

**Analysing the effects of local environment on the  
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1 **Analysing the effects of local environment on the source-sink balance of**  
2 ***Cecropia sciadophylla*: a new methodology based on model inversion.**

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23 **Abstract:**

24

25 • Functional-structural model (FSM) of tree growth have great potentials for  
26 the forestry field but their development, calibration and validation are hampered by  
27 the difficulty to collect experimental data at organ scale for adult trees. Owing to  
28 their simple architecture and morphological properties, 'model plants' such as  
29 *Cecropia sciadophylla* are of great interest to validate new models and  
30 methodologies since exhaustive descriptions of the plant structure and mass  
31 partitioning are accessible.

32 • The objective of this study was to propose a methodology and to analyse  
33 the influence of environmental conditions on the dynamics of trophic competition  
34 within the trees.

35 • Using data of 11 trees measured in September 2007 for calibration and  
36 data of 7 trees measured in December 2008 for validation, we present a method to  
37 estimate an integrated factor of local environment for each plant, based on model  
38 inversion of the GreenLab FSM. It provides as a result the complex dynamics of  
39 biomass allocation to the different components of the plants during their growth,  
40 according to the environmental pressure they underwent.

41 • Extension of the model to population level could be done by linking the  
42 integrated environment factor to a competition index.

43

44

## 45 **Introduction**

46

47 Classically, individual-based forestry models use simplified representations of tree  
48 crown and characterize the growth by variations of key indicators such as height  
49 or diameter at breast height (Pretzsch, 2002). In the last decades, a new class of  
50 plant growth models has emerged, representing trees at organ scale and integrating  
51 structural and functional processes, and their interactions with the environment  
52 (Sievänen et al., 2000; Prusinkiewicz, 2004). However, their potential application  
53 to the field of forest management is not straightforward. A major obstacle is model  
54 calibration and validation against adequate data. For adult trees, their high stature,  
55 complex structure, and long life span drastically increase the experimental work  
56 required to collect data at organ scale. So, practically, only global, aggregated or  
57 sampled measurements are used to develop and evaluate the models (e.g. in  
58 Perttunen et al., 2001; Lopez et al., 2008).

59 In that context, another promising approach is to consider 'model trees' with a  
60 reduced lifespan and structure complexity to build and validate FSTM. The  
61 neotropical genus *Cecropia* Loefl. is the most important genus of pioneer trees in  
62 the neotropics; it grows rapidly and ably colonizes gaps (Berg and Rosselli, 2005).  
63 It includes 61 species that possess several properties of a 'model tree'. *Cecropia*  
64 has a very simple architecture following a Rauh model (Hallé et al., 1978). Each  
65 node bears three lateral buds that potentially give rise to a branch (central bud)  
66 and two inflorescences (Zalamea et al., 2008), as illustrated in Fig. 1B. Branching

67 and flowering are immediate; growth is continuous (no period of cessation of  
68 growth). The number of phytomers constituting the whole tree remains relatively  
69 low even though the life span can reach several decades. In previous studies,  
70 Heuret et al. (2002) and Zalamea et al. (2008) have shown a high annual  
71 periodicity in reproductive and branching processes, as well as an alternation of  
72 long and short nodes, for *C. obtusa* and *C. sciadophylla* respectively. Additionally,  
73 their results indicate that it is possible to estimate the age of a tree by observing its  
74 morphology, due to the fact that stipules, leaves, inflorescences, and branches  
75 scars remain visible along growth axes.. This is especially interesting in these  
76 tropical zones where tree age determination is difficult.

77 The origins of these periodic patterns might be linked, among others, to climatic  
78 fluctuations and/or dynamic trophic competition during the plant development.  
79 The question is thus: how to analyse the effect of environment on source-sink  
80 balance?

81

82 Unravelling the environment influence from the trophic dynamics can be done  
83 using a FSTM. But determining how to define the environment factor to input in  
84 the model is complex since many factors interact together and are impossible to  
85 measure with accuracy. Therefore, in our approach, we chose to characterize the  
86 environment by a single variable, that would represent the integration of every  
87 environmental factors and would be an indicator of the plant potentiality at each  
88 growth step. For suitable models, this integrated environmental factor can be

89 estimated together with the model parameters using tree data.  
90 In this study, we present the application of that method, using inversion of the  
91 FSTM GreenLab (Yan et al., 2004; Mathieu et al., 2009), for analysing the  
92 environmental influence on the source-sink balance for *Cecropia sciadophylla*. A  
93 previous study of *Cecropia* using the GreenLab model was performed in Letort et  
94 al. (2009) using data of 11 trees that were measured in French Guiana in  
95 September 2007. However, the environment was considered as a constant factor. It  
96 did not allow to analyse the influence of the seasonal fluctuations of the Guyanese  
97 climate (alternation of dry and rain seasons) on plant growth. Especially internode  
98 lengths seem to be related to rainfall (Heuret et al., 2002; Zalamea et al., 2008). A  
99 new methodology had to be introduced and the model had to be adapted to take  
100 into account the intra-annual variations of the environmental pressure. Besides, a  
101 new set of data on seven trees was collected in December 2008 and was used as an  
102 independent dataset for validation of the method.

103

104 With the objective of using the model as a tool to unravel the ontogenic variations  
105 (low-frequency trend) and the environmental variations (high-frequency  
106 variation), the aims of this work are (i) to determine morphological allometries to  
107 simplify future measurements, (ii) to evaluate the ability of the GreenLab model  
108 to trace back the dynamics of internal trophic competition within the plants, and  
109 (iii) to evaluate the possibility of driving the morphological and architectural  
110 plasticity by a single control variable. Eventually this study paves the way to the

111 definition of an index of competition, in order to obtain a forest model based on  
112 individual trees with explicit architectures and to analyse the emergent properties  
113 at stand level.

114

## 115 **Materials and methods**

116

117 The individuals sampled for this study were taken from two sites in French  
118 Guiana: Saint-Elie road (5°17'N, 53°04'W) and Counami road (5°24'N, 53°11'W).

119

### 120 *Measures and experimental protocol*

121

122 In September 2007, 11 individuals were felled and measured, ten at Saint-Elie  
123 road and one at Counami Road. All the trees from Saint-Elie population were  
124 sterile and only one had branches. The tree from Counami road was pistillate and  
125 had branches.

126 In December 2008, dataset was completed with seven individuals measured at  
127 Counami Road. They were all sterile and without branches.

128

129 Trees were described node by node following the protocol defined by Heuret et al.  
130 (2002). Tree topology, *i.e.* the relative position nodes and axes, was recorded  
131 following the MTG formalism (Godin and Caraglio, 1998) and analysed using the  
132 Vplant package, the successor of AMAPmod (Godin et al., 1997) now integrated

133 in the OpenAlea platform (Pradal et al., 2009). The age determination of trees and  
134 annual growth delimitation were performed following the protocol proposed by  
135 Zalamea et al. (2008). For each phytomer, the following information was  
136 recorded: the length of the underlying internode, the diameter in the middle of the  
137 internode, and the presence of developed branches, inflorescences and/or leaves at  
138 each internode. The blade was weighed. For trees of 2007, blades were pressed  
139 between two plates of Plexiglas and then photographed using a digital camera  
140 with a focal length of 50 mm. Blade areas were estimated by analysing the  
141 photographs with the ImageJ freeware (<http://rsbweb.nih.gov/ij/>). The length, the  
142 diameter in the middle and the fresh weight of the petioles were recorded.  
143 Inflorescence or infructescence were weighted. The plant axes were then cut node  
144 by node, 1 cm above the top of the stipule scar. The length of the cut segment (not  
145 exactly equal to the internode as there is a 1 cm shift) was recorded as well as its  
146 fresh weight and two orthogonal diameters of the pith. Internodes, leaves,  
147 inflorescences, and petioles were dried at 103°C during 72 h and the dry mass was  
148 measured. For young individuals, the root system was extracted, washed, dried  
149 and weighed.

150

151 *Model of biomass production in GreenLab for Cecropia*

152

153 GreenLab is a dynamic model of plant growth that aims at simulating plant  
154 topological development, biomass production and allocation at organ scale. For



155 sake of simplicity, we use here the discrete version of GreenLab, where the  
156 simulation step is based on the rhythm of plant development both for the  
157 organogenesis part and for the functional part of the model. This simulation step is  
158 set as the duration between emission of two successive phytomers along the main  
159 axis and is called the Growth Cycle (GC). For *Cecropia* species, after some  
160 variability during the phase of growth establishment, the rate of emission of new  
161 phytomers is remarkably stable (Heuret et al., 2002): each axis increases by 2-3  
162 nodes per month for *Cecropia sciadophylla* (Zalamea et al., 2008).

163

164 At plant emergence, the initial biomass is provided by the seed,  $Q(0)$ . The,  
165 biomass production at every GC is set to be simply proportional to blade area  $S(t)$ ,  
166 multiplied by a factor that represent the environmental pressure,  $E(t)$  :

167 
$$Q(t) = \mu \cdot E(t) \cdot S(t) \quad (1)$$

168 where  $\mu$  can be seen as a coefficient of conversion of a given environmental input  
169  $E$  into biomass. No self-shading is taken into account in this equation, given the  
170 particular arrangement of leaves: they are located at tips of branches with  
171 phyllotaxy 5/13. Low self-shading was also reported by Kitajima et al. (2002) for  
172 *Cecropia longipes*. The environmental factor  $E(t)$  is defined in the next section.

173

174 *The environmental factor*

175

176 We decompose the environment factor into two parts: one with temporal

177 variations that corresponds to the climatic variations and is thus common to every  
178 plant of the same region; the other one is a constant relative site local index,  
179 defined on an arbitrary scale, which is a multiplicative factor that set the relative  
180 level of local conditions on each site compare to each others, thus accounting for  
181 local spatial variations. This integrated index might aggregate the levels various  
182 local factors such as soil quality, nutriment and water availability, local density,  
183 etc.

184 Climate in French Guiana is seasonal with a 3-months dry season from mid-  
185 August to mid-November and a rain season during the other 9 months.  
186 Additionally, a short dry season may occur in February and March.

187 A new function was added in the model to represent these seasonal variations of  
188 precipitations over an average year. The absolute value of a sinusoidal function  
189 was chosen, and truncated by a constant threshold  $B$  to set the duration of the dry  
190 season. The environmental factor integrated over month  $i$  ( $0 \leq i < T$  with the  
191 origin  $i=0$  in October at the middle dry season) for an average year is then defined  
192 as follows:

$$193 \quad e_i = m_i \cdot \text{Max} \left\{ B, \left| A \cdot \sin \left( \frac{i \cdot \pi}{T} \right) \right| \right\} \quad (2)$$

194 where  $T=12$  is the period (one year),  $A$  is the amplitude of the variations of  
195 precipitations that will be fitted to the precipitation data,  $B$  the truncation  
196 threshold: it corresponds to the average amount of precipitations during the dry  
197 season. The short dry season was included in the climate function using a

198 multiplicative factor,  $m_j$  ( $0 \leq m_j \leq 1$ ), which is equal to  $1-a$  ( $0 \leq a \leq 1$ ) during the  
 199 month  $m$  of the short summer season, and is equal to 1 otherwise.

200

201 The parameters  $B$ ,  $A$ ,  $a$  and  $m$  were estimated using the precipitation data of the St  
 202 Elie meteorological station from 1978 to 1991 (Fig. 2).

203

204 To use this function as control variable for the growth of *Cecropia* trees, we need a  
 205 change of variable from the calendar time to GC. A preliminary step is thus to  
 206 input the number of phytomers,  $T_y$ , emitted every year for each plant. Then, for a  
 207 given individual  $I$ , the environmental factor integrated over GC  $j$  of year  $y$  can be  
 208 defined as:

$$209 \quad E_{j,y}^I = E^I \cdot m_{j,y} \cdot \frac{T}{T_y^I} \cdot \text{Max} \left( B, \left| A \cdot \sin \left( \frac{j \cdot \pi}{T_y^I} + \varphi_0^I \right) \right| \right) \quad (3)$$

210 where the index  $I$  denotes the variables that are specific to each individual:  $E^I$  is  
 211 the relative local index;  $\varphi_0^I$  is the phase at origin: it depends on the time when the  
 212 plant  $I$  emerged from the seed;  $T_y^I$  is given for every plant  $I$  and each year  $y$ , based  
 213 on the annual growth delimitations recorded. The ratio  $T/T_y$  comes from the  
 214 change of variable and corresponds to a normalization the total amount of  
 215 precipitation received by each plant over the year.

216 The short dry season is modelled by:

$$217 \quad m_{j,y} = \begin{cases} 1-a & \text{if } \frac{m T_y^I}{T} \leq j < \frac{(m+1) T_y^I}{T} \\ 1 & \text{else} \end{cases} \quad (4)$$

218 This equation is valid if  $\varphi_0=0$  and a simple translation of phase is performed  
 219 otherwise.

220

221 *Model of biomass allocation*

222

223 The allocation process is modelled with two steps: first, biomass is allocated to the  
 224 four compartments of plant growth: primary growth of phytomers, biomass for  
 225 ring increment (secondary growth), expansion of inflorescences, roots, then there  
 226 is intra-compartment partitioning to each organ.

227 The root mass of young individuals allowed us to build a simple allometric  
 228 relationship for the biomass allocated to the root system at each GC: it is simply  
 229 set proportional to the biomass production. The remaining biomass,  $Q_r(t)$ , is  
 230 partitioned between the three other compartments in proportion to their respective  
 231 demands,  $D_c(t)$ , where  $c$  stands for primary growth (*pg*), inflorescences (*inflo*) and  
 232 ring increment (*ring*) respectively. So,  $D(t)$  being the plant total demand at GC  $t$ ,  
 233 *i.e.* the sum of the demands of the three compartments, the amount of biomass  
 234 that goes to compartment  $c$  is:

235 
$$Q_c(t) = D_c(t) \cdot \frac{Q_r(t)}{D} \quad (5)$$

236 with 
$$\begin{cases} c = pg : & D_{pg}(t) = \sum_{Buds(t)} P_b (1 - e^{-K_b(o) \cdot k}) \\ c = inflo : & D_{inflo}(t, n) = \sum_{Inflos(t)} P_{fl} \cdot \varphi(n; a_{fl}, b_{fl}, T_{fl}) \\ c = ring : & D_{ring}(t) = P_{rg} \cdot L(t) + K_{rg} \cdot \frac{Q_r(t)}{D} \end{cases}$$

237 where the demand for primary growth  $D_{pg}(t)$  is the sum of the demands of every  
238 active meristem (noted “Buds” in the equations), designed by its rank  $k$  and  
239 branching order  $o$ . Letort et al. (2009) have shown the existence of a transitory  
240 phase when meristems are young (at axis emergence). The duration of that  
241 transitory phase is driven by the parameter  $K_b(o)$ , that depends on the branching  
242 order  $o$ . Afterwards, meristems reach a stable phase where they all have similar  
243 sink  $P_b$  whatever their rank and branching order. Sink parameter  $P_b$  is taken as  
244 reference for the other compartment demands so its value can be arbitrarily set.

245 The demand of inflorescences  $D_{info}(t)$  is defined as the sum of the sink strength of  
246 every growing inflorescence of the plant at GC  $t$ . The sink strength is  $P_{fl}$  and its  
247 variations with inflorescence age  $n$  follow a beta law density function whose  
248 parameters are  $a_{fl}$ ,  $b_{fl}$ , and the expansion duration  $T_{fl}$  (see Yin et al. (2003) and  
249 Christophe et al. (2008) for expression and use of beta law density function).

250 The demand for ring increment is assumed to consist of two parts: the first one is  
251 proportional to the total length of all axes of the plant. The sink linear density is  
252  $P_{rg}$ . The second one is proportional to the ratio of biomass supply to demand,  $Q/D$ .  
253 It implies that vigorous plants invests relatively more in their ring compartments,  
254 compared to plant that are stressed and have thus a low  $Q/D$  value.

255

256 The intra-compartment partitioning is straightforward for the compartments of  
257 primary growth and inflorescence growth: each component receives an amount of  
258 biomass proportional to its demand. Then, inside each bud, biomass is partitioned

259 between blade, petiol and internode using allometric proportions  $p_b$ ,  $p_p$ , and  $p_i$ :  
260 indeed, data analysis revealed a good proportionality between organ mass and  
261 phytomer mass (see Results part). The partitioning of ring biomass to each  
262 phytomer follows the principles similar to those of the Pipe model of Shinozaki et  
263 al. (1964): each internodes receive an amount of biomass proportional to its length  
264 and to the total area of blades localized above it in the tree architecture (see Letort  
265 et al. (2008) for further details).

266

267 Allometric relationships link organ volume and its geometrical dimensions.  
268 Internode length is calculated from internode volume by assuming a cylinder  
269 shape:

$$270 \quad l = Be \cdot V^\beta \quad (6)$$

271 Blade area is calculated from blade mass by:

$$272 \quad S = \frac{M}{SBM} \quad (7)$$

273 where  $SBM$  is the specific blade mass ( $\text{g} \cdot \text{cm}^{-2}$ ). The parameters  $Be$  and  $SBM$  are of  
274 special interest for *Cecropia* since they have a strong influence on the source-sink  
275 balance: internode length determines ring demand; blade area determines the plant  
276 production. It was also observed that they vary with time and among different  
277 individuals. Therefore a mechanistic modelling was the objective: these  
278 allometries were set dependent on the source-sink balance of each plant.

279 Classically, the ratio of biomass supply to demand,  $Q/D$ , is taken as a key variable

280 of the GreenLab model and is considered as an index of the level of internal  
 281 trophic competition (Mathieu et al., 2009). Here, the variations of  $Q/D$  are from  
 282 two sources: the high frequency variations represent the response of the plant to  
 283 seasonal environmental stress while the low-frequency variations represent the  
 284 global trend of trophic competition. Since it seems not realistic to have so fast  
 285 variations of these allometries, we extract this low-frequency trend: we define the  
 286 variable  $A_T(Q/D(t))$  which is the average of the  $Q/D$  values over the previous year.  
 287 So the following equations were chosen:

$$288 \quad (1) \quad Be(t, k) = Be_{min} + Be_{max} \cdot \exp(-K_{Be} \cdot k \cdot A_T(Q/D(t))) \quad (8)$$

289 at GC  $t$  and rank  $k$ , where  $Be_{min}$ ,  $Be_{max}$  and  $K_{Be}$  are parameters to estimate.

$$290 \quad (2) \quad SBM(t) = \text{Min} \{ SBM_{max}, SBM_{min} + K_{SBM} \cdot A_T(Q/D(t)) \} \quad (9)$$

291 where  $SBM_{max}$  is the SBM at measurement date, input for each tree,  $SBM_{min}$  is the  
 292 minimal observed value and  $K_{SBM}$  is a parameter to estimate.

293

294 Additionally, leaf functioning duration was also set as an affine function of  $A_T(Q/D)$ .  
 295 It was indeed observed that the number of active leaves varied with tree  
 296 development and environmental conditions. A leaf appearing at GC  $t$  will stay  
 297 photosynthetically active during  $T_a$  GC:

$$298 \quad T_a(t) = T_{a,min} + K_a \cdot A_T(Q/D(t)) \quad (10)$$

299 where  $T_{a,min}$  is the minimal value that was observed and  $K_a$  is a parameter to  
 300 estimate.

301

302 *Parameter identification of the model*

303

304 Some allometric relationships were first estimated directly from the data, using the  
305 R software (R Development Core Team (2008)). In particular, we used the data  
306 from 2007 to derive a model for a faithful prediction of blade area using petiol  
307 fresh sectional area. Indeed, large blades produces more biomass that needs to be  
308 exported to the rest of the plant and thus necessitate a large sectional area of the  
309 corresponding petiol. Another advantage is that is very easy to measure. The  
310 allometry was then applied to estimate blade areas for the 2008 data.

311 Then target files were filled with the data of tree topology (position of branches  
312 and inflorescences), and data of organ mass and dimensions of the 11 trees of the  
313 2007 and 2008 protocols: internode dry mass, length, diameter; blade dry mass  
314 and area; petiol dry mass; inflorescence dry mass, for each phytomer. Additionally,  
315 a file giving the number of phytomers emitted per year was input for each plant.  
316 The shape of environmental variations was set using the parameters estimated on  
317 the precipitation data. The estimation of the relative local index for each plant site  
318 and of the remaining hidden parameters was performed using the *Digiplant*  
319 software (Cournède et al., 2006). An adaptation of the 2-stage Aitken estimator  
320 was used, where the observations are classified into groups with respect to the  
321 type of organs (that have potentially very different size orders) and the error term  
322 of each group has common unknown variance and errors are mutually independent  
323 (Zhan et al., 2003; Cournède et al., 2011). Only the data from 2007 protocol were



324 used for estimating the model parameters. Then data from 2008 protocol were  
325 used for validation, only estimating their relative local index of environment.

326

## 327 **Results**

328

### 329 *Data analysis*

330

331 Fig. 1C-D shows two of the measured individuals (ID 4 and 10). Tab. 1 presents  
332 some characteristics of the measured trees. The oldest measured trees are 8 year-  
333 old and had approx. 230 phytomers on the main stem. There is a large inter-tree  
334 variability: for instance, Tree 9 is five years younger than Tree 8 but is nearly as  
335 large (approx. 40 kg). For trees 1, 2, and 30, that all have between 50 and 55  
336 phytomers, aerial mass varies from 0.2 to 5.5 kg.

337 Root dry mass was measured for the eight youngest individuals of 2007  
338 measurements. The ratio between root mass and total mass was found of 0.19 in  
339 average (s.d. 0.059).

340 Tree age results from the procedure of year delimitation based on the sequence  
341 analysis of organ dimensions along the main stem, and based on the position of  
342 branches and inflorescences when they were present (Fig. 3).

343

344

345 The allometry relationship between blade area ( $\text{cm}^2$ ) and petiol sectional area

346 (mm<sup>2</sup>) was obtained using n=523 data points, giving a coefficient of 35.18  
347 (R<sup>2</sup>=0.975; Fig. 4A). More precisely, a key variable of our model is the SBM  
348 (blade dry mass/ blade area): Fig. 4B shows the comparison between SBM  
349 calculated from measured or estimated blade areas. The results are satisfying  
350 except for low values of petiol section.

351

352 For intra-phytomer partitioning of biomass, observations of young phytomers  
353 (n=540 leafy phytomers) suggested a linear model of organ dry mass with respect  
354 to phytomer dry mass. To be biologically realistic, it was imposed that organ mass  
355 is zero when phytomer mass is zero. Fig. 5 and Tab. 2 present the results for  
356 blades ( $y = 0.7177 \cdot x$ , R<sup>2</sup>=0.99), petiols ( $y = 0.2080 \cdot x$ , R<sup>2</sup>=0.97) and internodes  
357 ( $y = 0.07423 \cdot x$ , R<sup>2</sup>=0.81). Note that Individual 9 was not included (although  
358 represented on the graphs) since its high values of internode mass let suspect that  
359 secondary growth might not be negligible for this individual even on young  
360 phytomers.

361

362 *The environmental factor, representing precipitations at St Elie station.*

363

364 Analysis of our precipitation data showed that the so-called “short summer of  
365 March” was more likely found in February ( $m=4$  in Eq. (4)). The parameters  
366 estimated for the environmental fluctuations over an average year are given in Tab  
367 2. The comparison between recorded and fitted data is presented in Fig. 2.

368

369 *Fitting results.*

370

371 Tab. 2 gathers the values of the parameters used in the simulations. The values of  
372 the model hidden parameters and individual local environment indices were  
373 estimated using the 11 individuals of 2007 protocol. Fitting in parallel their data of  
374 organ dimensions and mass represented in total more than 4600 data points, while  
375 the number of degrees of freedom (number of parameters to identify in parallel)  
376 was 24. Some parameters were fixed, based on observations and biological  
377 knowledge: the initial biomass, coming from the seed, was set to 0.1g; the  
378 parameter  $\beta$  defining internode shape was set to 0.9 since internode length was  
379 highly variable; duration of inflorescence expansion was observed to last  
380 approximately 7 GC; the initial value of leaf functioning duration was set to 7  
381 according to the minimal number of active leaves observed on young plants;  
382 primary growth compartment (buds) was chosen as the reference for the model of  
383 proportional sinks and could be set arbitrarily: the value 10 was chosen. It is  
384 interesting to note that the ratio between the sink bud parameters  $K_b(1)$  and  $K_b(2)$   
385 is 1.04, which means that the demand of the apical meristem of branches follows  
386 nearly the same trajectory as that of the main stem. The parameters  $P_{rg}$  and  $K_{rg}$  are  
387 close but the resulting ring demand consists in fact at approximately 90% of the  
388 part of the demand which depends on the total axis length (linear density of sink  
389 for rings).

390

391 Fig. 6 presents some of the fitting graphs: measured and simulated values of  
392 internode mass (a), blade mass (b), petiol mass (c) and inflorescence mass (d) for  
393 the main stems of the 11 individuals. The sinusoidal variations of internode mass  
394 are generated by the environmental fluctuations. Although the fitting accuracy  
395 looks correct at visual inspection, the coefficient of determination are relatively  
396 low (0.43, 0.79, 0.43, 0.45, 0.50 for internode mass, diameter, blade mass, blade  
397 area, and petiol mass respectively) because of the sinusoidal shape of these curves.  
398 The coefficients of determination for the cumulated values (internode, blade and  
399 petiol compartments) are all above 0.98.

400 The validation with data from 2008 are acceptable: coefficients of determination  
401 are 0.43, 0.75, 0.07, and 0.18 for the same variables. The inaccuracy on blade and  
402 petiol mass is due to some variability in the number of active leaves that are  
403 present. For cumulated values, the coefficient of determination are also all above  
404 0.98.

405 Although not perfect, these fittings prove that it is possible to reproduce the large  
406 variability that was observed for our target trees with a common model where the  
407 environmental pressure is integrated into a single factor.

408

409 The variations of the biomass supply to demand ratio  $Q/D$  are presented in Fig.  
410 7(A). The strong fluctuations are related to the seasonal variations of the  
411 environment. Fig. 7(B) shows the global trend of  $Q/D$ : its values were averaged

412 over one year. A strong increase was observed after the appearance of the first tier  
413 of branches for tree 8 and tree 10. In contrast, the growth inflorescences decreased  
414 the  $Q/D$  ratio, as expected.

415

## 416 **Discussion**

417

418 The relative simplicity of *Cecropia* architecture made it possible to analyse the  
419 growth of the tree with the GreenLab model, using a complete description at the  
420 same scale as the simulation scale. It even offered the possibility to include in total  
421 18 plants in the analysis. The advantage of multi-fitting (fitting several plants in  
422 parallel) have been demonstrated for crops with GreenLab (Guo et al. 2006) and is  
423 even more crucial for trees given their high variability. By fitting several plants in  
424 parallel, we expect to extract a set of stable parameters that would be  
425 representative of the species, and to avoid that the fitting would be too much  
426 perturbed by individual random particularities of single plants (known as problem  
427 of over-optimisation). Additionally, it allows testing the robustness of the model  
428 and its ability to simulate several plants with the same parameter values, with only  
429 one site-specific factor to explain the observed variability.

430

431 Simulations using the parameter values estimated in this multi-fitting process  
432 provides the dynamics of the different compartment biomass and of the ratio of  
433 biomass supply to demand for each plant. No obvious conclusion can be drawn

434 concerning the link between this ratio and the appearance of the first tiers of  
435 branches and inflorescences. Nevertheless, it shows that tree 8 has a ratio of  
436 biomass supply to demand,  $Q/D$ , a bit lower than that of tree 10, which might  
437 explain its later emission of branches. But given that tree 9 had a very high  $Q/D$   
438 ratio but no branches, it is likely that other factors than the trophic competition are  
439 involved in the appearance of branches. From Fig. 7, it seems that branches  
440 contribute greatly to the plant production and are more sources than sinks. The  
441 interpretation of Fig. 7 suggests new hypotheses for the senescence of *Cecropia*:  
442 when an axis grows in height, its production tends to reach a saturation level while  
443 its demand increases regularly because of the increasing load of rings. If no  
444 branches appear, this would end to the death of the plant.

445

446 However, this behaviour is strongly linked to the modelling choices, as illustrated  
447 by the comparison with the curves found in Letort et al. (2009), that were obtained  
448 with a constant environment and a less mechanistic model. In particular, several  
449 weaknesses of the current model can be highlighted. Two variables are still input  
450 directly in the simulation instead of being modelled: the maximal value for the  
451 specific blade mass and the number of phytomers emitted per year. The latter is all  
452 the more important when considering the annual environmental variations, since a  
453 difference of phase would perturb the fitting results. But questions remains on  
454 what factors affect the organogenesis rhythm and it is likely that strong random  
455 effects induce the variability observed during the first years after plant emergence.

456 A second question that arise from this work is the possible existence of  
457 interactions between the plant structure and its strategy for biomass allocation.  
458 First, the presence of stilt-roots has been observed on some individuals, but were  
459 considered as part of the root system in this study. But, given the particular  
460 candelabrum-like architecture of *Cecropia* and the important heights that they can  
461 rapidly reach, a natural hypothesis would be that the appearance of stilt-roots, as  
462 well as the demand of the ring compartment, could be influenced by requirements  
463 to ensure the mechanical stability of the tree. Such hypothesis could be  
464 investigated in parallel by an experimental approach and by a model-based  
465 approach: indeed, since the calibrated model faithfully reproduce internode masses  
466 and dimensions along the main stem, it would be possible to calculate the  
467 biomechanical stresses in the trunk at each growth step, as done by Qi et al. (2009)  
468 with the GreenLab model for a virtual tree. Thus, virtual experiments could be  
469 performed to understand the potential relationship between ring increment or stilt-  
470 root growth and the mechanical stability of the tree.

471

472 A result of our study was the introduction of an environmental factor that  
473 consisted of two parts: one for the temporal variations, related to the amount of  
474 precipitations over an average year; and the other one, constant through time and  
475 set for each individual, that corresponds to the global level of environmental  
476 pressure on the plant, as the integration of many different factors. This might look  
477 like an oversimplification, in contrast with most FSTM that integrate the effects of

478 many environmental factors (PAR, water, nitrogen content, etc) on the plant  
479 growth at fine scales (e.g. Lopez et al. (3008)). But in natural conditions, it is  
480 difficult to characterize the environment of each plant in details because of the  
481 numerous local heterogeneities and to unravel the respective influences of the  
482 different factors. The choice of a single, integrative factor might then be  
483 considered and in our study, the large inter-plant variability of the data was  
484 successfully reproduced. The interest of a model where tree growth and,  
485 potentially, architecture (see Mathieu et al., 2009) are driven by a single  
486 environmental factor, is that it paves the way to extension from individual-based  
487 model to population level (Cournède et al. 2008). Indeed, this simple  
488 environmental factor could be related to an index of competition to simulate the  
489 growth of a stand.

490

491

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493

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620 **Tables**

621

622

623

624 Tab. 1. Characteristics of trees measured in September 2007 (ID 1 to 11) and

625 December 2008 (ID 29 to 48).

626

ID	Age	NbPhyts	Loc	H (m)	DBH (cm)	AerMass(kg)	RootMa.(kg)
1	2	55	E	3.61	3.9	5.481	0.96
2	2	55	E	2.97	2.3	1.092	0.216
3	2	45	E	2.2	1.2	0.341	0.054
4	1	18	E	0.35	-	0.038	0.009
5	1	29	E	0.08	-	0.002	0.00047
6	2	33	E	0.71	-	0.07	0.0297
7	2	37	E	0.77	-	0.125	0.044
8	8	248	E	9.87	9.3	40.72	-
9	3	74	E	7.72	9.5	40.605	-
10	8	391	C	12.64	13.4	71.741	-
11	2	52	E	1.49	1.6	0.486	0.083
29	3	86	C	3.87	2.9	1.057	-
30	2	51	C	1.63	1.1	0.179	-
31	2	67	C	2.92	1.91	0.512	-
40	4	99	C	6.16	5.7	4.092	-
41	2	70	C	1.73	1.2	0.193	-
42	2	69	C	2.98	2.44	0.7	-
48	4	74	C	4.8	4.25	2.389	-

627

ID: identifier index, Age: ontogenetical age (years), Nphyt.: total number of

628

phytomers,

629

Loc. : location (E:Saint-Elie, C: Counami), H: height (m), DBH: diameter at

630

breast height (cm),

631

AerMass: total aerial fresh mass (kg), RootMa.: fresh mass of the root system

632

(kg).

633

634



635 Tab. 2. Parameters used in the simulations: parameters for the climate function  
636 fitted on St Elie precipitation data, allometries estimated directly from the data,  
637 relative local index for each tree (from 1 to 11 for trees of 2007 and from 1 to 7  
638 for trees of 2008) and model hidden parameters estimated against the data of  
639 2007.

<b>Climate function (temporal variation of the environment)</b>		
<i>A</i>	Amplitude	430.8mm
<i>B</i>	Threshold	74.81mm
<i>m</i>	Month of short dry season	4 (Febr.)
<i>a</i>	Coef. Short dry season	0.446
<b>Allometries estimated directly from data</b>		
<i>r</i>	Biomass proportion to roots	19.00%
<i>Q<sub>0</sub></i>	Initial biomass	0.1g
<i>p<sub>b</sub></i>	Blade sink coefficient	0.7177
<i>p<sub>p</sub></i>	Petiol sink coefficient	0.208
<i>p<sub>i</sub></i>	Internode sink coefficient	0.07423
<b>E': Relative local index for each tree</b>		
<i>2007 trees</i>	1.03; 0.81; 0.62; 0.52; 0.33; 0.37; 0.30; 0.98; 1.12; 0.67	
<i>2008 trees</i>	0.50; 0.37; 0.70; 0.70; 0.36; 0.67; 0.83	
<b>Parameters common to all trees</b>		
<i>μ</i>	Production efficiency	6.4 · 10 <sup>-5</sup>
<i>P<sub>b</sub></i>	Bud Sink	10 (fixed)
<i>K<sub>b</sub>(1)</i>	Bud sink param. order 1	0.0062
<i>K<sub>b</sub>(2)</i>	Bud sink param. order 2	0.0064
<i>P<sub>fl</sub></i>	Inflorescence Sink	4.89
<i>T<sub>fl</sub></i>	Inflo.expansion duration	7 (fixed)
<i>a<sub>fl</sub>, b<sub>fl</sub></i>	Inflo param. expansion	1.82, 22.8
<i>P<sub>rg</sub></i>	Linear sink of rings	0.024
<i>K<sub>rg</sub></i>	Q/D-coefficient sink of rings	0.024
<i>SBM<sub>min</sub></i>	Initial Specific Blade Mass	0.00749 (fixed)
<i>K<sub>SBM</sub></i>	Q/D-coefficient for SBM	0.0012
<i>β</i>	Internode shape coefficient	0.9 (fixed)
<i>Be<sub>min</sub></i>	Initial Be (internode shape coef.)	75.1
<i>Be<sub>max</sub></i>	Final value of Be	2.66
<i>K<sub>be</sub></i>	Q/D-coefficient for Be	0.0069
<i>Ta<sub>min</sub></i>	Initial Leaf functioning duration	7 GC (fixed)
<i>K<sub>a</sub></i>	Q/D-coefficient for Ta	1.0

640

641 **Captions of figures**

642

643 Fig. 1. Habit of *Cecropia sciadophylla*. Sequence of internodes of an axis (A),  
644 young inflorescence (B), youngest (C) and oldest (D) individuals 4 and 10, that  
645 were measured in 2007 (respective heights: 35cm and 12m).

646

647 Fig. 2. Fitting of pluviometry data from St Elie station.

648

649 Fig. 3. Age determination for tree 10. Internode length (bold line) and pith  
650 diameter (line) of internodes along the main stem and localization of branches  
651 (triangles) and inflorescences (circles).

652

653 Fig. 4. (A) Blade area with respect to fresh petiol section and (B) dry SBM  
654 calculated using measured blade area (dark symbols) or blade area that was  
655 estimated using the petiol fresh sectional area (open symbols). Gray symbols are  
656 plants from the 2008 measurements, for which blade area was not measured.

657

658 Fig. 5. Biomass allocation for primary growth: blade dry mass (A), petiol dry mass  
659 (B), and internode dry mass (C) with respect to phytomer dry mass, for each  
660 branching order.

661

662 Fig. 6. Measured (dots) and simulated (lines) values of internode mass (a), blade

663 mass (b), petiol mass (c) and inflorescence mass (d) for the main stems of the 11  
664 individuals from the data of 2007.

665

666 Fig. 7. Variations of the biomass supply to demand ratio: values at each GC (A)  
667 and average values over one year (B) to extract the global trend. Triangles and  
668 circles represent the date of appearance of branches and inflorescences. Note: for a  
669 better distinction of the curves, Graph A was truncated in its highest values.

670 **Figures**

671

672



673

674 Fig. 1.

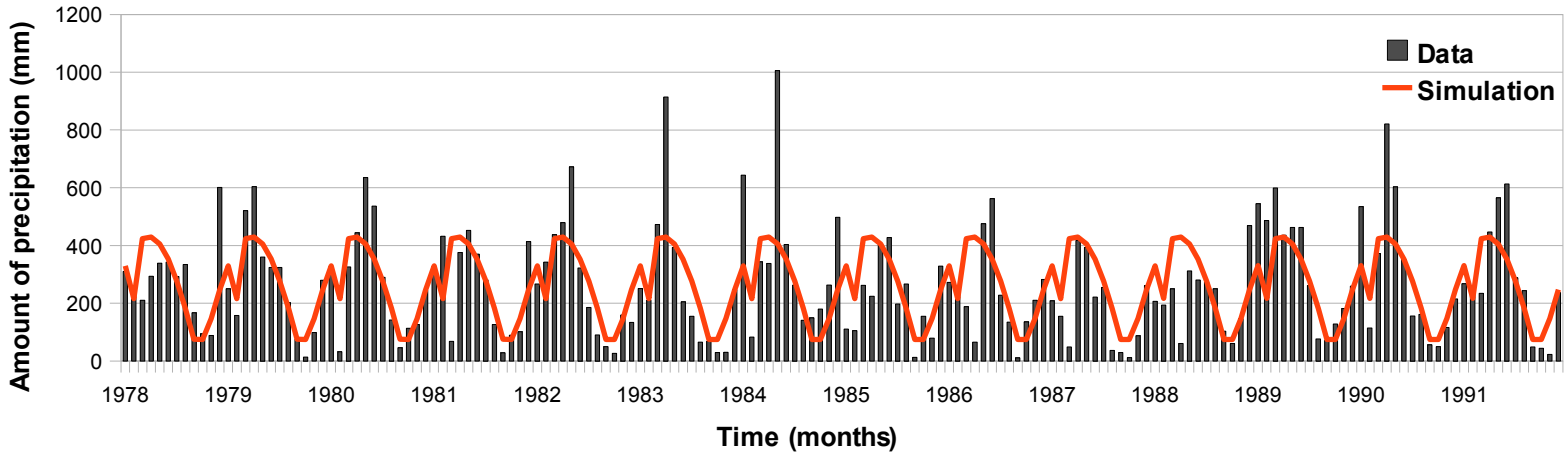
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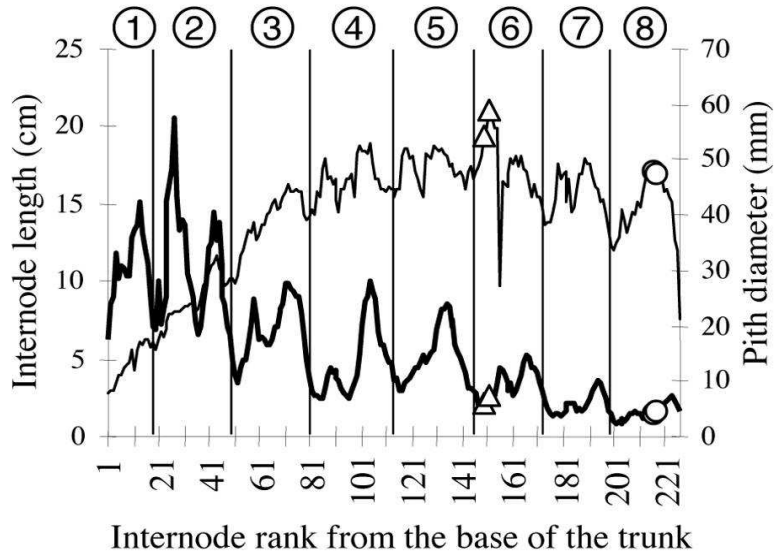


681 Fig. 2.

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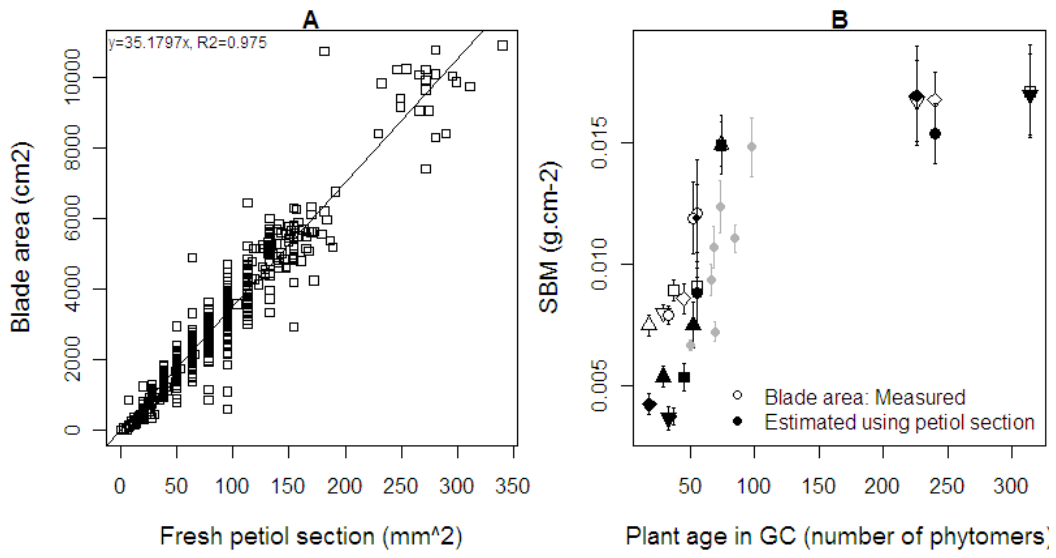


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686 Fig. 3.

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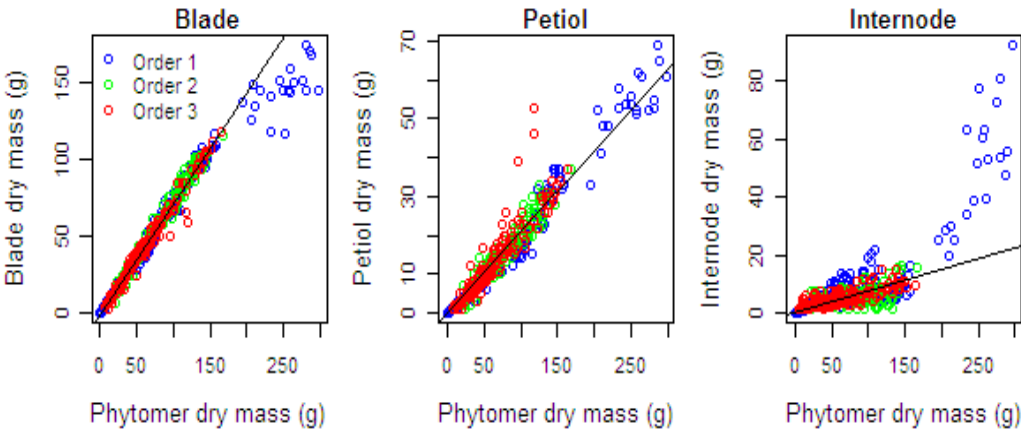
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690 Fig. 4.

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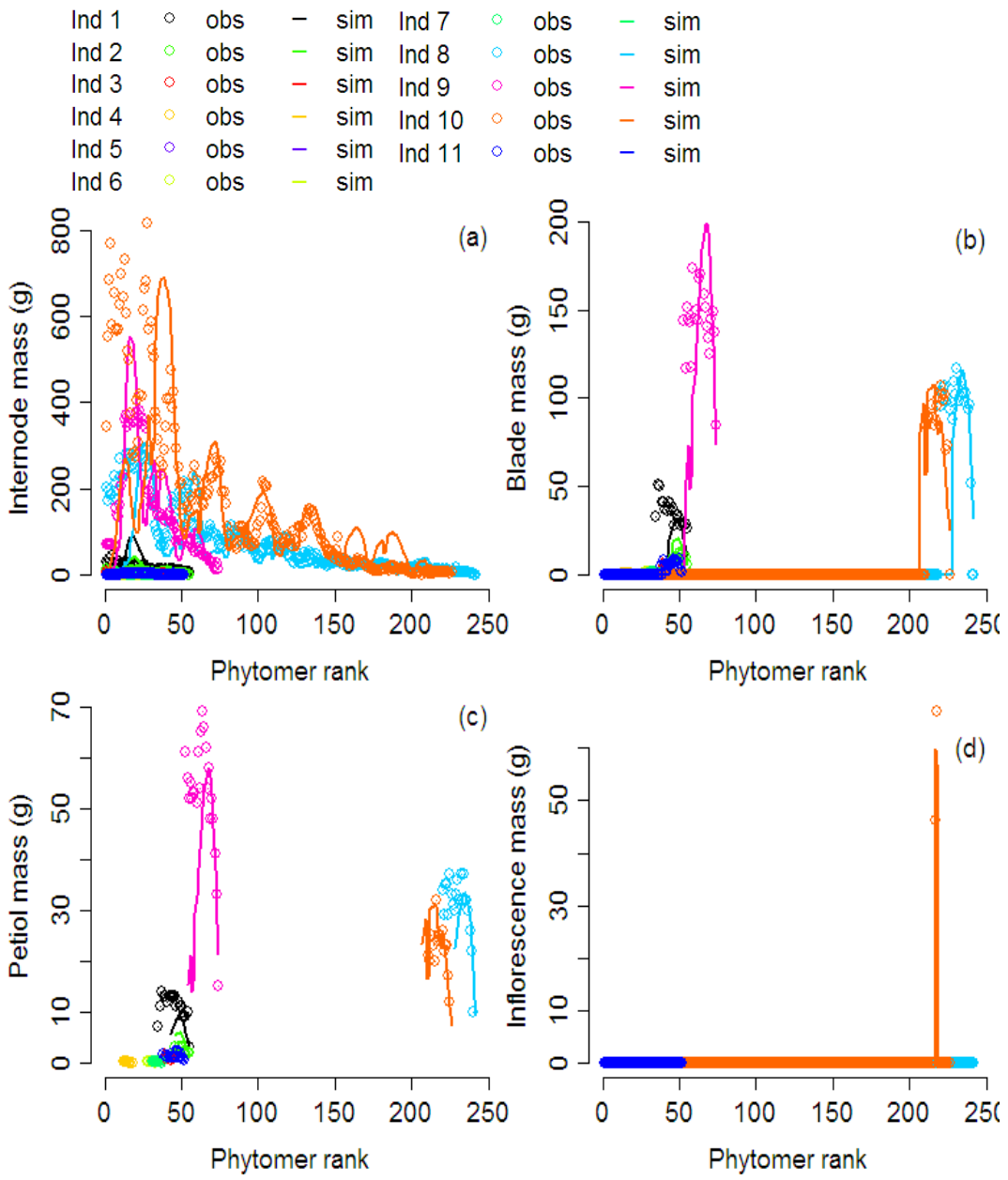


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695 Fig. 5.



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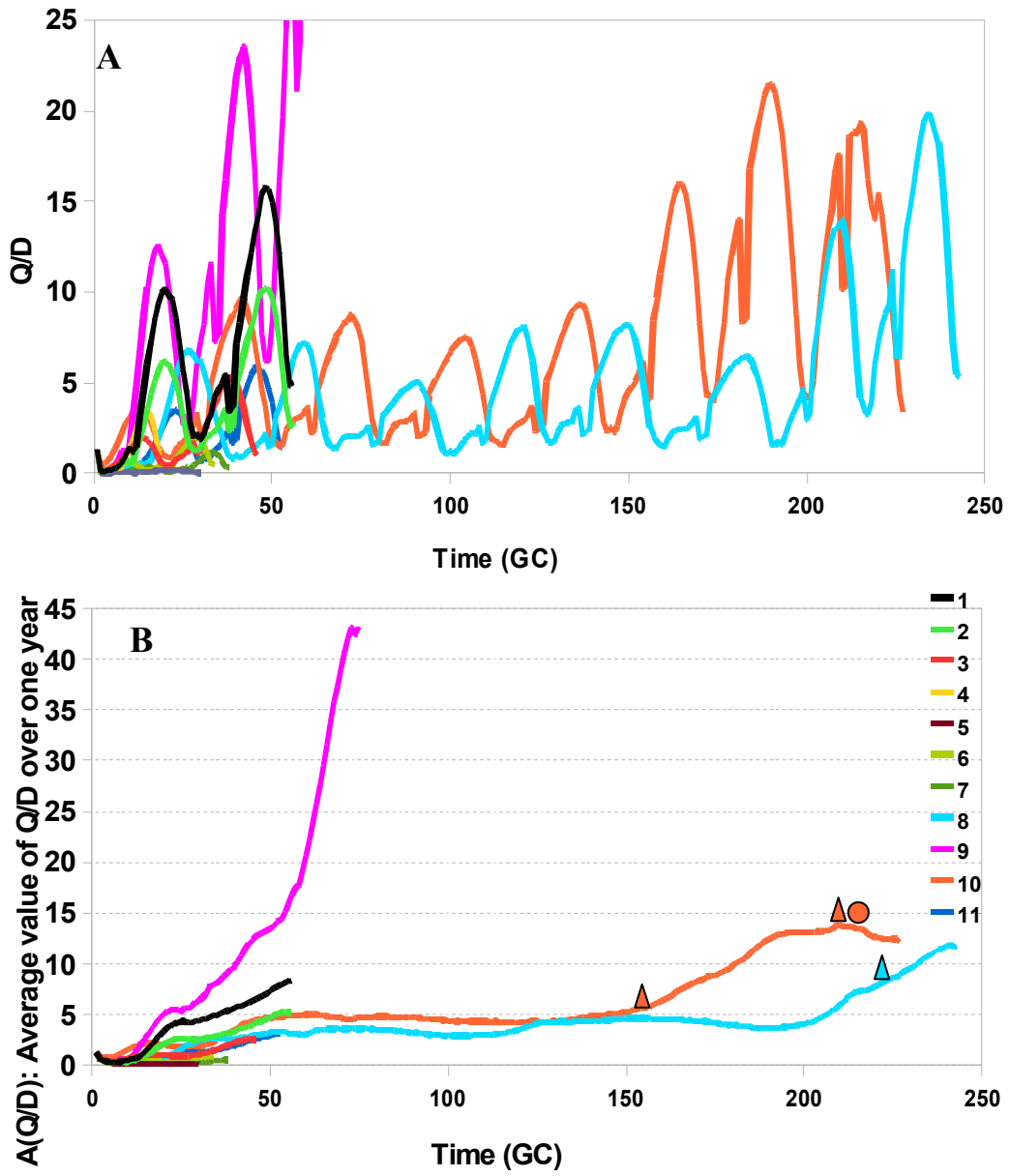
697 Fig. 6.

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702 Fig. 7.

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