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## Modeling of light transmission under heterogeneous forest canopy: an appraisal of the effect of the precision level of crown description

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## Abstract

- Context: Light availability in forest understorey is essential for many processes, it is therefore a valuable information regarding forest management. However its estimation is often difficult and direct measurements are tedious. Models can be used to compute understorey light but they often require a lot of field data to accurately predict light distribution, particularly in the case of heterogeneous canopies.
- Aims: The influence of the precision level of crown description was studied with a model, M $\mu$ SLIM, that can be used with both detailed and coarse parametrization with the aim of reducing to a minimum field data requirements.
- Methods: We analyzed the deterioration of the prediction quality of light distribution to the reduction of inputs by comparing simulations to transmitted light measurements in forests of increasing complexity in three different locations.
- Results: With a full set of parameters to describe the tree crown (i.e. crown extension in at least 8 directions, crown height and length), the model accurately simulated the light distribution. Simplifying crown description by a geometric shape with a mean radius of crown extension led to deteriorated but acceptable light distributions. Allometric relationships used to calculate crown extension from trunk DBH seriously reduced light

32 distribution accuracy.

33

## 34 **Introduction**

35 Light in forest understorey is a fundamental resource driving many processes  
36 related for example to regeneration growth, vegetation cover and composition,  
37 and animal habitat (Balandier *et al.* 2009). Light quality is fundamental for  
38 morphogenetic processes, whereas light quantity drives processes linked to carbon  
39 acquisition. In this article only light quantity is considered.

40 For a long time light in forest has only been considered as a factor controlling tree  
41 growth, especially in the case of regular even-aged stands in the temperate area. In  
42 that context, tree density has been managed to get a very dark understorey with  
43 often a bare soil, sign that trees absorbed the maximum of radiations (Perrin  
44 1963). Nowadays a silviculture closer to nature (also named continuous cover  
45 forestry) with natural regeneration is promoted or rediscovered (Hale 2009).  
46 Irregular uneven-aged stands often with mixed species are managed with partial  
47 cutting to create gaps in the forest canopy. These gaps favor some patch of light  
48 essential to tree regeneration but also promote the development of understorey  
49 vegetation that can compete with young trees and compromise forest dynamic  
50 (Balandier *et al.* 2009). Under these conditions, in order to sustain young tree  
51 growth while avoiding too dense understorey vegetation, it is essential to  
52 proportion light by the size of the gaps (Gaudio *et al.* 2011).

53

54 However estimating light quantity in forest understorey is not so easy (Lieffers *et*  
55 *al.* 1999). On one hand, visual assessment are strongly biased by the  
56 meteorological conditions, the hour of the day and the operator himself. On the  
57 other hand, direct measurements by sensors are often tedious, expensive, require  
58 technical competences, and their results also depend on the meteorological  
59 conditions and the solar pathway on the day of measurement (Pukkala *et al.*  
60 1993).

61

62 Since the pioneer work of Monsi and Saeki (1953), many models simulating light  
63 interception and transmission by plant canopies have been developed (see Myneni  
64 *et al.*, 1989 and Sillon and Puech, 1994 for reviews) and offer an operative  
65 alternative. They are based on, either statistical relationships between vegetation  
66 characteristics such as cover, leaf area or leaf area index (LAI) and light  
67 transmission, or explicit description of the canopy topology and geometry as  
68 elements intercepting light. When forest canopy is homogeneous, i.e. even-aged  
69 pure regular stands, statistical models predict mean light quantity in forest  
70 understorey with an acceptable accuracy (Balandier *et al.* 2006b; Hale *et al.* 2009;  
71 Sonohat *et al.*, 2004). However prediction quality of that type of models decreases  
72 drastically with the increase in heterogeneity of the stand structure (Balandier *et*  
73 *al.* 2010). In particular in irregular uneven stands a statistical mean has no sense  
74 because it does not reveal the light distribution between understorey and gaps

75 which is of most interest for the forester. With that information, local light  
76 availability to favor tree regeneration, plant biodiversity, or animal habitat for  
77 example can be estimated (Balandier *et al.* 2006a).

78

79 In that case, complex models with an explicit 3D-description of elements  
80 intercepting light give more accurate results. The approach of these models  
81 usually involve the use of numerous tracing (sun) rays coming from different  
82 points in the sky to a particular point within the stand and compute transmission  
83 along those rays taking into account foliage characteristics, thus generating a  
84 detailed 2D-map of light availability in the understorey (Cescatti 1997; Brunner  
85 1998; Stadt and Lieffers 2000; Courbeau *et al.* 2003; Mariscal *et al.* 2004 ).  
86 However these models require abundant field measurements to parametrize them.  
87 These measurements, like a map of tree location on the site, the 3D-geometry of  
88 each tree crown with information on leaf area density, distribution and clumping  
89 inside the crown, are tedious and often difficult to obtain. Moreover, for  
90 management purpose, a detailed 2D-map of light availability in the understorey is  
91 not always required. For the forest manager an histogram of light transmittance at  
92 the plot level (i.e. percentage of soil per class of transmitted light, without  
93 knowing the spatial distribution of the light transmittance) can be sufficient.

94 From a scientific point of view, there is a need to identify the key elements of  
95 plant architecture that are necessary to consider to correctly predicts different  
96 processes including light transmission, at different scales. Indeed, "simplifications

97 which are unacceptable at a detailed level of representation can become  
98 acceptable at a more integrated level (Tardieu, 2010). However the difficulty is to  
99 define what the key elements are and the emerging properties linked to them  
100 related to such or such a scale of description.

101

102 M $\mu$ slim is a model especially designed to bridge the gap between the statistical  
103 and explicit approach. It can be seen as a multi-scale mixed model in the sense  
104 that the light interception estimation method can be changed at each scale (Da  
105 Silva *et al.* 2008). Furthermore, M $\mu$ slim was designed to to work with any type of  
106 envelope encompassing the vegetation for which light attenuation is to be  
107 computed, thus allowing precise description of complex canopy and crown  
108 shapes. This feature allowed to overcome the restriction to analytically defined  
109 envelope used in other models (Norman and Welles, 1983; Cescatti 1997).  
110 Although it was initially dedicated to study light interception by isolated trees, its  
111 versatile design and multi-scale approach made its adaptation to use at canopy  
112 scale easy. Therefore we were able to use it to analyse how the deterioration of the  
113 canopy description influences the accuracy of the light histogram simulated at the  
114 plot level. Our objective was to specify the minimum field data needed by the  
115 model to be able to accurately simulate the light distribution. Our experimental  
116 design was as follow, 1) compare the simulated light distribution using the more  
117 detailed description of the canopy with measured data on the field, 2) analyze the  
118 statistical distance between histograms simulated for decreasing levels of

119 description and measured data.

120

## 121 **Material and Method**

### 122 **1. Forest sites and plots**

123 Three forest sites located in France with a total of 8 plots were used with  
124 increasing canopy structure complexity; 5 monospecific even-aged stands made  
125 up from *Pinus sylvestris* L. or *Pinus nigra* Arnold, 2 mixed *Quercus petraea* L. -  
126 *Pinus sylvestris* L. uneven-aged stands and 1 mixed *Abies alba* – *Pinus sylvestris*  
127 – *Fagus sylvatica* L. uneven-aged stands (Tab.1).

128 The Scots pine stands are located in the Chaîne des Puys, a mid-elevation volcanic  
129 mountain range at a place named Fontfreyde (Tab. 1). The elevation is 900 m  
130 a.s.l., mean annual rainfall is about 820 mm, and mean annual temperature is  
131 about 7°C. The soil is a volcanic brown soil at pH 6.0 with no mineral deficiency.  
132 The pines were 30 to 50-year-old at time of measurement, with a density ranging  
133 from 500 to 2300 stem ha<sup>-1</sup> (Tab. 1). They are mainly regular even-aged stands.  
134 Some other species can be locally present such as *Betula pendula*.

135 The mixed oak – pine stands are located in the National forest of Orleans, in the  
136 sub-part named Lorris. They are typical stands of temperate plain forest with a  
137 mild climate (mean annual rainfall 720 mm; mean annual temperature 10.8°C)  
138 and acidic sandy poor soils temporarily flooded in winter or spring. They are  
139 irregular uneven-aged stands. Median DBH are about 18 cm, whereas some  
140 individuals, in particular of Scots pine, can reach 70 cm. Some other species are



141 locally present such as *Betula* sp., *Carpinus betulus*, *Sorbus torminalis*, *Malus*  
142 *sylvestris* or *Pyrus communis*.

143 The third site is located in the South-East of France, in the mountainous area  
144 named Mont Ventoux. One plot, VentouxC7, on the southern side of the  
145 mountain, 1100 m a.s.l., is an old even-aged *Pinus nigra* plantation, almost  
146 regular, with some pine and beech seedlings, on a flat area. The second plot,  
147 Ventoux34, on the northern side of the mountain, 1400 m a.s.l., is a mixed  
148 irregular stand with advanced regeneration of *Abies alba* and *Fagus sylvatica* with  
149 some taller saplings almost reaching the open overstorey of old planted *Pinus*  
150 *sylvestris*, and some other scattered species (*Sorbus aria*, *Acer opalus* ...). The  
151 climate is mountainous with Mediterranean influences (mean annual temperature  
152 is 8.6°C and 6.7°C, and mean annual rainfall is 1080 mm and 1360 mm, for  
153 VentouxC7 and Ventoux34, respectively). The soils are a calcosol (VentouxC7)  
154 and a colluvial rendosol (Ventoux34), 20 cm and 50 cm deep in average,  
155 respectively, with a high stone content (50% and 75% resp.), both with a silty clay  
156 texture, on a fissured limestone. The median DBHs approximate 38 and 15 cm  
157 (for the first and the second plot respectively) with some trees reaching 50 cm.

158

## 159 **2. Canopy structure measurements**

160 All trees in a square area, the experimental unit (Fig.1a), of size approximately  
161 three times the height of dominant trees, were identified (species), located by their  
162 x, y coordinates, and measured for their total height and Diameter at Breast Height

163 (DBH). Top and bottom crown heights were also measured. Lateral crown extents  
164 was assessed by visually projecting to the soil its characteristic points (i.e. the  
165 points that better describe the crown irregularities) in, at least, four directions, but  
166 sometimes with more than 8 directions when necessary. The azimuth and distance  
167 of those points from trunk were then measured (Fig.1b and c).

168

### 169 **3. Light measurements**

170 The light measurements were conducted in the central zone of the experimental  
171 unit. The surrounding zone where dendrometric measures were done acts as a  
172 buffer zone accounting for the attenuation of the encompassing forest (Fig.1a.).  
173 The light measurements were achieved using a square grid composed of 64 PAR  
174 sensors, namely *Solems PAR/CBE 80* sensors. Each sensor was separated from its  
175 neighbour in both direction by 2 to 3.5m depending on the considered plot (i.e.  
176 depending on the mean size of the trees). This distance was set by previous  
177 computation based on geostatistics (data not shown) and so that two contiguous  
178 measurements (points) can be considered as independent. Light measurements  
179 were done for each plot during 24h during summer to take the full sun course into  
180 account. One additional PAR sensor, *Sunshine sensor BF2*, was positioned  
181 outside of the experimental unit in full light to measure global (total) and diffuse  
182 incident radiation. This extra sensor uses an array of photodiodes with a  
183 computer-generated shading pattern to measure incident solar radiation and the  
184 D/G ratio, i.e. the diffuse to global radiation ratio. Transmittance for each point in

185 the understory is then computed as the ratio of light measured in the understory  
186 divided by the incident value. The D/G ratio is taken into account for simulating  
187 the transmittance with the model.

188

#### 189 **4. Model description**

190 Estimation of light transmission is a process that requires first the stand  
191 reconstruction. Then, the light attenuation within each crown must be defined so  
192 that the light model can compute the transmittance under the entire canopy.

##### 193 ◦ Canopy reconstruction

194 From the dendrometric measurements on the field, a mockup of the stand is  
195 generated. This generation involves the construction of a crown (and trunk) for  
196 each tree of the stand and its positioning. To reconstruct the 3D envelopes of the  
197 trees from the field measurements, we used the PlantGL library (Pradal *et al.*  
198 2008). This library contains several geometric models, including different types of  
199 envelopes and algorithms to reconstruct the geometry of plants at different scales.  
200 In this work, we used the *skinned surface* which is a generalization of surface of  
201 revolution with varying profiles being interpolated. The envelope of a skinned  
202 hull is a closed skinned surface which interpolates a set of profiles  $\{P_k, k = 0, \dots,$   
203  $K\}$  positioned at angle  $\{\alpha_k, k = 0, \dots, K\}$  around the  $z$  axis, where  $K$  is the  
204 number of profiles used to generate the skinned surface. This surface is thus built  
205 from any number of profiles with associated direction. In such case, a profile is  
206 supposed to pass through common top and bottom points and at an intermediate

207 point of maximum radius, i.e. the height of the crown maximum width. Two  
208 shape factors,  $C_T$  and  $C_B$ , were used to describe the shape of the profiles above  
209 and below the maximum width. Mathematically, two quarters of super-ellipse of  
210 degree  $C_T$  and  $C_B$  were used to define the top and bottom part of the profiles, see  
211 Da Silva *et al.* (2008) for details. Note that our envelopes can be viewed as  
212 extension of Cescatti (1997)'s asymmetric hull with profiles in any direction  
213 instead of the restricted cardinal directions. Flexibility of our model enabled us to  
214 measure the most adequate profiles in case of irregular crowns. The 3D envelope  
215 of a tree was thus obtained using a skinned surface generated from profiles  
216 defined from an angle, a maximum width and its associated height and two shapes  
217 factors. The trunk of the tree was represented as a cylinder of DBH diameter, the  
218 height of the cylinder being set to the crown bottom height. The 3D representation  
219 of an experimental unit is presented in Fig.2.

220       ◦ Estimation of light transmission

221 The light transmission under such reconstructed stand was computed using the  
222 multi-scale light interception model (M $\mu$ SLIM) presented in Da Silva *et al.*  
223 (2008). For each direction of incoming light, a set of beams was cast and the  
224 attenuation of each beam through the canopy was estimated. In the present study,  
225 the model was a simple two-scale model where the porous envelopes of crowns  
226 constituted the finest scale and the stand, the coarser scale. In replacement of the  
227 delicate estimation of leaf area density (LAD), a global opacity value,  $p_{gl}$ , was  
228 associated with each envelope of the reconstructed stand, the trunks were

229 considered opaque organs, thus their opacity was 1. Crowns global opacity were  
 230 estimated from field photographs shooting vertically different parts of the crown.  
 231 Each image was digitized, segmented to black and white and then the pixels were  
 232 counted using *PiafPhotem* software (Adam *et al.*, 2006). The ratio of black pixels  
 233 to the total number of pixels yielded the opacity of the crown while the ratio of  
 234 white pixels to the total number of pixels produced the crown porosity, hence  
 235 porosity = 1 - opacity. However, the opacity of each individual crown was not  
 236 directly estimated using this method because the segmentation procedure still  
 237 required human intervention. Instead a global opacity value per species was  
 238 estimated over a sample of pictures (Tab.1). M $\mu$ SLIM allowed then to compute  
 239 the light transmission of the canopy by considering the light attenuation of each  
 240 beam. The light attenuation for one beam is computed according to the opacities  
 241 of the crowns encountered along its trajectory and according to the path length  
 242 within each of these crowns. The porosity expression that takes the beam  
 243 travelling distance into account is related to  $G$  (Chen and Black 1992; Ross 1981;  
 244 Stenberg 2006), the extinction coefficient that depends on light direction and leaf  
 245 inclination distribution, and  $LAD$ , the leaf area density. It can be expressed as:

$$p = \frac{1}{\beta} \sum_{b \in B} (1 - \exp(-G.LAD.l_b)) , \quad (1)$$

246 where  $B$  is the set of beams  $b$ ,  $\beta$  is its cardinality, and  $l_b$  is the path length of the  
 247 beam into the crown. To take this distance into account, we thus need to  
 248 determine the quantity  $G.LAD$ .

249 The global opacity value can be regarded as the result of opacity estimation using  
250 Beer-Lambert law in a infinite horizontally homogeneous layer:

$$p_{gl} = 1 - \exp( -G .LAI ) . \quad (2)$$

251 This relation yields an expression for  $G.LAI$ , where  $LAI$  is the leaf area index. In  
252 the case of crowns with a finite volume,  $V$ , the usual definition of  $LAI$  can be  
253 extended to be expressed as a function of the total leaf area,  $TLA$ , and the  
254 projected envelope area,  $PEA$  (Sinoquet *et al.* 2007)

$$LAI = \frac{TLA}{PEA} , \quad (3)$$

255 and since  $LAD$  is the ratio of total leaf area to crown volume,

$$LAD = \frac{TLA}{V} . \quad (4)$$

256 We can express  $G.LAD$  as

$$G.LAD = \frac{G.LAI .PEA}{V} = \frac{-\log(1 - p_{gl}).PEA}{V} . \quad (5)$$

257 Using this  $G.LAD$  value with equation (1) naturally leads to a smaller envelope  
258 opacity value than  $p_{gl}$ . This is due to the fact that the negative exponential of a  
259 mean value is less than the mean of negative exponential values. Therefore a  
260 numerical approximation was carried out using the value from equation (5) as the  
261 starting value to speed-up convergence. The process stopped when the opacity  
262 computed using equation (1) was equal to the global opacity within a user-defined  
263 error,  $\epsilon$ . This  $G.LAD$  approximation was done once for each crown and for each

264 direction, and stored for further usage. The crown opacity for each beam,  $p_b$ , was  
265 then computed using the expression

$$p_b = 1 - \exp(-G \cdot LAD \cdot l_b) . \quad (6)$$

266 The light transmission of the canopy along one direction was estimated by  
267 computing, for each beam, its total opacity resulting from its travelling through  
268 the canopy, i.e. possibly going through multiple crowns, see Da Silva *et al.* (2008)  
269 for algorithmic and computational details. Experimental conditions were  
270 simulated by using two sets of incoming radiation directions. The first set, for  
271 diffuse light, discretized the sky hemisphere in 46 solid angle sectors of equal  
272 area, according to the Turtle sky proposed by Den Dulk (1989). The directions  
273 used were the central direction of each solid angle sector. The second set, for  
274 direct light, was used to simulate the trajectory of the sun, and the directions were  
275 dependant of the location (latitude, longitude), the day of the year, and on the time  
276 step used for the sun course discretization (approx. 25 directions in this work).  
277 Each of these directions was associated with a weighting coefficients derived from  
278 the Standard Over Cast (SOC) distribution of sky radiance (Moon and Spencer  
279 1942). The porosity is directly the ratio of transmitted light to incident light, a  
280 value of 1 means that all light goes through while a value of 0 means that no light  
281 goes through. The grey-level image constituted by the beam porosity values is  
282 therefore a shadow map of the canopy transmittance. For each defined direction,  
283 M $\mu$ SLIM was used to compute the opacity values of the beams and to produce  
284 such an image in a plane orthogonal to the light. To ensure both results precision

285 and fast computation, a lineic density of 150 was used for the beam sampling (Da  
286 Silva *et al.*, 2008), thus generating 150 x 150 pixels images. The images were  
287 then projected on the ground and rotated according to the light directions azimuth.  
288 Images from each set of incoming radiation directions were merged by using the  
289 weighting coefficients producing two intermediate images, one for the integrated  
290 transmittance of diffuse light and one for the direct light. Finally, these two  
291 images were merged using the diffuse to total ratio, D/G, measured from the extra  
292 sensor in the field. The grey-level values of pixels, from 0 (black) to 1 (white),  
293 represented the transmittance classes simulated by M $\mu$ SLIM. The simulated light  
294 transmittance of the central zone could then be compared to the field  
295 measurements.

296

## 297 **5. Virtual experiments**

298 To assess the effect of the deterioration of canopy description on the simulated  
299 light histogram, we generated five different types of mockups for each stand with  
300 decreasing amount of information on canopy architecture.

- 301 1. The *asymmetric* mockup where *all available dendrometric* data are used to  
302 generate asymmetric crowns.
- 303 2. The *simple mean* mockup where crowns are represented by simple  
304 geometric shapes, cones for pines, spheres otherwise, and where the radius  
305 of each shape is the *mean of the measured radii*.
- 306 3. The *simple max* mockup where crowns are represented by simple



307 geometric shapes, cones for pines, spheres otherwise, and where the radius  
308 of each shape is the *maximum of the measured radii*.

309 4. The *allometric radius* mockup where crowns are represented by simple  
310 geometric shapes, cones for pines, spheres otherwise, and where the *radius*  
311 of each shape is obtained from *allometric relation with DBH*.

312 5. The *allometric* mockup where crowns are represented by simple geometric  
313 shapes, cones for pines, spheres otherwise, and where the *radius* of each  
314 shape and the *height* of cones are obtained from *allometric relation with*  
315 *DBH*.

316 For every type of mockup, the values for the height of crown base and for the  
317 height of the cones (except for the *allometric* type) are the measured ones.

318 Allometric relations were defined as linear model between DBH and mean radius  
319 and, for pines, between DBH and height. The relations obtained from field  
320 measurements data are described in Tab.2, and Fig.2 shows 3D reconstructions  
321 using two different types of crown shapes.

322 To complement the attenuation effect of the buffer zone for low elevation  
323 radiations, it was necessary to add an artificial cylindrical wall surrounding the  
324 zone of interest. The wall was centered on the zone of interest with a radius of the  
325 zone of interest size. The height of the wall was set to the mean base crown height  
326 of trees in the zone of interest. The coefficient of transmission of the wall (i.e.  
327 wall opacity) was calibrated using *in silico* simulation experiments with the stands  
328 of one site and then validated using the other stands from independent sites.

329 Adequacy of this method will be discussed further on.

330

### 331 **6. Model estimation**

332 The model outputs were qualitatively and quantitatively compared to experimental  
333 data. The qualitative estimations were carried out by comparing the light  
334 transmittance Cumulative Distribution Functions (CDF) to determine over- and/or  
335 under-represented light transmittance class. The quantitative estimations were  
336 achieved with the Kolmogorov–Smirnov test (K-S test) and the absolute  
337 discrepancy index, AD (Gregorius 1974; Pommerening 2006). The K-S test is a  
338 non-parametric test for the equality of continuous, one-dimensional probability  
339 distributions that can be used to compare two samples. It quantifies the maximum  
340 distance between the empirical CDF of two samples. The null distribution of this  
341 statistic is calculated under the null hypothesis that the samples are drawn from  
342 the same distribution. The p-value of the K-S test represents the  $\alpha$  level at which  
343 the null hypothesis can be rejected (i.e. a p-value  $> 0.1$  means that the null  
344 hypothesis cannot be rejected at 10% or lower level).

345 The absolute discrepancy index is defined as:

$$AD = \frac{1}{2} \sum_{i=1}^n |s_i - s'_i| \quad AD \in [0,1] \quad (7)$$

346 where  $n$  is the number of classes,  $s_i$  is the relative frequency in class  $i$  of the first  
347 distribution, and  $s'_i$  is the relative frequency in class  $i$  of the second distribution.  
348 AD is defined as the relative proportion that needs to be exchanged between the

349 classes if the first distribution were to be transformed into the second distribution.  
350 Correspondingly, 1-AD is the proportion common to both distributions, a value of  
351  $AD = 1$  means that both distributions have no common class, whereas  $AD = 0$   
352 signifies that the distributions are absolutely identical (Pommerening 2006).  
353 Both quantitative analysis were carried out with light measurements as reference  
354 values and the results are shown in Tab.3.

355

356

## Results

357 The comparison between the CDF of the measured light transmittance and the  
358 ones obtained with the different mockups, as shown in Fig.3, were used to  
359 qualitatively assess the quality of the model prediction and the effect of  
360 deterioration of crown shape description. The CDF provides an alternate  
361 representation to light transmittance histograms that facilitates comparison  
362 between different distributions. The importance of a specific light transmittance  
363 class is given by the slope of the CDF at that point, i.e. a non represented class  
364 will yield a null slope and the more substantial the class, the steeper the slope  
365 (Fig. 3). The classes of high importance will be titled as main classes whereas the  
366 classes of low significance will be designated as minor classes.

367

368 *Simulation with asymmetric mockups*

369 The light model using the asymmetric mockups was able to simulate light  
370 transmission distribution similar to the measurement with a level of confidence of

371 the K-S test above 5% for all stands except Fonfreyde5 (3%) and Fonfreyde1  
372 (<1%). In that case, the mean comparison yielded a statistically significant  
373 difference for the same two stands. However, the AD values were below 0.3 for  
374 all stands with a mean of 0.21 (Tab.3).

375 In the case of Fonfreyde1, the measured transmitted light were almost evenly  
376 distributed in only two light transmittance classes, [0-5] and [5-10]. The simulated  
377 distribution showed the same two main classes with an unbalance in favor of the  
378 [0-5] class. Although the p-value of the K-S test allowed to reject the hypothesis  
379 that the measured and simulated light distribution were similar, the AD value was  
380 below the mean value of all stands. The simulated transmittance of Fonfreyde2  
381 were almost identical to the measured ones despite the missing [0-5] class in the  
382 simulation (i.e. simulated CDF slope is null through entire [0-5] class). The best  
383 values for both the p-value and AD were obtained for this stand. In the case of  
384 Fonfreyde3 the difference in the standard deviation (Tab.3) between the measured  
385 and simulated light distributions was a good indicator of the fact that the lower  
386 and higher classes, [15-25] and [50-60] respectively, were not simulated to the  
387 profit of the median classes [30-40] as shown by the *Asymmetric* CDF being  
388 below and then above the CDF of measurements. On the contrary, in the case of  
389 Fonfreyde5, the *Asymmetric* CDF started below and ended above the  
390 measurement one, indicating that the median classes ([10-20]) were under  
391 simulated to the benefit of the [30-35] class that did not appear in the  
392 measurements and the [5-10] one that have very low substance. The highest AD

393 values were obtained for these two stands.

394 The simulated distributions for Lorris38 correctly rendered both the main and  
395 minor classes with, however, a less pronounced peak for the [5-10] class  
396 expressed by the more abrupt slope of the measured CDF. There were no missing  
397 or extra classes simulated and the AD was just above the mean value. Similarly to  
398 Lorris38, the main and minor classes of Lorris255 were correctly simulated  
399 without any missing or extra classes. Within each group, main and minor, some  
400 classes were under-represented to the benefit of the over-represented ones.  
401 However these discrepancies were subsidiary as the very high p-value and the  
402 below-the-mean AD attest. In the case of VentouxC7, the simulated distribution  
403 reproduced the bell-shape of the measured one but with slightly heavier tails due  
404 to the two extra classes on the sides of the distribution, [35-40] and [65-70]. Note  
405 that the isolated [10-15] measured class was not simulated, as shown by the  
406 advent of a proportion difference between measurements and simulation.  
407 Similarly to Lorris255, a high p-value and a low AD were observed despite of  
408 these differences. Finally, the simulated distribution for Ventoux34, whereas  
409 correctly simulating the two main classes, [0-5] and [5-10] accounting for almost  
410 70% of the transmittance distribution, increased the unbalance between them in  
411 favor of the lowest one. The minor classes were adequately simulated but without  
412 respecting the discontinuity shown in the measurements as indicated by the above-  
413 mean AD.

414

415 *Simulation with the simple mean mockups*

416 Replacing the asymmetric by the *simple mean* mockups significantly reduced the  
417 p-values of the KS test, except for Fonfreyde1 and Fonfreyde3, but yielded AD  
418 values below 0.3, except for Fonfreyde5 and VentouxC7, that were similar to the  
419 ones obtained with the *asymmetric* mockups as shown by the slight increase of the  
420 mean AD to 0.24. The principal effect of this change of crown shape on the  
421 distributions of light transmittance compared to the distributions obtained with the  
422 *asymmetric* crowns was to reduce the most represented classes to the benefit of  
423 the minor ones. This was comparable to the crushing effect obtained on a  
424 Gaussian function by increasing its variance parameter. The variance increase was  
425 indeed observed for all stands but Lorris255 and interestingly, the two sample t-  
426 test indicated statistically significant differences for Fonfreyde5, VentouxC7 and  
427 Lorris255. This effect actually benefited Fonfreyde1, Fonfreyde3 and Lorris38  
428 simulation results. The p-value increased and AD decreased significantly for  
429 Fonfreyde1 and Fonfreyde3, whereas for Lorris38, both values decreased.

430

431 *Simulation with the simple max mockups*

432 The *simple max* approach yielded light transmittance distributions that were  
433 significantly shifted to the lower transmittance classes, i.e. left shifted CDF (Fig.  
434 3). This effect was visible on the simulation results of all stands but was less  
435 pronounced for Fonfreyde3 and VentouxC7. The dramatic increase of the AD  
436 mean value to 0.6 well illustrated this behavior but mean comparison was

437 sufficient to assess the importance of the discrepancies.

438

#### 439 *Simulation with allometric mockups*

440 The use of the *allometric radius* and *allometric* mockups yielded similar results as  
441 illustrated by comparable means and variances and similar mean AD values, 0.345  
442 and 0.333, respectively. The effect of this change of crown shape on the  
443 distributions of light transmittance was similar to the *simple mean* effect with the  
444 addition of a slight shift toward higher transmittance classes, indicated by right  
445 shifted CDF (Fig. 3). The p-values were significantly reduced except for  
446 Fonfreyde1, Fonfreyde5 and Ventoux34, but only for Fonfreyde1 this increase of  
447 the p-value was associated with a decrease of AD (Tab.3).

448

#### 449 *Comparison between all simulations*

450 The AD results (Fig.4) show that the *asymmetric* mockups yielded the  
451 distributions closest to the measurement, the *simple mean* approach deteriorated  
452 slightly the results whereas the *simple max* approach had dramatic effect. Using  
453 *allometric* crowns yielded results in between but closer to the *simple mean* ones.  
454 These results confirmed the classification trend yielded by the two-sample t-test  
455 analysis that showed no statistically significant differences between the  
456 measurements and the *asymmetric* and *simple mean* approaches on one side,  
457 between the two *allometric* approaches on the other side and showed the  
458 segregation of the *simple max* one.

459

460

## Discussion

461

462 *Statistical considering*

463 Our study on the impact of the deterioration of the accuracy of crown  
464 representation on simulated light transmission highlighted some statistical issues.

465 In spatially explicit transmittance models, a spatially point to point comparison

466 approach between measured and modeled transmittance generally shows little

467 agreement because small errors in crown location, often coming from errors

468 during field measurements, yields large local differences in transmittance

469 (Mariscal *et al.* 2004), particularly when the proportion of direct radiation is

470 important (Groot *et al.* 2004). However only considering a mean and variation

471 around this mean (e.g. SD) could lead to some errors (e.g. underestimation of area

472 fully lighted) due to distribution non centered on mean with sometimes a long tail

473 or several modes. To avoid this problem we compared the simulated distribution

474 of light transmittance to the measured ones using two different non parametric

475 descriptors, the K-S test and the AD index.

476 Although commonly used, and mathematically well-founded, the K-S test showed

477 some limitations when applied to peculiar distributions as the one from

478 Fonfreyde1. The problem stems directly from the test definition where the

479 accordance between two distributions is based on the maximum distance between

480 the CDFs. When the distribution shows very low dispersion, a small difference in



481 distribution can yield a big maximum distance between CDFs and therefore a  
482 rejection of the null-hypothesis from K-S test. On the contrary, the AD index that  
483 measures the changes required to transform one distribution into the other is  
484 robust in regard of the distribution dispersion. Even though AD is very well suited  
485 to quantify the difference between distributions or to classify results, the AD value  
486 is not associated with any confidence index. Hence it is up to the user to define the  
487 threshold under which distributions will be considered similar. Consequently,  
488 combining the use of the K-S test and the AD index allowed us to accurately  
489 compare and assess the differences between simulated and measured light  
490 distributions.

491

#### 492 *Model evaluation*

493 The goal of the present study was not to validate, *stricto sensus*, the model  
494 M $\mu$ SLIM. Such an evaluation would require an independent data set of light and  
495 tree measurements. Our objective was to evaluate the quality of light predictions  
496 with increasing deterioration of the crown description. However the comparison  
497 of light measurements (with 64 sensors regularly distributed on a square grid in  
498 the plot) and the simulation with full asymmetric crown description (i.e. crown  
499 radius extension in 4 to 8 directions + crown height and length) showed the good  
500 quality of simulated light distribution (K-S p-value > 0.10 or AD <0.3). Results  
501 are in the range of models using similar scales of description (e.g. Brunner 1998;  
502 Cescatti 1997; Gersonde *et al.* 2004; Groot 2004; Mariscal *et al.* 2004; Stadt and

503 Lieffers 2000).

504 As pointed out by Norman and Welles (1983), the computation of beam path  
505 lengths is a crucial procedure. Due to the multi-scale design of M $\mu$ SLIM, in  
506 addition to the possibility of using any type of envelope, an analytical resolution  
507 as proposed by Norman and Welles (1983) or Cescatti (1997) was not an option.  
508 This task was instead performed by ray tracing algorithms that determine and  
509 analyse the path of each cast ray among the canopy crown shapes (Wang and  
510 Jarvis, 1990). With the ever increasing computational power of graphic cards  
511 available to high level operations, this formerly time consuming procedure can  
512 now be executed for many direction without impairing the model performances.

513

514 To avoid the problem of low elevation angles ; i.e. interception of light by very far  
515 elements close to the horizon in the field, whereas not represented in the model,  
516 we had to come up with an alternative to the classical solution of canopy  
517 duplication or projection on torus. These approaches are based on the strong  
518 assumption of canopy homogeneity ; using them with our strongly heterogeneous  
519 stands would introduce a non controlled approximation that would, in turn, induce  
520 bias in the results interpretation. Instead we chose to estimate the radiative  
521 parameters of the surrounding environment using an inverse modeling approach  
522 through the addition of an opaque wall. The wall opacity was calibrated using  
523 Fonfreyde stands data with full asymmetric crown description. The value was then  
524 used as a parameter to run the simulations for the stands from the two other

525 independent sites at the same level of crown description. Finally, the model  
526 predictions were compared to the field light measurements. The results suggest  
527 that the coefficient of transmission of the wall properly represented the radiative  
528 properties of the environment, at least for low elevation angles. Moreover,  
529 considering our objective, the opaque wall approach provided a simple solution  
530 saving significant computational time otherwise required by the canopy  
531 duplication. This approach seems thus promising and simple to set-up but would  
532 benefit from more complete sensitivity analysis, in particular on wall size or  
533 position.

534 One interest of our model is that crown porosity is simply estimated by a vertical  
535 photograph of tree crown (extension of the method of Canham *et al.* 1999) and  
536 seems to support accurate results in light distribution; however the extent to which  
537 this parameter influenced the results needs to be more adequately studied. As  
538 pointed out by Stadt and Lieffers (2000) determination of leaf and shading  
539 elements (branch, trunk) is often critical in light transmission modeling.

540

#### 541 *Effects of crown description deterioration*

542 Our results corroborate that differences in crown shape and size is a key  
543 determinant of light transmittance as stated by Vieilledent *et al.* (2010). Moreover,  
544 this study confirmed the importance of crown shape when simulating spatialized  
545 light transmittance and endorse the sensitivity to variations in the crown geometry  
546 parameters, especially the crown radius parameter, as already reported (Beaudet *et*

547 *al.* 2002; Brunner 1998; Cescatti 1997). However a crown mean radius with  
548 crown height and spatialization seem to be a good alternate (Courbaud *et al.* 2003)  
549 to detailed measures (i.e. measurement of crown extension in 4 to 8 directions)  
550 even though simple shape like spheres and cones are known to be inadequate  
551 (Mariscal *et al.* 2004). Other shapes should be tested, more in relation with tree  
552 species architecture. Simplifying the crown representation in the tRAYci model to  
553 average values for species and canopy strata resulted in little reduction in the  
554 model performance (Gersonde *et al.* 2004). Describing tree crown extension with  
555 4 to 8 radius is typically non feasible in practice in management or inventory  
556 operations, whereas assessing mean crown diameter may be acceptable in some  
557 cases. Therefore an approach that starts with simple shapes that can later be  
558 deformed using an optimization process (Boudon and Le Moguedec 2007; Piboule  
559 *et al.* 2005) should be considered in further studies. Indeed previous studies  
560 showed the importance of crown asymmetric plasticity in response to local light  
561 availability and space, among other factors (Vieilledent *et al.* 2010 and references  
562 in it).

563

564 However using an *Allometric* approach would be more comfortable. The problem  
565 is that the use of relationships between tree DBH and crown diameter or crown  
566 height often decreased transmittance distribution prediction, whereas not for all  
567 stands. With the allometric approach, the model generated smaller crown than  
568 *simple mean*, thus same effect with shift to higher transmittance. We only tested

569 linear relationships and non-linear functions could have led to slightly better  
570 results (Beaudet *et al.* 2002) ; however many authors pointed out that the  
571 predictive functions for crown radius from e.g. DBH has proved elusive (Stadt *et*  
572 *al.* 2000) as they are often highly affected by uncontrolled factors such as climate  
573 hazards, stand density, or thinning operations (as probably reflected in the  
574 Fontfreyde's plots). There is often a high variability in tree allometry from an  
575 individual to another (Vieilledent *et al.* 2010). Actually the R<sup>2</sup> of the relationships  
576 linking crown diameter to trunk diameter in that study are not excellent but in the  
577 range of those commonly found in other studies (e.g. about 0.7 in Pinno *et al.*  
578 2001 or Pukkala *et al.* 1993).

579

#### 580 *Effects of the stand complexity*

581 High light variability is generally recorded in forests due to temporal variations of  
582 the sun path and heterogeneous spatial arrangement of light intercepting elements  
583 in irregular and/or mixed stands (Courbaud *et al.* 2003; Pukkala *et al.* 1993). In  
584 stands with a clumped structure (i.e. tree clumps alternating with large gaps), only  
585 an approach at tree scale with spatialization can correctly predict transmittance,  
586 whereas in dense stands, a Beer-Lambert law can be applied at the stand canopy  
587 scale (Balandier *et al.*, 2010). It is however important to note that in dense stands,  
588 importance of small gaps within tree crowns due to different causes (diseases,  
589 broken branches, not taken into account in the simulation) can lead to noticeable  
590 differences as such of Fontfreyde 1 (Fig.3) (Beaudet *et al.* 2002). Low density

591 stands Fonfreyde3 and VentouxC7 are less affected by the *simple max approach*  
592 probably because the crown “increase” is not enough to fill the 'big' gaps in the  
593 canopy. Problems of crown overlaps, in fact very difficult to quantify in the field,  
594 are also probably less critical than in dense stands.

595 As already pointed out by Courbaud *et al.* (2003) or Balandier *et al.* (2010) the  
596 problem is that it is very difficult to generalize results recorded on a site for a  
597 particular stand structure to other sites or stands with other species or structures.  
598 This argues in favor of studying the effect of stand structure in interaction with the  
599 scale of stand description; this could be done for instance by the use of point  
600 process analysis.

601

602

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606

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610

611

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## Tables

771

772

773

Table 1: Plot description. Each plot was approximately 50m x 50m

Site	Latitude Longitude	Elevation (m)	Density (stem ha <sup>-1</sup> )	Mean Height (m) (Min- Median-Max)	D.B.H. (cm) (Min- Median-Max)	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Tree species	Basal area (%)	Opacity
<b>Fonfreyde1</b>	47°42'N 02°58'E	920	2353	7.3	7	54	Pinus sylvestris	99.4	0.835
				14.5	16		Other species	0.6	
				18.4	33				
<b>Fonfreyde2</b>	47°42'N 02°58'E	920	1103	7.2	7	33	Pinus sylvestris	73.6	0.835
				14.5	17		Other species	26.4	
				18.3	42				
<b>Fonfreyde3</b>	47°42'N 02°58'E	920	563	6.3	9	22	Pinus sylvestris	90.4	0.835
				14.2	21		Other species	9.6	
				18.2	37				
<b>Fonfreyde5</b>	45°41'N 02°59'E	910	710	11.3	9	42	Pinus sylvestris	96.2	0.835
				18.3	28		Other species	3.8	
				23	43				
<b>Lorris38</b>	47°47'N 02°34'E	150	664	4	7	32	Pinus sylvestris	56.7	0.79
				16.1	17		Quercus petraea	34.2	
				29.3	71		Other species	9.1	
<b>Lorris255</b>	47°49'N 02°26'E	150	607	3.7	7	24	Pinus sylvestris	36.7	0.79
				17	19		Quercus petraea	57.5	
				22.3	47		Other species	5.8	
				7.4	7		Pinus nigra	98.0	0.84

Table 2: Allometric relation between DBH and crown mean radius and height. Linear models of the form  $a*DBH + b$  were used for both mean radius and height

	Tree species	Site	Slope (a)	Intercept (b)	R <sup>2</sup>
Mean Radius	Pinus	Fonfreyde	2.62	13.91	0.72
		Lorris	2.29	50.64	0.57
		Ventoux	1.86	69.28	0.83
	Quercus petraea	Lorris	2.73	129.69	0.60
	Fagus sylvatica	Ventoux	3.98	75.56	0.82
	Acer opalus	Ventoux	10.10	9.68	0.66
	Betula pendula	Fonfreyde	2.35	79.12	0.67
		Lorris	2.13	94.36	0.29
	Carpinus betulus	Lorris	7.18	74.78	0.36
	Populus tremula	Lorris	4.86	19.90	0.86
Sorbus torminalis	Lorris	3.19	135.01	0.67	
	Ventoux	2.88	85.38	0.71	
Height	Pinus	Fontfreyde	0.08	10.09	0.47
		Lorris	0.10	10.27	0.64
		Ventoux	0.12	2.25	0.93



Table 3 Simulation results for the different mockups reconstruction. The p-value of the K-S test and the absolute discrepancy index (AD)

were obtained with the measured light values as reference. Means with the same letter indicate that the difference between the means are not statistically significant at  $\alpha=10\%$  for an independent two-sample t-test.

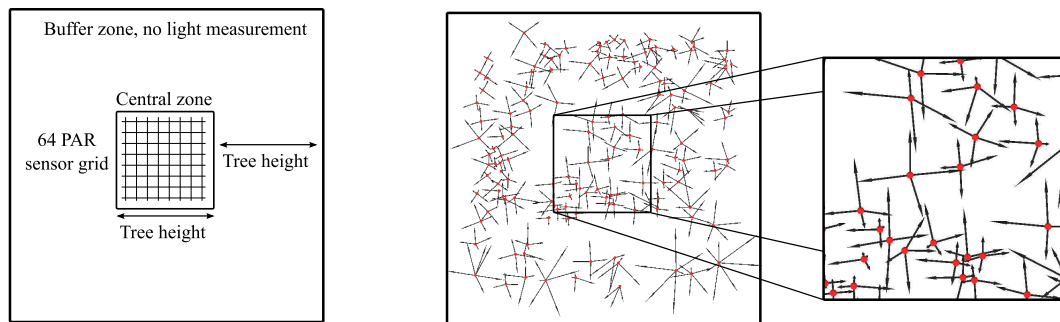
Stand\Mockup	Measures	Asymmetric	Simple Mean	Simple Max	Allometric Radius	Allometric	
Fonfreyde1	Mean	5.15 <sup>a</sup>	4.19 <sup>b</sup>	5.06 <sup>a</sup>	0.44 <sup>c</sup>	4.29 <sup>b</sup>	4.14 <sup>b</sup>
	Std	1.3	1.71	2.41	0.57	2	2.02
	p-value		1.3e-5	9.8e-3	<1e-5	7.1e-5	3.1e-5
	AD		0.203	0.063	0.516	0.141	0.172
Fonfreyde2	Mean	14.7 <sup>a</sup>	14.69 <sup>a</sup>	15.72 <sup>a</sup>	7.19 <sup>c</sup>	21.37 <sup>b</sup>	20.32 <sup>b</sup>
	Std	3.58	3.18	4.62	3.14	4.18	3.89
	p-value		0.987	0.05	<1e-5	<1e-5	<1e-5
	AD		0.078	0.219	0.75	0.594	0.531
Fonfreyde3	Mean	38.08 <sup>a,b</sup>	37.05 <sup>a</sup>	39.58 <sup>b</sup>	25.81 <sup>c</sup>	48.09 <sup>d</sup>	43.18 <sup>c</sup>
	Std	9.46	5.73	8.66	9.3	7.71	7.35
	p-value		0.08	0.52	<1e-5	1.3e-5	9.8e-3
	AD		0.281	0.234	0.453	0.406	0.329
Fonfreyde5	Mean	16.89 <sup>a</sup>	19.29 <sup>b</sup>	18.87 <sup>b,d</sup>	9.52 <sup>c</sup>	16.81 <sup>a,b,d</sup>	18.32 <sup>a,d</sup>
	Std	4.37	6.68	7.94	6.35	7.43	8.32
	p-value		0.03	0.017	<1e-5	9.8e-3	0.05
	AD		0.281	0.344	0.578	0.406	0.406
Lorris38	Mean	8.43 <sup>a</sup>	8.41 <sup>a</sup>	8.61 <sup>a</sup>	0.645 <sup>c</sup>	15.79 <sup>b</sup>	16.09 <sup>b</sup>
	Std	6.85	5.54	5.99	1.31	7.66	7.91
	p-value		0.126	0.029	<1e-5	1.9e-5	<1e-5
	AD		0.219	0.172	0.781	0.344	0.359
Lorris255	Mean	20.8 <sup>a</sup>	21.33 <sup>a</sup>	25.36 <sup>b</sup>	5.49 <sup>c</sup>	21.1 <sup>a</sup>	21.1 <sup>a</sup>
	Std	9.93	7.14	7.01	4.99	11.54	11.42
	p-value		0.758	0.029	<1e-5	0.16	0.203
	AD		0.172	0.25	0.844	0.281	0.266
VentouxC7	Mean	53.34 <sup>a</sup>	54.3 <sup>a,b</sup>	57.38 <sup>d</sup>	47.72 <sup>c</sup>	55.66 <sup>a,b</sup>	54.87 <sup>b,d</sup>
	Std	7.06	5.91	7.5	9.9	7.74	7.68
	p-value		0.52	2e-4	7e-5	0.005	0.017
	AD		0.172	0.359	0.375	0.266	0.281
Ventoux34	Mean	12.25 <sup>a,b</sup>	8.87 <sup>a</sup>	10.54 <sup>a</sup>	3.44 <sup>c</sup>	16.85 <sup>b</sup>	17.05 <sup>b</sup>
	Std	15.29	11.35	13.52	7.9	19.59	19.74
	p-value		0.05	9.8e-3	<1e-5	0.274	0.188
	AD		0.25	0.266	0.391	0.281	0.281

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## Captions of Figures

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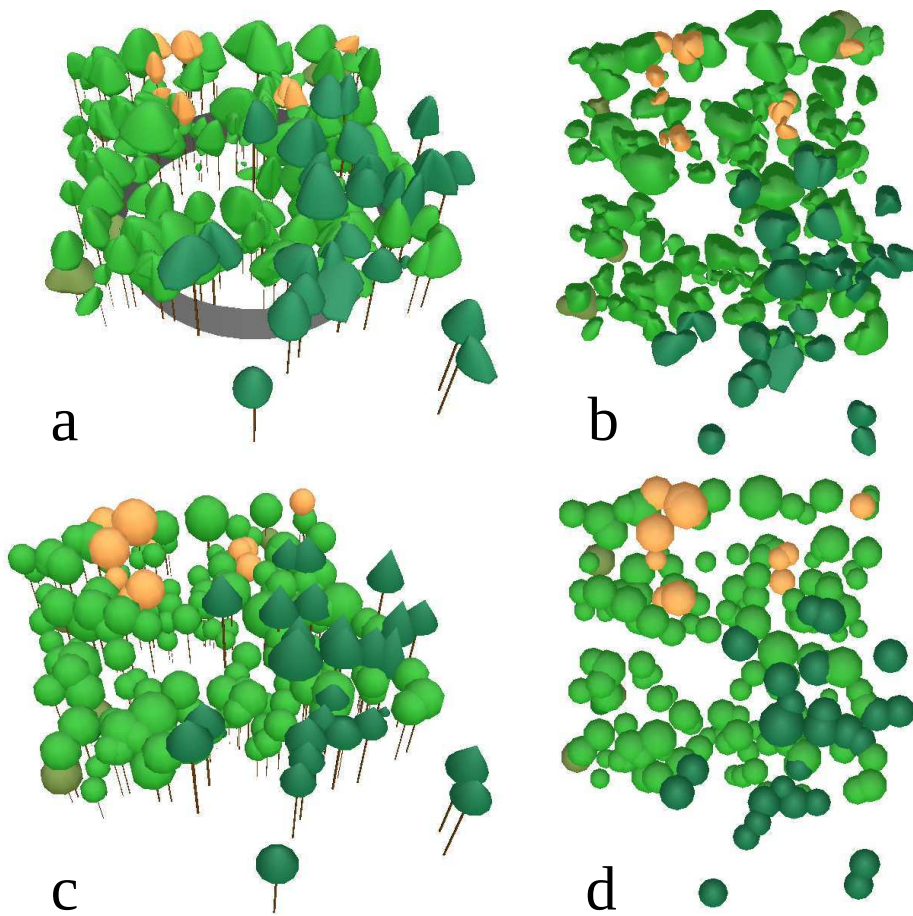
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a.

b.

c.

*Figure 1: a. Experimental Unit. b. Field data: each dot locates a tree (its trunk), and each arrow defines a specific azimuth and distance from the trunk, characterizing the crown extend. c. Zoom in on the interest zone where light measurements were conducted.*



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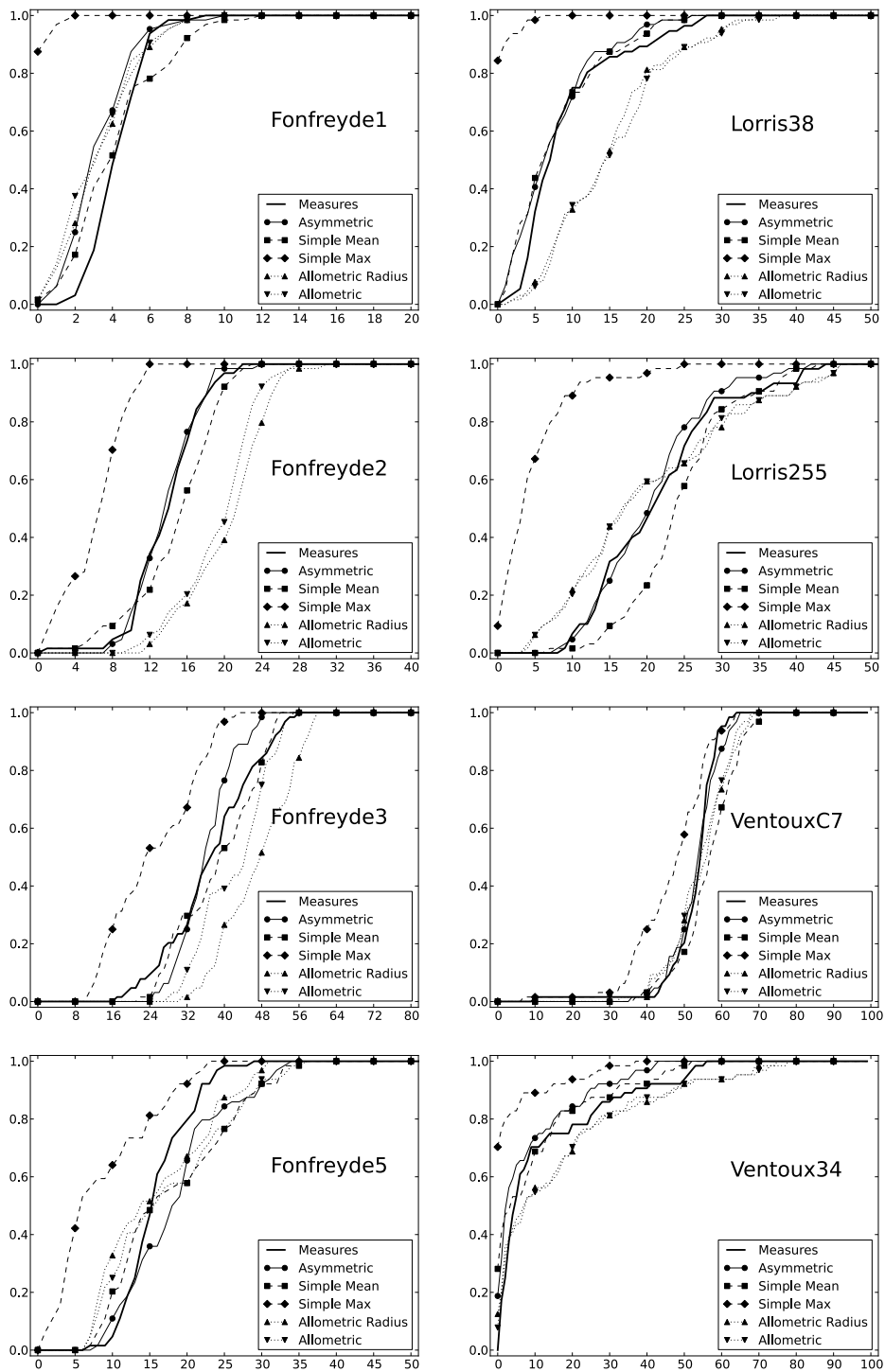
*Figure 2: 3D reconstruction of the Lorris255 experimental unit using the asymmetric crowns, side view(a) and top view(b), and using the crowns from the allometric radius approach, side view(c) and top view(d). Colors are used to visually differentiate between tree species: dark green for pine (*Pinus sylvestris* L.), green for oak (*Quercus petraea* L.), orange for birch (*Betula* L.), and brown for hornbeam (*Carpinus betulus* L.)*

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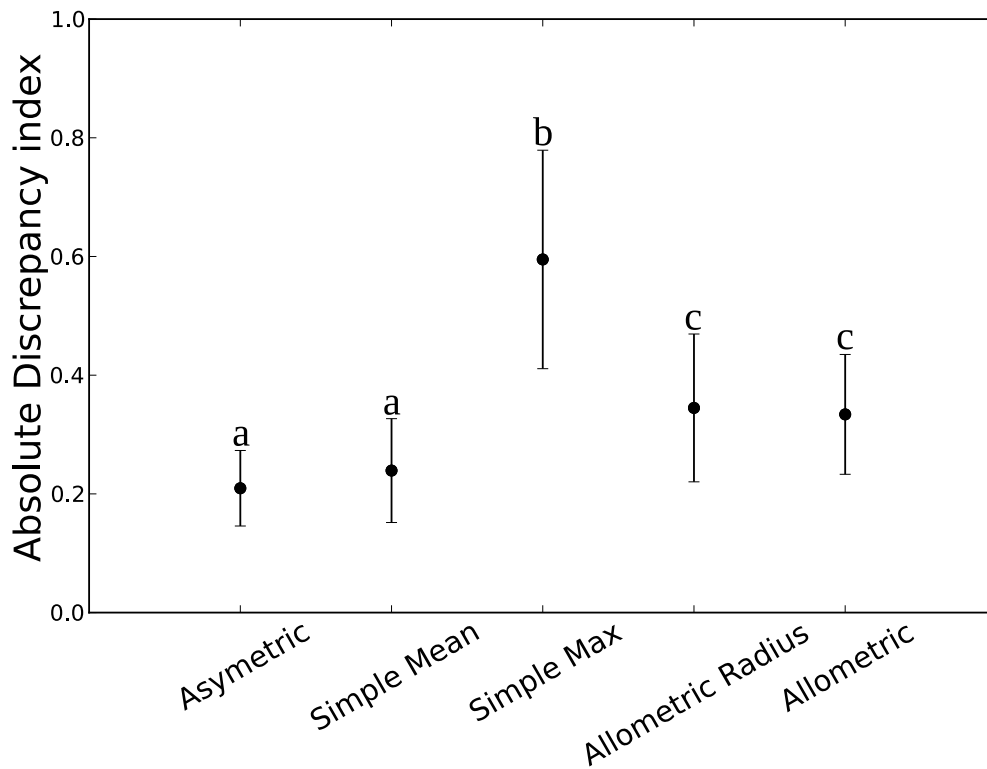
Proportion



Transmittance (%)

Figure 3: Cumulative Distribution Function (CDF) of light transmittance for each stand and for every mockup type. Note that for legibility purpose the x-axis scale was adapted for each stand.

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Figure 4: The points represent the mean of AD calculated for each type of mockup over all stands, the bars being the standard deviation. Same letter above the bars indicate that the difference between the means are not statistically significant at  $\alpha=10\%$  for an independent two-sample t-test.