explicitly with the dynamics of cell growth, division, and maturation.

---

## Process based model sheds light

R. Touchan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The model computes the integral growth rate  $Gr$  and simulates conifer tree-ring formation from three variables: solar radiation, daily surface air temperature, and soil moisture (Vaganov et al., 2006).

The  $Gr$  on a specific day  $t$  is modeled as

$$5 \quad Gr(t) = g_l(t) \min\{g_T(t), g_w(t)\},$$

where  $g_l(t)$ ,  $g_T(t)$ ,  $g_w(t)$  are partial growth rates depending on light  $l$ , temperature  $T$ , and soil moisture  $w$ .

The partial rate  $g_l(t)$  is a function of latitude, declination angle, and hour angles (Gates, 1980). A water-balance equation is used to determine the water content in the soil from daily mean temperature and precipitation (Thornthwaite and Mather, 1955; Alisov, 1961):

$$10 \quad \Delta W = f(P) - E - \Lambda W, \quad (W_{\min} \leq W \leq W_{\max})$$

where  $\Delta W$  – first difference of water content in the soil,  $f(P)$  – precipitation amount in the soil,  $E$  – tree transpiration,  $\Lambda W$  – water drainage from the soil (Vaganov et al., 2006).

The rates  $g_T(t)$ ,  $g_w(t)$  are defined as piece-wise linear functions (Vaganov et al., 2006; Evans et al., 2006; Anchukaitis et al., 2007) (see Fig. 1).

In the paper we used the VS-model (Version 5.0) that was developed in Fortran by A.V. Shashkin (Vaganov et al., 2006). The VS-model is multi-parametric (see Table 1), and a main difficulty is to determine biologically reasonable parameters which provide a good approximation of the initial tree-ring chronology, such that the simulated tree-ring curve is highly correlated with the tree-ring chronology.

Appropriate temperature parameters for the conifer trees, such as the Aleppo pine chronology that was used in the model, were selected based on published studies of natural (uncontrolled) systems (Deslauriers and Morin, 2005; Rossi et al., 2006, 2007, 2008). It is difficult to define water-use efficiency in dry environments because conifer trees respond differently from one environment to the other (Oberhuber and Gruber,

**Process based model  
sheds light**

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2010; Gruber et al., 2010). Therefore, optimal parameters have been chosen manually by trial and error using the model and average daily variation of model soil moisture from 1959–2004 (Table 1, Figs. 3 and 4). A split-sample procedure that divides the full period (AD 1959–2004) into two subsets (1959–1981 and 1982–2004) was also used to verify model stability.

### 3 Results and discussion

#### 3.1 VS-model calibration and verification

Based on estimated optimal parameters (see Table 1) we have obtained highly significant positive correlation between the initial residual chronology and estimated growth curve ( $r = 0.76$ ,  $p < 0.001$ ) for the calibration period 1982–2004 (Fig. 2). Then we used these parameters on an independent time period 1959–1981 to evaluate the capacity of the model to fit the initial residual chronology for a period not used to calibrate, or tune, the model. The resulting high positive correlation ( $r = 0.63$ ,  $p < 0.001$ ) between curves (Fig. 2) confirms that VS-model can be used to estimate a non-linear tree-growth response to climate changes in the past for specific local drought conditions, as well as to simulate tree growth (particularly cambial activity and cell formation) under extreme environmental changes.

#### 3.2 Analysis of internal model characteristics

The VS-model allows us to analyze features of tree-ring growth response in specific environmental conditions. For example, we can estimate the partial influence of temperature and precipitation (soil moisture) on tree-ring formation, the water content in the soil during the growing season, and the start and end date of the growing season. Moreover, we can trace the process of cell formation in the tree ring under conditions for which we have cell measurements for model verification (Vaganov et al., 2006). The estimated soil moisture in our region is shown by the VS-model to increase at

## Process based model sheds light

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the start of each year, reach a maximum in April, and then monotonically decrease till August. We note that these results are consistent with experimental observations for water content of soil in that region (Kleeberg and Koplitz-Weissgerber, 1983).

One of the most interesting questions concerns the limiting influence of climatic variables on tree growth during the growing season. Standard multiple regression techniques using monthly climatic data cannot address that question. It is necessary to consider nonlinear influences operating down to at least the daily time step in estimating tree growth by climatic forcing (temperature, precipitation and solar irradiation) (Vaganov et al., 2006).

The VS-model output of partial tree growth rates shows that at the start of each year growth rate  $g_T(t)$  is less than  $g_w(t)$ , and that tree growth is limited by temperature until April (Fig. 3). From April to August soil moisture is the limiting factor to tree-ring growth: partial  $g_w(t)$  is generally less than partial  $g_T(t)$  (Fig. 3).

An integral growth rate  $Gr(t)$  lower than the model-specified minimum cambial cell growth rate  $V_{cr}$  indicates no growth. Accordingly, our results suggest that cambial activity stops in the middle of July and does not resume until next year (Fig. 4), despite partial growth rates  $g_T(t)$  and  $g_w(t)$  being favorable for resumption of growth again after August (Fig. 4). The reason growth does not resume is day-length (or solar irradiance), which decreases in September. In this case,  $g_l(t)$  is the common limiting growth factor beginning in late August.

The time plot of average integral growth rate (Fig. 4), and its position relative to the minimum cambial growth rate can be analyzed to compute various growth statistics. For our example, the average duration of the growing season is 191 days, and the standard deviation of the growing season is 82 days. On average, soil moisture limits tree-ring growth during for 128 days and temperature for 63 days.

The VS-model indicates the start of the growing season varies. The mean start date is the 34th day of year with standard deviation 26 days. The start of the growing season is defined by the rate of cambial cell growth. If the rate of growth is more than 0.1, the growing season is assumed to have started (see Table 1,  $V_{cr}$ ). The growing

**BGD**

8, 11089–11105, 2011

## Process based model sheds light

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



season is assumed to end when the integral growth rate  $Gr(t)$  falls below 0.1. Note that this happened in June–July of a recent year. During the 1982–2004 analysis period the principal limiting factor is soil moisture, indicated by the VS-model to have limited growth in 67 % of the growing season days.

### 5 3.3 Drought simulation and tree growth response

Tree-growth simulations will depend to some extent on the settings of all parameters. An especially important algorithm of VS-model utilizes a balance ratio between precipitation and soil moisture. Specifically, soil moisture eventually becomes stable with lower precipitation because a direct decrease of precipitation (up to 50 %) involves a decrease of tree transpiration. The sensitivity of soil moisture to precipitation in the VS-model can be varied by changing the setting of the drainage coefficient  $\Lambda$ , defined as an additional fraction (portion) of water evaporating from soil and not included in the tree transpiration (Vaganov, 2006). As a sensitivity experiment, we varied  $\Lambda$  from 0.0005 to 0.007 (with step 0.0005), generated a tree-ring chronology with each setting, and observed the change in chronology statistics. The each step increase in drainage coefficient over this range corresponds to an increasing of the water deficit by about 5 %. Such a change of drainage coefficient was strongly reflected in the tree-ring growth response. The primary effect was an amplified variance and increased skewness of tree-ring chronology with decreased  $\Lambda$  (Table 2, and Fig. 5). This result highlights the importance of parameter settings in the VS-model, as a lower  $\Lambda$  could result in a more sensitivity of tree growth to precipitation.

## 4 Conclusions

The process-based VS model skillfully reproduces a time series of a regional *Pinus halepensis* tree-ring chronology for Tunisia as a function of climate alone. The chronology simulated by the model correlates strongly with the original chronology for the calibration period used to tune the model parameters ( $r = 0.76$ , AD 1982–2004). Perhaps

## Process based model sheds light

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



more important, the model effectively generates a tree-ring chronology for an earlier period of time outside the tuning window ( $r = 0.63$ , AD 1959–1981). The results suggest that at least for this species, daily precipitation, temperature and day length alone are sufficient under the model framework to generate ring-width variations.

5 The model also yields important diagnostic information on the tree-growth response to climate. For example, the model shows that the average duration of the growing season is 191 days, and that on average soil moisture limits tree-ring growth for 128 days and temperature for 63 days in that 191-day window. The strength of the VS-model is its ability to simulate a non-linear tree-growth response to climate changes. In  
10 the Mediterranean region and elsewhere such simulations can be used to help explain observed patterns of tree-growth variation in the past and to simulate tree growth under extreme environmental changes.

Output from the processes-based VS model includes the partial influence of temperature and precipitation (soil moisture) on tree-ring formation, the water content in  
15 the soil during the growing season, and the start and end date of the growing season. Potential applications of this type of information include assessment of likely impact of regional warming on tree-ring indices, and evaluation of the capability of particular tree species to sense climate fluctuations in various seasonal time windows.

V-S modeling and direct cell measurements enable us to estimate cell dynamics  
20 of tree-ring formation in this extremely dry Mediterranean environment, and to better understand how tree growth there is forced by climate.

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---

## Process based model sheds light

R. Touchan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Process based model  
sheds light**

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Aloui, A. and Serre-Bachet F.: Analyse dendroclimatologique comparée de six populations de  
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**BGD**

8, 11089–11105, 2011

---

## Process based model sheds light

R. Touchan et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Table 1.** Optimal model parameters used in the paper. Description of parameters is according to Evans et al. (2006).

Parameter	Description (Units)	Value
$T_{\min}$	Minimum temperature for tree growth ( $^{\circ}\text{C}$ )	8.000
$T_{\text{opt1}}$	Lower end of range of optimal temperatures ( $^{\circ}\text{C}$ )	16.00
$T_{\text{opt2}}$	Upper end of range of optimal temperatures ( $^{\circ}\text{C}$ )	24.00
$T_{\max}$	Maximum temperature for tree growth ( $^{\circ}\text{C}$ )	28.00
$W_{\min}$	Minimum soil moisture for tree growth, relative to saturated soil (v/vs)	0.040
$W_{\text{opt1}}$	Lower end of range of optimal soil moistures (v/vs)	0.140
$W_{\text{opt2}}$	Upper end of range of optimal soil moistures (v/vs)	0.220
$W_{\max}$	Maximum soil moisture for tree growth (v/vs)	0.500
$W_0$	Initial soil moisture (v/vs)	0.100
$W_w$	Minimum soil moisture (wilting point)	0.020
$T_{\text{beg}}$	Temperature sum for initiation of growth ( $^{\circ}\text{C}$ )	120.0
$t_{\text{beg}}$	Time period for temperature sum (days)	10.00
$l_r$	Depth of root system (mm)	1500
$P_{\max}$	Maximum daily precipitation for saturated soil (mm/day)	20.00
$C_1$	Fraction of precip. penetrating soil (not caught by crown) (rel. unit)	0.720
$C_2$	First coefficient for calculation of transpiration (mm/day)	0.120
$C_3$	Second coefficient for calculation of transpiration (mm/day)	0.175
$\Lambda$	Coefficient for water drainage from soil (rel. unit)	0.000
$t_c$	Cambial model time step (days)	0.200
$V_{\text{cr}}$	Minimum cambial cell growth rate (no units)	0.100
$D_0$	Initial cambial cell size ( $\mu\text{m}$ )	4.000
$D_{\text{cr}}$	Cell size at which mitotic cycle begins ( $\mu\text{m}$ )	8.000
$V_m$	Growth rate during mitotic cycle ( $\mu\text{m}/\text{day}$ )	1.000
$D_m$	Cambial cell size at which mitosis occurs ( $\mu\text{m}$ )	10.00

**Process based model  
sheds light**

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Process based model  
sheds light**

R. Touchan et al.

**Table 2.** Descriptive statistics of simulated tree-ring curves obtained by different values of drainage coefficient  $\Lambda$ .

Value of $\Lambda$	Valid $N$	Mean	Median	Std. Dev.	Skewness	Kurtosis
0.0000	27	1.000000	1.020000	0.307221	0.378544	-0.592857
0.0005	27	1.000370	0.970000	0.340458	0.387063	-0.684560
0.001	27	1.000000	1.000000	0.368448	0.267631	-0.773945
0.002	27	0.998519	0.880000	0.452359	0.487916	-0.753685
0.003	27	0.999259	0.830000	0.543691	0.461367	-0.967795
0.004	27	0.999259	0.820000	0.649005	0.487053	-0.810461
0.005	27	1.000000	0.750000	0.747786	0.539394	-0.656162
0.006	27	1.000370	0.670000	0.884958	0.667495	-0.751095
0.007	27	1.001481	0.640000	1.073842	0.967962	-0.246651

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

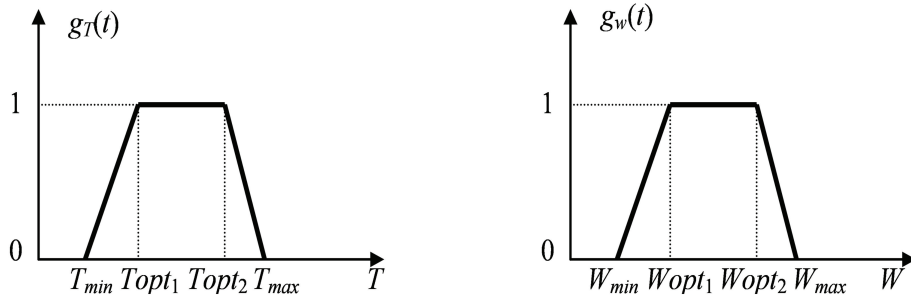
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 1.** Piece-wise linear functions which define partial growth rates depended on temperature  $T$  and soil moisture  $W$ .

**Process based model sheds light**

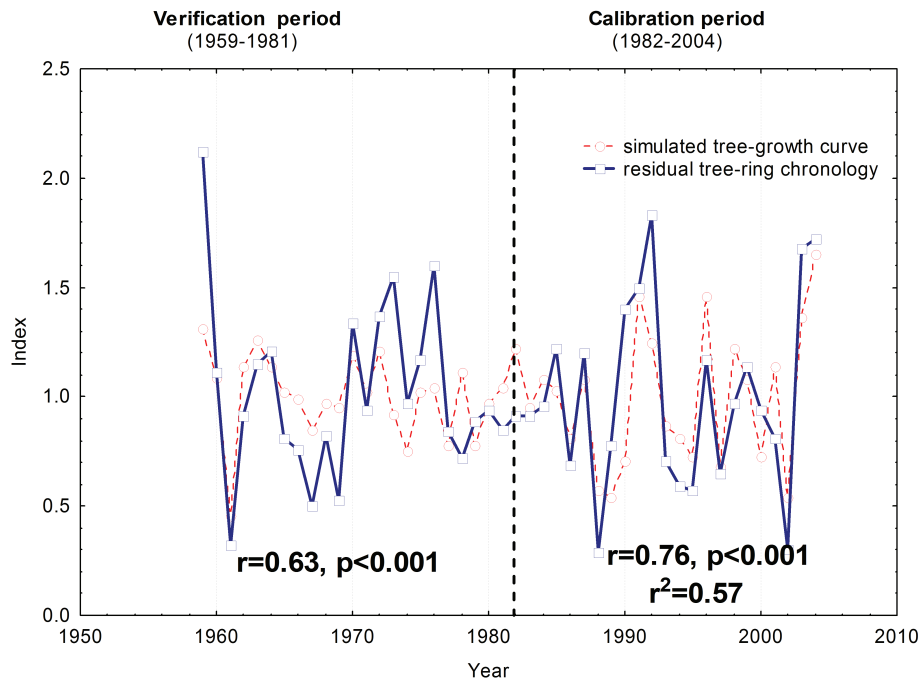
R. Touchan et al.

<a href="#">Title Page</a>	
<a href="#">Abstract</a>	<a href="#">Introduction</a>
<a href="#">Conclusions</a>	<a href="#">References</a>
<a href="#">Tables</a>	<a href="#">Figures</a>
<a href="#">◀</a>	<a href="#">▶</a>
<a href="#">◀</a>	<a href="#">▶</a>
<a href="#">Back</a>	<a href="#">Close</a>
<a href="#">Full Screen / Esc</a>	
<a href="#">Printer-friendly Version</a>	
<a href="#">Interactive Discussion</a>	



## Process based model sheds light

R. Touchan et al.



**Fig. 2.** Variations of initial tree-ring residual chronology (blue solid line) and simulated tree-growth curve (red dashed line) for calibration period (1982–2004) and verification period (1959–1981).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Process based model sheds light

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

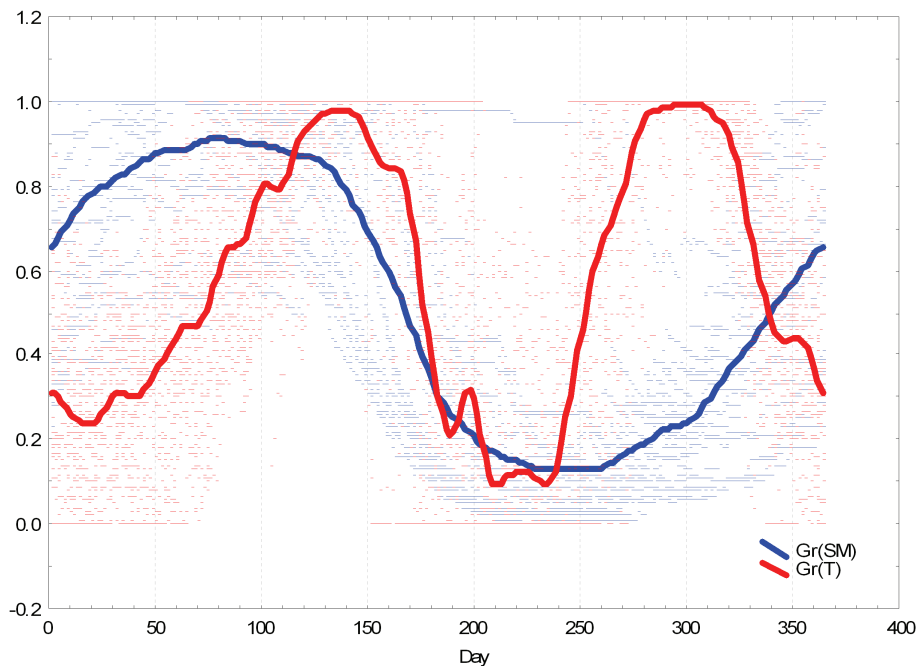
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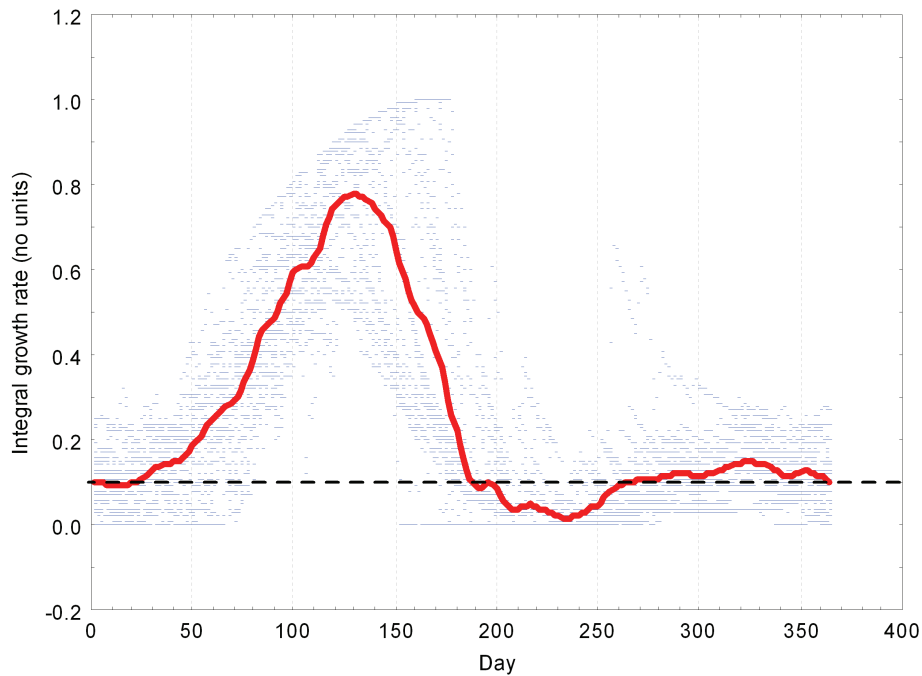
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Interactive Discussion



**Fig. 3.** Partial growth rates depending on soil moisture  $g_w(t)$  (blue line) and temperature  $g_T(t)$  (red line) for 1982–2004 fitted by negative exponential smoothing (McLain, 1974). Blue and red dots on the graph are daily values of partial rates superimposed on each other for each year.



**Fig. 4.** Average integral growth rate  $Gr(t)$  (red line) for calibration period (1982–2004) fitted by negative exponential smoothing (Mclain, 1974). Dashed line corresponds to minimum cambial cell growth rate  $V_{cr}$ .

**Process based model  
sheds light**

R. Touchan et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

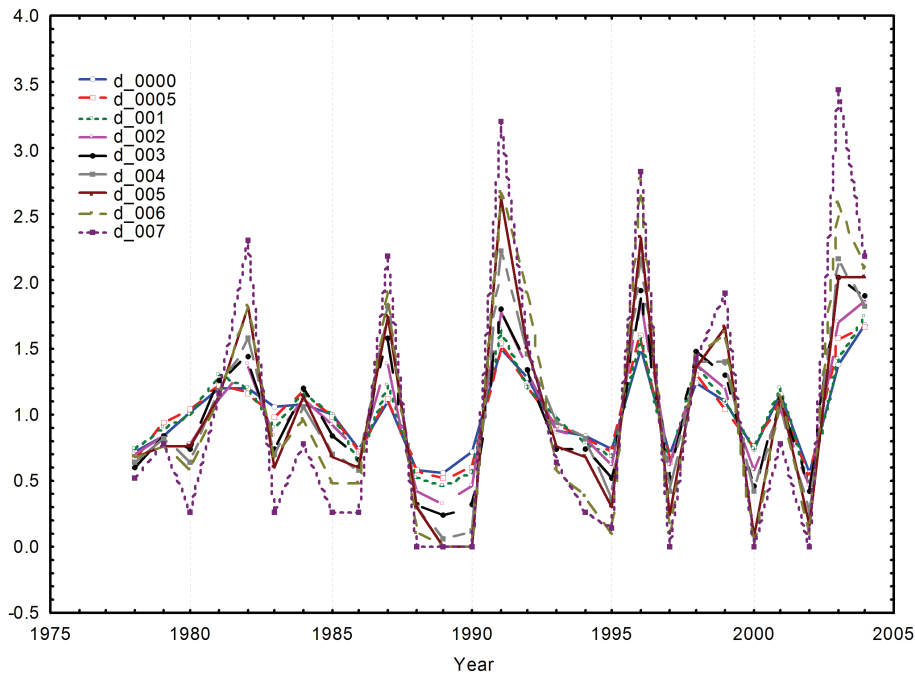
Interactive Discussion





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R. Touchan et al.



**Fig. 5.** Simulated tree-ring growth curves by different values of drainage coefficients.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

