Proceedings of the 7th International Conference on Functional-Structural Plant Models, Saariselkä, Finland, 9 - 14 June 2013. Eds. Risto Sievänen, Eero Nikinmaa, Christophe Godin, Anna Lintunen & Pekka Nygren. http://www.metla.fi/fspm2013/proceedings. ISBN 978-951-651-408-9.

Simulating the effect of extreme climatic events on tree architecture with a minimal FSPM

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Highlights: Tree response to extreme climate events is a hot topic. Minimal mathematical modelling of the interaction between tree growth and climate variation may help better understand how trees cope with extreme climatic events.

Keywords: Plant architecture, DRAFt model, Plant growth, Functional-Structural model, minimal mathematical modelling.

INTRODUCTION

Empirical studies and climate predictions highlight that climate change is associated with increasing occurrences of extreme climatic events (e.g. drought, heat wave and spring frost, Girard *et al.* 2012).

As trees develop a perennial structure, two hypotheses can be made: (i) the structure records past climatic events and thus may be affected for several years after a single extreme event and (ii) the same tree at different age may be affected differently by extreme climatic events.

The aim of this study is to test *in silico* these two hypotheses with a functional-structural tree model. This requires a model that can be analytically studied, and in which plant functions (organ size, carbon capture) and development (organ number per type) are emergent properties of the simulations. For instance the GREENLAB model (de Reffye & Hu, 2003) has many useful properties for analytical study, but the development sub-model remains relatively complex (i.e. high realism), in particular, the number of axes types is set by parameters. On the other hand, the model LIGNUM (Perttunen *et al.* 1996, 1998) contains a simple development sub-model, but the sub-model for plant function is complex. It depends on simulations of light interception that prevent analytical study and also require complex parameter calibration (e.g. organs shapes, morphogenetic responses to incident light).

DRAFt model (Taugourdeau *et al.* 2012) is a compromise between the two modeling approaches. In DRAFt, the approach to modeling plant functions is similar to GREENLAB when the developmental modelling is similar to LIGNUM. In summary, DRAFt is based on simple developmental and functional rules, but is expected to be less realistic than GREENLAB or LIGNUM. Moreover, DRAFt includes just 6 parameters, including a parameter that can be linked with the effect of climate. Finally, crown complexity is truly an emergent property of simulations.

MODEL: DRAFt

DRAFt (Demande, Répartition, Architecture & Fonctionnement with discrete time) is a recent FSPM model presented by Taugourdeau, Barczi & Caraglio (2012). This model provides interesting properties for *in silico* experiments as simulated crown complexity emerges from modelled processes and its equation system can be analytically studied.

DRAFt is an iterative, discrete time, growth cycle model that decomposes each successive growth cycle, typically a year, into 6 sequential substeps:

1. Growth Unit (GU) primary growth based on previous iteration carbon allocation (or taken from a seed at first iteration)
2. Branching on new GUs (bud production)
3. Carbon assimilation by new GUs
4. Carbon allocation to primary and secondary growth (compartment scale)
5. Secondary growth at GU scale from carbon allocated to secondary growth compartment
6. Carbon allocation to each bud from carbon allocated to primary growth compartment

Details about hypothesis and equations can be found in Taugourdeau *et al.* (2012). Among the 6 parameters, two parameters are critical for the present study:

- a set the among of biomass assimilated by a unit of GU length. Q_t the among of biomass assimilated at time t is the product of a and the sum of new GU lengths: $Q_t = a.\sum_i \quad GUlength_{t,i}$.

- cf is the ratio between GU length and initial diameter and is assumed constant. It allows to compute GU length and initial diameter based on its initial volume, Vinit (i.e. its biomass): $GUlength_i = \sqrt[3]{\frac{4*cf^2}{\pi}.Vinit_i}$.

An implementation of DRAFt was achieved using Xplo software from the AMAPstudio free-to-use package (Griffon and de Coligny, 2012; http://amapstudio.cirad.fr). It is written in Java and generates the corresponding ArchiTree topology and allows simple shaping geometry for 3D rendering purpose. Another implementation of DRAFt was achieved using R software.

ANALYTICAL STUDY

Effect of climate variations on shoot lengths

Thanks to the DRAFt formalism, the first consequences of an extreme event can be analytically studied. Let assume that a may vary along the simulation: $Q_t = a_t.\sum_i \quad GUlength_{t,i}$ and may remain constant except for a given time step: $a_{t=T} = V_a.a_{t\neq T}$ with V_a the relative variation of biomass assimilation efficiency at year T. Let $GUlength_{t=T+1,i}$ be the length of a GU the year that follows T. According to DRAFt assumptions it can be demonstrated that (*cf.* Taugourdeau *et al.* 2012 for variables and parameters descriptions):

$$GUlength_{t=T+1,i} = \sqrt[3]{\frac{4.\mathrm{cf}}{\pi}.db_i.\frac{V_a.a_{t\neq T}.\sum_i \quad GUlength_{t,i}}{D_{t=T+1}}},$$

$$GUlength_{t=T+1,i} = \sqrt[3]{V_a}.C_{t=T+1}$$

with $C_{t=T+1}$ the length of the same GU if the extreme event do not occurs (i.e. V_a=1). As cube-root function is a function with decreasing slope, it implies an asymmetric response of GU lengths to opposite extreme events: for example, +20% of biomass assimilation efficiency, implies +6.3% of shoot lengths ($\sqrt[3]{1.2}$), when -20% of biomass assimilation efficiency, implies -7.2% of shoot lengths ($\sqrt[3]{0.8}$). This is a key result as assimilation is proportional to lengths of GUs in DRAFt and drives following cycle assimilation.

The asymmetric response is mainly the consequence of two model assumptions: (i) the amount of assimilated biomass is proportional to GU lengths and (ii) the GU length:initial diameter ratio is constant and implies a cubic root relationship between GU length and allocated biomass (i.e. GU volume, see Taugourdeau *et al.* 2012 for details).

Naturally this analytical demonstration only deals with the following year and avoids more complex responses during the rest of the simulation linked with threshold effect on branching.

NUMERICAL STUDY

Effect of tree architecture on tree responses to extreme climatic events

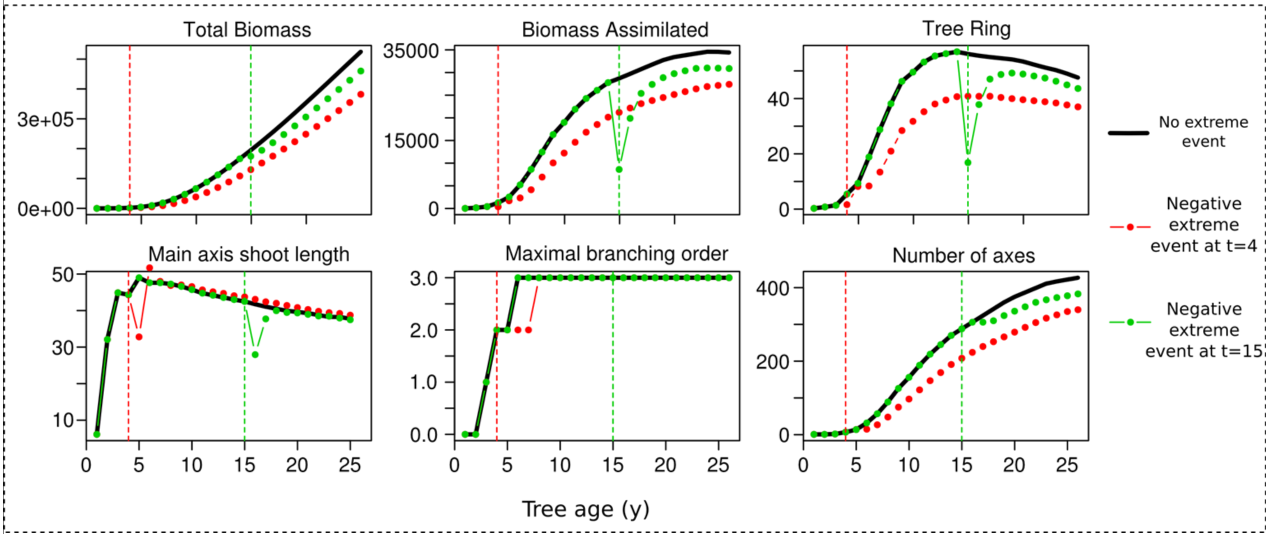
3 simulations were run with the same set of parameters (*Q0*=0.2, *dc*=.01, *cf*=30, *a*=5, *vb*=25, *da*=0.65), except for parameter a. In the first case, a remained constant along the whole simulation, in the two others cases a remained constant along the whole simulation except for the 4th or the 15th growth cycle (i.e. year) when a was reduced by 70% (i.e. a reduction of 70% of the carbon assimilated at this particular growth cycle) and returned to the original value after this extreme event.

No extreme event | Negative extreme event at t=4 | Negative extreme event at t=15

Tree architecture and extreme climate event: virtual plants simulated with AmapStudio. Red dots provide the location of GUs that were produced during the year that follows the extreme event.

Thanks to DRAFt emerging properties, most of the studied architectural output variables are affected for several years after the extreme event. But, the system is, at least partially, resilient: after 3 years main axis shoot length trends return to the "regular" trend which is consistent with empirical results on the effect of

2003 extreme summer drought on mediterranean *Pinus halepensis* tree architecture (Girard *et al.* 2012). The analytical results of the previous part also predict this resilience: a decrease of 20% only implies a decrease of -7.2% of following year assimilation.



Tree architecture and extreme climate event: quantitative results. Vertical dashed lines correspond to the timing of the negative extreme event (see main text for details).

It is evident that for the later extreme event, the maximal branching order shows no shift compared to the reference which may be related to the absence of any mortality rules in the model.

Results also show the critical importance of the timing of the extreme event on tree responses: the late extreme event has a lower impact on tree growth and architecture.

CONCUSION

The analytical analysis highlights the central role played by GU constant allometry assumptions in DRAFt. It opens new perspectives for empirical studies on tree. For instance, does trees change their shoot shape in response to extreme climate events to reduce their consequences?

From the numerical simulations, we can conclude that an extreme event affects simulated tree architecture for several years and that younger trees appear more sensitive to an extreme event than older ones. We also suspect that the DRAFt model may be improved with some additional features (flexible shoot allometry, mortality and reserve capabilities) to better react to extreme events. This hypothesis must be reinforced by comparison to empirical data.

Similar analytical and/or numerical studies should be made on other Tree FSPMs (e.g. GREENLAB and LIGNUM) to characterize their behavior in response to extreme climate events.

ACKNOWLEDGMENTS

OT was funded by a PhD grant of the French research ministry and by a postdoctoral grant of the Chaire de recherche CRSNG/Hydro-Québec. Y. Caraglio and C. Nock provided useful comments on the manuscript.

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