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Rapid assessment of forest canopy and light regime using smartphone hemispherical photography

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1 **Rapid assessment of forest canopy and light regime using smartphone**
2 **hemispherical photography**

3 **Running head:** Smartphone hemispherical photography

4

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18 Abstract

- 19 1. Hemispherical photography (HP), implemented with cameras equipped with “fish-eye” lenses, is
20 a widely-used method for describing forest canopies and light regimes. A promising technological
21 advance is the availability of low-cost fish-eye lenses for smartphone cameras. However,
22 smartphone camera sensors cannot record a full hemisphere. We investigate if smartphone HP is
23 a cheaper and faster but still adequate operational alternative to traditional cameras for
24 describing forest canopies and light regimes.
- 25 2. We collected hemispherical pictures with both smartphone and traditional cameras in 223 forest
26 sample points, across different overstorey species and canopy densities. The smartphone image
27 acquisition followed a faster and simpler protocol than that for the traditional camera. We
28 automatically thresholded all images. We processed the traditional camera images for canopy
29 openness and site factors estimation. For smartphone images, we took two pictures with
30 different orientations per point and used two processing protocols: i) we estimated and
31 averaged total canopy gap from the two single pictures; ii) merging the two pictures together,
32 we formed images closer to full hemispheres and estimated from them canopy openness and
33 site factors. We compared the same parameters obtained from different cameras and estimated
34 generalized linear mixed models (GLMMs) between them.
- 35 3. Total canopy gap estimated from the first processing protocol for smartphone pictures was on
36 average significantly higher than canopy openness estimated from traditional camera images,
37 although with a consistent bias. Canopy openness and site factors estimated from merged
38 smartphone pictures of the second processing protocol were on average significantly higher than
39 those from traditional cameras images, although with relatively little absolute differences and
40 scatter.

41 4. Smartphone HP is an acceptable alternative to HP using traditional cameras, providing similar
42 results with a faster and cheaper methodology. Smartphone outputs can be directly used as they
43 are for ecological studies, or converted with specific models for a better comparison to
44 traditional cameras.

45 **Key-words:** total gap fraction, canopy openness, light regime, site factors

46 **1. Introduction**

47 Solar radiation is fundamental in forest ecosystems as it drives plant photosynthesis, morphogenesis,
48 and fluxes of carbon, water and energy between soil, vegetation, and the atmosphere (Ligot &
49 Balandier 2014). The analysis of the light intercepted by the tree crowns has been the basis for
50 various ecological studies, especially for the dynamics of the vegetation growing under canopy cover
51 (e.g. Pacala et al. 1996; Finzi & Canham 2000; Duchesneau et al. 2001; Coates et al. 2003). Evans &
52 Coombe (1959) started using hemispherical photography (HP) for light analysis in forest research
53 after they discovered the “ingenious ‘fish-eye’ camera” developed by Hill (1924) for cloud
54 observations. Later, Anderson (1964a; 1964b; 1966) made a crucial contribution to the computation
55 of light transmittance through tree crowns by using such photographs. HP is now considered the
56 most widely-used ground-based method for describing both canopy characteristics and forest light
57 regimes (Promis *et al.* 2011; Chianucci & Cutini 2013). It is an indirect method for measuring the light
58 transmittance with an associated level of error that can occasionally be substantial (Ligot & Balandier
59 2014). However, its advantage over instantaneous light measurement is that its results do not
60 inherently vary with time of day, time of year, or cloud cover. Direct measurements of light, such as
61 quantum sensors, can be heavily affected by the conditions at the time of the observations
62 (Anderson 1966), requires longer and more expensive data collection and are more difficult to be

63 linked to stand conditions (Čater *et al.* 2013). Another photographic method used in forested
64 environments is cover photography, which does not use a fish-eye lens and is focused more on
65 canopy parameters analysis such as the leaf area index (Macfarlane *et al.* 2007; Chianucci & Cutini
66 2013).

67 Hemispherical photography is commonly implemented with analogue or digital cameras equipped
68 with 180° field-of-view (FOV) “fish-eye” lenses pointing upwards. The first processing step is to
69 estimate the amount of sky visible through the canopy, by classifying each pixel of the photo as
70 belonging either to the sky or to any blocking element from the vegetation (canopy, leaf, branches or
71 stems) (Gonsamo *et al.* 2011). This is usually carried out by thresholding the image, which is done by
72 selecting a brightness value and considering the image pixels above this as belonging to the sky and
73 below to vegetation. Thresholding can be manual, if the operator visually decides the best brightness
74 value to use, or automatic, if software-based techniques are applied to make the process objective
75 and reproducible (Nobis & Hunziker 2005). Photo exposure, by affecting the quality of the image, can
76 strongly affect the thresholding process (Rich 1990). Specifically, over-exposure can lead to
77 overestimation of the sky fraction, but there are various methods available to tackle this issue
78 (Beckschäfer *et al.* 2013).

79 From a thresholded HP image, various methodologies and software have been developed to estimate
80 several variables, sometimes leading to a confusion in terminology (see Gonsamo *et al.* 2013). For
81 canopy structural characteristics, canopy openness (usually defined as proportion of sky visible from
82 a point) is one of the most common parameters estimated with this technology. The light
83 transmittance of the canopy has been described largely using the Site Factor definition from
84 Anderson (1966): the percentage of incident solar radiation at a given site compared to the total
85 incident solar radiation in the open over the same period. This analysis requires the knowledge of the

86 position of each gap on the hemisphere and the geographical location of the photo so that the sun
87 track can be superimposed onto the hemisphere.

88 Film handling and processing constraints slowed the widespread adoption of HP until digital
89 photography and computer software become available, leading to an increase in the use of this
90 methodology (Chianucci & Cutini 2012). Today, another potential technological advance in this field is
91 the availability of low-cost fish-eye lenses for smartphone and tablet cameras. One published case
92 has already shown that for canopy cover analysis, the proportion of the forest floor covered by the
93 vertical projection of the tree crowns (Korhonen *et al.*, 2006), smartphone HP is comparable to HP
94 using traditional cameras (Tichý 2015). However, that study involved the use of a specific smartphone
95 app (GLAMA - Gap Light Analysis Mobile Application) that is useful for on-the-fly analysis in the field
96 but less so for larger-scale studies, due to reduced processing options. Another smartphone app,
97 HabitApp (McDonald & McDonald 2016; Deichmann *et al.* 2017) allows a quick analysis of canopy
98 cover but again with limited processing options.

99 Cameras traditionally employed for HP record circular photos, while smartphone cameras take only
100 diagonal photos, following the definition of Schneider *et al.* (2009) (Figure 1). Circular HP records the
101 full hemisphere visible from the lens, while the diagonal photos consider a smaller rectangular area.
102 The fish-eye lenses available for smartphones at the beginning of this study only provided a FOV of
103 up to 160°, thus reducing even further the view compared to circular HP. Both these issues will surely
104 lead to different estimations of canopy openness between the cameras. The bias is expected to be
105 towards higher values of openness in the smartphone HP since it excludes some of the peripheries of
106 the image, the areas of the hemisphere usually more prone to be obscured. We are not aware of any
107 studies where Site Factors are calculated from diagonal pictures. A sun track could be still laid on the
108 pictures but there will be portions of the hemisphere where the computation of the light

109 transmittance will not be possible. However, in circular HP studies the area at higher zenith angles
110 (closer to the horizon) has sometimes been excluded from either canopy openness or light
111 transmittance computations, for exactly the reason that is more likely to be obscured (Machado &
112 Reich 1999) or because is prone to many sampling and optical errors (Gonsamo *et al.* 2010). Sky areas
113 located at the periphery have also less luminosity and a lower contribution to the Site Factor than
114 areas located close to the zenith (Anderson 1964a). Thus, it is possible that even if less accurate,
115 smartphone diagonal HP could provide adequate information and in more quantity on both canopy
116 structure and Site Factors, and, if a bias is present, it could be individuated and corrected. The
117 challenge is to verify that the potential reduced accuracy of such measurements does not outweigh
118 the benefits of using a cheaper, faster, less encumbering, more wide-spread technology with internet
119 connectivity. With smartphone HP, every forestry practitioner (or citizen scientists following the
120 recent trends) could carry out quick canopy or light analysis without the need for extra tools other
121 than a small fish-eye lens that fits in a pocket. This could potentially lead to an amount of data
122 substantially larger than in the traditional studies with smoothing of the probable errors present in
123 the single measurements.

124 The main objective of the present research is to determine if smartphone HP is an adequate
125 operational alternative to traditional circular HP in describing canopy structural parameters and the
126 light regime under canopy cover. For smartphone images, we will take two pictures with different
127 orientations per sample point and use two processing protocols: i) we estimate total canopy gap from
128 the two single pictures, and average the values; ii) by merging the two pictures together, we form
129 images closer to full hemispheres, so that we will be able to estimate from them canopy openness
130 and Site Factors as in circular HP. We verify if smartphone values can be directly compared to circular
131 HP ones, or, if a bias is present, whether models can be applied to transform and remove the bias.

132 The values estimated from traditional circular HP images will be considered in our study the “ground
133 truth” data against which we compare the smartphone HP estimates.

134 **2. Methodology**

135 **Canopy and light parameter definitions**

136 Of the various structural canopy parameters, we considered in this study: *Canopy Openness* (CO), the
137 area fraction of the sky hemisphere that is unobstructed by canopy or other blocking elements when
138 viewed from a single point; and *Total Gap* (TG), the ratio of the number of sky pixels to the total
139 number of pixels in a hemispherical image (Gonsamo *et al.* 2011). The difference between the two
140 parameters is that the Canopy Openness calculation weights the gaps according to their position on
141 the hemisphere, due to the geometric distortion produced by the fisheye lens (Gonsamo *et al.* 2011).
142 This process assigns a lower weight to sky pixels located in the portions of the hemisphere with lower
143 zenith angles, which are closer to the top of the hemisphere. For light regime measurements, we
144 considered the *Indirect Site Factor* (ISF) as the transmittance through the canopy of the diffuse solar
145 radiation generated by an overcast sky, the *Direct Site Factor* (DSF) as the transmittance of the direct
146 solar radiation from a clear sky, and the *Global Site Factor* (GSF) as the total radiation that comprises
147 both those components (Hale *et al.* 2009). All the Site Factors were considered averaged over one-
148 year period. Indirect Site Factor is thus independent of the location and orientation of the photo: it is
149 necessary only to know the zenith angle of the gaps (Anderson 1966). To calculate DSF and
150 subsequently GSF, a sun track is overlaid on the photo to analyse how each gap interacts with the
151 direct sunlight at different moments of the day and of the year (Anderson 1964a). In all cases, the
152 values range from zero (fully closed canopies and no light) to one (no canopy cover and full light).

153 Study sites

154 We collected data from 223 sample points distributed in 24 stands located in eight forests across the
155 UK to consider different species, overstorey and geographical conditions (see Table 1). For each
156 stand, we laid out ten sample points with a random-systematic approach. We drew random transects
157 on a desktop map and placed on them evenly-spaced points, later identified in the field using a GPS
158 receiver. The distance between points varied with the size of the stand. Since most of the stands
159 were originated by artificial planting, transects were not laid out parallel to each other to avoid
160 following the planting lines. When carrying out the field survey, if a sample point fell in an open gap
161 with no overstorey we relocated it under canopy cover if possible, otherwise it was discarded (thus
162 some stands had less than 10 sample points).

163 We assigned to each compartment a categorical variable named OV according to the overstorey main
164 species, with the following levels: “broadleaves” for mixed stands composed mainly of European
165 beech (*Fagus sylvatica* L.) and oaks (*Quercus petraea* (Matt.) Liebl. and *Q. robur* L.); “douglas” for
166 Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), sometimes associated with broadleaves; “larch”
167 for European and Japanese larch (*Larix kaempferii* (Lamb) Carr. and *L. decidua* Mill.); “pine” for
168 Corsican and Scots pine (*Pinus nigra* subsp. *laricio* Maire and *P. sylvestris* L.); and “spruce” for Sitka
169 spruce (*Picea sitchensis* (Bong.) Carr.).

170 Data collection

171 At each sample point we took circular hemispherical colour photos in quick succession, under
172 overcast sky or beneath a clear sky after sunset (Fournier *et al.* 1996). We employed either a Nikon
173 Coolpix 4500 or a Nikon Coolpix 990 equipped with Nikon FC-E8 183° Fish-Eye Converter Lens with
174 azimuthal equidistant projection. Of the 223 sample points, in 145 we took hemispherical photos at a
175 fixed height of 130 cm, while in 78 points (the ones in Newborough, Mortimer and Wykeham forests)

176 we took them above a regenerating seedling or sapling which varied from 30 cm to 200 cm, as part of
177 another research (data unpublished). The camera was positioned on a tripod and oriented to the
178 North using a compass and upwards to the zenith using a level. We took a picture using the
179 automatic exposure and then three more with respectively -0.3, -0.7 and -1 Exposure Values (EV) to
180 obtain at least one picture with good contrast between sky and canopy (Hale *et al.* 2009). The Nikon
181 Coolpix 4500 recorded pictures of 2048 x 1536 pixels, the Nikon Coolpix 990 pictures of 2272 x 1704
182 pixels. Due to this difference, we had to keep the pictures separated during some of the processing
183 steps, but the results (see later) did not differ between the two cameras, simply called “circular HP”
184 from here onwards.

185 In the same spot as each circular HP, and at the same height, we collected diagonal hemispherical
186 colour photos with a Samsung Galaxy Grand Prime smartphone, equipped with a built-in CMOS 8.0
187 MP camera and a 150° Aukey fish-eye lens with azimuthal equidistant projection. We took the
188 pictures immediately after reaching the point and with fewer precautions regarding the sky
189 conditions (i.e. sometimes we waited for overcast sky conditions for the circular HP acquisitions, but
190 never for the smartphone). We held the smartphone by hand, keeping it levelled and pointing
191 upwards as best as we could. We took two pictures, once aligning the smartphone North-South and
192 once East-West with the aid of a compass, always using the automatic exposure. The smartphone
193 pictures had pixel dimensions of 3264 x 1836. We purposely followed a faster protocol and used less
194 equipment (no tripod and no level) for collecting the smartphone HP.

195 **Image processing**

196 We automatically classified all the circular HP images using two systems. The first was the Ridler &
197 Calvard (1978) iterative selection method applied to the blue channel of the pictures, where
198 differences between sky and vegetation pixels are most evident. We used this method with the

199 function `IsoData` from the software Fiji (Schindelin *et al.* 2012). For the second method, we used the
200 colour-based algorithm `enhanceHemiphoto` (from now on called EnhanceHP) from the package
201 *Caiman* (Diaz & Lencinas 2015) in R (R Core Team 2016). The EnhanceHP function combines the Ridler
202 & Calvard (1978) method with a fuzzy pixel-based classification based on the colour attributes of hue,
203 lightness and chroma, working more efficiently where differences between sky and vegetation pixels
204 are less evident. More documentation is available in Diaz & Lencinas (2015). We applied the CIMES-
205 FISHEYE software package (Gonsamo *et al.* 2011) to the outputs of both classification methods. We
206 extracted the gap fraction information for each portion of the hemisphere with the function `GFA`,
207 using a grid of 24 azimuth sectors and 18 zenith annuli. This information was the input for the
208 following functions of the package: `OPENNESS` to obtain the Canopy Openness, `PARSOC` for the
209 Indirect Site Factors (using the Standard Overcast Sky model) and `PARCLR` for the Direct Site Factor.
210 Using the same procedure as Hale *et al.* (2009), which in turn followed the recommendations of the
211 Met Office (2006), we calculated the Global Site Factor as in Equation (1).

212
$$\text{Equation (1) } \text{GSF} = 0.65 \times \text{ISF} + 0.35 \times \text{DSF}$$

213 We repeated the above estimations simulating a FOV of 150° by considering all the area comprised
214 between the zenithal angles 75°-90° as obstructed, and obtained the same parameters, named
215 CO150, ISF150, DSF150, and GSF150.

216 For processing the smartphone pictures, we used two approaches. The first was to obtain Total Gap
217 separately from the East-West (E-W) and North-South (N-S) pictures in each sample point. After
218 classifying each image with both the `IsoData` and `EnhanceHP` functions as above, we used the
219 package *Raster* (Hijmans 2016) of the R Statistical Software to calculate Total Gap as the ratio of
220 white pixels (gaps) to the total pixels. We estimated Total Gap for both the N-S and E-W smartphone
221 photos, and then the average for each pair.

222 The second approach was to merge the two original pictures in each sample point and create a new
223 one with the largest possible visible portion of the full hemisphere. We merged the images with the
224 open source software 'Hugin', which automatically aligns and blends two or more images. The main
225 use of Hugin is producing panoramic views but we developed scripts to batch process our canopy
226 photos. Minor deviations from the N-S and E-W axes were frequent with the handheld smartphone,
227 and we arbitrarily decided to use the E-W picture as the reference image for correct alignment. We
228 thresholded all merged images with both the IsoData and Enhance function as above.

229 Using CIMES-FISHEYE as above, we estimated CO_{sm}, ISF_{sm}, DSF_{sm} and GSF_{sm} ("sm" for smartphone)
230 for each picture and each classification method. We carried out the calculations considering a full
231 180° FOV hemisphere, by setting up the GFA function of CIMES to extract the gap fraction of a larger
232 circle than just the area covered by the merged images. Given that the diagonal length of one
233 smartphone HP corresponds to 150°, we used a circle having a diameter equal to the diagonal length
234 multiplied by the ratio 150°/180°. The software considered the portions of the hemisphere not
235 covered by the merged images as obstructed (specifically, the area between the zenithal angles 75°-
236 90° and the corners not covered by merging the two pictures; in total around half of a full circular HP
237 image. See online supplementary information for more details).

238 We carried out all the image processing with automatic and repeatable batch scripts. Figure 2 shows
239 the workflow of the image processing. The original and merged pictures were JPG format and were
240 transformed during the thresholding into TIFF. The free software IrfanView was then used to batch
241 convert all the files to BMP format for CIMES-FISHEYE. The online supporting information shows
242 examples of the circular, single smartphone and merged smartphone HP images, highlighting the
243 corresponding coverage.

244 Statistical analysis

245 To determine if there were significant differences between the thresholding methods, we compared
246 the TG and CO estimations of the two methods when applied to the same camera pictures. To assess
247 the differences between the estimations from circular images when different FOV were considered,
248 we compared the respective CO and Site Factor estimations.

249 Then we compared the following parameters estimated from the different cameras but using the
250 same thresholding method: CO from circular HP images (only FOV 180°) and TG from smartphone HP
251 images (both single orientation and average values); CO, ISF, DSF, and GSF from circular HP images
252 (only FOV 180°) and from merged smartphone HP images. We estimated Generalized Linear Mixed
253 Models (GLMMs) of circular HP parameters as functions of the corresponding smartphone HP values.
254 We tested as fixed effects the overstorey type both as a main term and as an interaction, to account
255 for differences between species. We also included terms related to the different circular camera
256 ("camera_type", with the values of either "N990" or "N4550") and the data collection methodology
257 ("height_from_ground", with the values of either "130cm" or "variable"), to verify if such differences
258 were significantly affecting the relationship. We used a random effect of compartments nested
259 within forests, to account for the sampling structure. From a global model including all the above
260 effects, we then assessed reduced models with fewer effects using the Aikake Information Criteria
261 (AIC), and selected the one with the lowest AIC as the best model for each analysis (Symonds &
262 Moussalli 2011). We carried out all analyses using the packages *nlme* (Pinheiro *et al.* 2016) and *stats*
263 in R (R Core Team 2016).

264 **3. Results**

265 Figure 3 shows the value distribution for GSF calculated from the circular HP images, using the
266 EnhanceHP method, to provide a reference for the range of data. The areas surveyed in this research
267 varied from low light transmittance (GSF around 0.05) to medium-high level of transmittance (GSF
268 around 0.60), with most of them falling in the range GSF 0.20-0.30. However, the range was not even
269 across different overstorey types.

270 **Comparison of thresholding methods**

271 Canopy parameters estimated from the pictures taken by the same camera (respectively the
272 averaged Total Gap for smartphone and Canopy Openness for circular HP images), but classified with
273 the different methods, were slightly lower for the EnhanceHP method than the IsoData (mean of
274 differences respectively -0.023 for TG and -0.027 for CO, p -value < 0.001 for both). This means that
275 more pixels were classified as canopy elements with EnhanceHP. A visual analysis of the thresholded
276 images confirmed that EnhanceHP correctly identified as vegetation many elements that were
277 mistaken for sky by the IsoData method. That was true not only in the few obvious cases of high
278 exposure images but also for small vegetation elements under good contrast. Since all the following
279 analyses showed better correlations between the values from the circular and smartphone cameras
280 when EnhanceHP was applied to both rather than the IsoData method, we present here only the
281 former. Additional results for the IsoData method can be found in the online supporting information.

282 **Comparison of different FOVs for circular HP**

283 Values of CO, DSF and GSF when estimated from circular HP images with FOV 150° were significantly
284 lower than from FOV 180° (p < 0.001) although the difference was very small in absolute terms: the
285 mean of the differences between the different FOV estimations were, respectively, -0.001 (standard

286 deviation, st.dev., 0.009), -0.013 (st.dev., 0.022) and -0.004 (st.dev., 0.010). No significant difference
287 was present for ISF.

288 **Comparison of circular HP with non-merged smartphone HP**

289 The comparison of Canopy Openness from circular HP images and Total Gap from smartphone HP
290 images (averaged between the two pictures), using the EnhanceHP method, is shown in Figure 4. TG
291 values from the smartphone pictures were higher than CO values from circular HP images: mean of
292 differences 0.12, st.dev. 0.04. In relative terms, TG values from the smartphone pictures on average
293 were 165% of the CO values from circular HP images. The GLMM structure with lowest AIC
294 maintained overstorey type only as interaction term, while both the differences in the circular
295 camera type and the height from the ground did not affect the relationship. See Table 2 for the AIC
296 comparison between model structures, and Table 3 for more details of the selected model. The effect
297 of the overstorey type was that for the same increase in the values of observed TG, the predicted CO
298 values increased more rapidly for larch and pine than for broadleaves, with Sitka spruce and Douglas
299 fir having an intermediate effect.

300 The TG values from Smartphone pictures taken with different orientation in the same point, both
301 classified with EnhanceHP, were not statistically significant ($p = 0.53$). However, when we used the
302 TG values estimated only from the E-W and N-S pictures, instead of the averages, in the above model
303 the results were slightly less accurate in both cases, although better for the E-W than the N-W
304 pictures (results not shown).

305 **Comparison of merged Smartphone HP with circular HP**

306 The comparisons between the outputs estimated from the circular and the merged smartphone HP
307 images, using the EnhanceHP method, are shown in Figure 5. The smartphone values were on
308 average significantly different from the circular ones ($p < 0.05$ in all cases): mean of differences

309 respectively 0.004 for CO (st.dev. 0.031), 0.042 for ISF (st.dev. 0.037), -0.012 for DSF (st.dev. 0.047),
310 and 0.023 for GSF (st.dev. 0.040). In relative terms, the smartphone values on average were
311 respectively the 102% (for CO), 115% (for ISF), 93% (for DSF), and 109% (for GSF) of the values of the
312 circular HP values. For the CO, ISF and GSF models, the GLMM structure with lowest AIC maintained
313 overstorey type as interaction term, while for the DSF both the main and interaction term were
314 dropped. In all cases, the differences in the circular camera type and the height from the ground did
315 not affect the relationship. See Table 2 for the AIC comparison between model structures, and Table
316 3 for more details of the selected models. When the effect of the overstorey type was present, it
317 meant again that for same increase in the values of observed smartphone HP values, the predicted
318 circular HP values increased more rapidly for larch and pine than for broadleaves, with Sitka spruce
319 and Douglas fir having an intermediate effect.

320 **4. Discussion**

321 The results of the study suggest that smartphone-based hemispherical photography can be used as a
322 faster and cheaper alternative to traditional camera sets. We demonstrate methods to obtain canopy
323 structural parameters and Site Factors with the advantage of less expensive equipment and faster
324 data collection time. We purposely carried out the smartphone image acquisition with a simpler
325 protocol that does not need extra tools (such as a tripod or a level) or to wait for the best sky
326 conditions. The rationale was to test a methodology that could be applied by any forest practitioner
327 in a speedier way, potentially obtaining a higher amount of data. In this case study, a smartphone is
328 used only for the image acquisition, while the processing is done subsequently in a computer. Thus,
329 for example, in a crowd-sourcing project various operators can acquire the images in the field and,
330 using other smartphone applications, upload them to a central server where the more advanced
331 processing here described can take place.

332 While we carried out the smartphone pictures acquisition with fewer precautions, generally the
333 images showed an acceptable quality in terms of exposure and contrast between sky and canopy and
334 in turn the thresholding process gave good results. This is likely due to a combination of factors. The
335 new sensors and in-camera processing of the smartphones are likely better than the now almost 20-
336 years-old Nikon Coolpix. The smaller FOV of the smartphone fisheye lens may have reduced the
337 direct sunlight hitting the sensor. The generally favourable sky conditions of the UK (high latitude,
338 cloudy climates) have likely also played an important role, so that in other geographical areas the
339 same precautions regarding direct sunlight may have to be applied also to smartphone hemispherical
340 photography. However, where sub-optimal contrast between sky and canopy occurred in some of
341 our smartphone pictures, the EnhanceHP function from the *Caiman* package gave good results during
342 the thresholding. This method was designed to work with sub-optimal images, while the IsoData
343 function requires good contrast pictures.

344 The small differences between parameters estimated from circular HP images with a FOV of 150° and
345 180° demonstrate that the reduced FOV of the smartphone fisheye lens could not be the main source
346 of difference between the two cameras, which most likely are the diagonal character of the camera
347 sensors and the lower quality of the images. New smartphone camera sensors and lenses are likely to
348 be developed continuously, influencing both issues due to changes in the resolution of sensors and
349 the quality and FOV of the lens, and then in turn affecting the analyses carried out in this study with
350 our particular combination of smartphone and fish-eye lens. However, given that the same fisheye
351 lens is used, the smartphone camera used can be considered representative of the average sensor
352 resolution and quality nowadays available, and if only new sensors will have likely better
353 characteristics. In any case, we suggest verifying the real FOV of the conversion lens.

354 Total Gap, obtained from the simple processing protocol of single smartphone pictures, was
355 consistently higher than the Canopy Openness values from circular hemispherical images, as
356 expected. The bias between those values in this study was consistent and with a reduced deviation,
357 suggesting that there is still potential to use Total Gap from smartphone pictures in ecological study
358 as a substitute to traditional circular camera analysis, either as it is or transformed by using the
359 model provided. Taking two pictures in the same point and averaging the results improved the results
360 without significantly increasing the time required for data collection and processing, so we advise this
361 operation for future studies.

362 Through the more advanced merging protocol we obtained processed smartphone pictures that
363 could be used for estimation of Canopy Openness and Site factors. The mean differences and
364 standard deviations between the parameters from different cameras were relatively small. This
365 suggests that the smartphone camera outputs could be used in place of those from a circular camera.
366 As already discussed, the areas close to the horizon not covered by the smartphone HP images did
367 not greatly affect the Canopy Openness and Indirect Site Factor estimation. However, the different
368 coverage was expected to give poorer results in the estimation of Direct Site Factor, which is a
369 function also of the location of the gaps in relation to the sun track. Particular gaps with a large
370 contribution to this Site Factor in circular hemispherical images might be excluded from merged
371 smartphone images. In addition, the handheld alignment of the smartphone in the field are likely to
372 have introduced additional errors in the sun track overlay. However, for the Direct Site Factor the
373 mean difference between the circular and smartphone cameras were even lower than for other
374 parameters. For the Global Site Factor, which in the UK depends more from the Indirect than Direct
375 Site Factor, the differences between cameras were similar to the former. The best model structures
376 for Canopy Openness, Indirect and Global Site Factor, included the overstorey type as interaction
377 term, i.e. the relationship was affected by the different species' foliar and crown architecture.

378 Overstorey type was not included in the model for Direct Site Factor, which is likely more affected by
379 large gaps falling around the sun track, and less by the overall fine gap structure. However, there
380 were few replicates for some classes (i.e. only two broadleaved stands out of 24), and the range of
381 canopy openness sampled within classes was not equal (i.e. for broadleaved stands it was lower than
382 for pine and larch stands).

383 In conclusion, we believe that the cheaper and faster methodologies here described for smartphone-
384 based hemispherical photography provide reliable parameters that can be used as substitutes for
385 those estimated from circular cameras. Smartphone outputs could be employed as they are in forest
386 ecology studies, such as for assessment of different sites or as inputs for ecological modelling, or
387 converted with specific transformation models for a better comparison between cameras. The range
388 of application of the models provided here outside the forest and sky conditions and smartphone
389 specifications considered in this study has not been tested. Since we first designed this study, new
390 smartphone fish-eye lenses promising wider angles (up to 180° and even more) are available on
391 online marketplaces, providing different but hopefully more accurate results when applying the
392 methodologies here described. Due to rapid technological development, smartphone hemispherical
393 photography could potentially gain increasing importance in future years.

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396 Research Council of Buenos Aires, Argentina, for his assistance on how to use the package *Caiman*;
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398 **Data accessibility**

399 The dataset used for this study is stored on the Dryad Digital Repository
400 <https://doi.org/10.5061/dryad.f6506> together with the main scripts used for the processing of the
401 smartphone hemispherical images with R Statistical software and Hugin.

402 **Authors contribution**

403 Simone Bianchi designed the original work and methodology, carried out the data acquisition,
404 analysis and interpretation, and prepared the manuscript. Christine Cahalan and Sophie Hale critically
405 contributed to the data interpretation and manuscript revision. James Gibbons critically contributed
406 to the methodology development, the data analysis and interpretation, and manuscript revision.

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499 smartphone. *Journal of Vegetation Science*, **27**, 427–435.

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505 **Figures legends**

506 Figure 1. Circular hemispherical images with a full-frame camera (left) versus diagonal smartphone
507 hemispherical images (right). Adapted from Schneider et al. (2009).

508 Figure 2. Simplified workflow of the various steps of image processing, from the original pictures to
509 the output values.

510 Figure 3. Boxplots of Global Site Factor (GSF) from circular hemispherical images for different
511 overstorey species. The horizontal line shows the median value, the boxes the values between the
512 first and third quartile, the vertical lines are an additional 1.5 Inter Quartile Range above and below
513 them.

514 Figure 4. Scatterplot of Canopy Openness (CO) from circular image with Total Gap (TG) from
515 smartphone, showing the line of identity (dashed black line), both estimated using the EnhanceHP
516 method. Smartphone values were obtained by averaging the single images results for each plot.

517 Figure 5. Scatterplots of Canopy Openness and Site Factors (respectively ISF for Indirect, DSF for
518 Direct, and GSF for Global Site Factor) estimated from different cameras, using EnhanceHP method,
519 showing the line of identity (dashed black line). Smartphone values were obtained from merged
520 images.

521 **Tables**

522 Table 1. Overview of the study sites

Forest	Location (WGS84)	Overstorey type	Number of stands	Number of sample points
Clocaenog (Wales)	53° 04' N, 3° 24' W	spruce	4	39
		larch	1	10
Kielder (England)	55° 13' N, 2° 27' W	spruce	4	37
Aberfoyle (Scotland)	56° 13' N, 4° 21' W	larch	2	20
		spruce	1	9
Treborth (Wales)	53° 13' N, 4° 10' W	broadleaves	1	10
Newborough (Wales)	53° 09' N, 4° 20' W	pine	2	20
Mortimer (England)	52° 21' N, 2° 45' W	broadleaves	1	8
		douglas	1	9
Coed-Y-Brenin (Wales)	52° 48' N, 3° 53' W	douglas	2	17
Wykeham (England)	54° 16' N, 0° 33' W	pine	4	36
		spruce	1	8
Total			24	223

523 Table 2. Aikake Information Criteria comparison between different generalized linear mixed model
 524 structures for all analyses. TG is Total Gap, CO is Canopy Openness, ISF, DSF and GSF are respectively
 525 Indirect, Direct and Global Site Factor (“sm” for smartphone HP). In the formulas, y and x are the
 526 respective circular HP and smartphone HP parameter considered, OV is the overstorey type, camera
 527 is the type of Nikon Coolpix used for circular images, and HFG is the height from the ground at which
 528 the pictures were taken (see Methodology). The lowest AIC values are shown in bold.

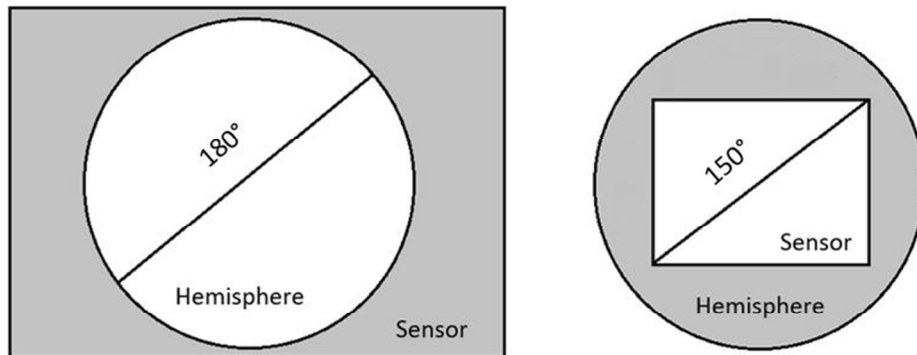
Model	CO ~ TG	CO ~ Cosm	ISF ~ ISFsm	DSF ~ DSFsm	GSF ~ GSFsm
y ~ x + x:OV + OV + camera + HFG	-984	-980	-852	-761	-877
y ~ x + x:OV + OV + camera	-991	-988	-861	-768	-885
y ~ x + x:OV + OV	-999	-997	-869	-776	-894
y ~ x + x:OV	-1019	-1016	-891	-792	-916
y ~ x + OV	-990	-980	-869	-780	-894
Y ~ x	-1009	-997	-885	-795	-908

529

530 Table 3. Results of generalized linear mixed models between the outputs estimated by circular and smartphone HP pictures, using the
 531 EnhanceHP method. CO is Canopy Openness, TG is Total Gap, ISF, DSF and GSF are respectively Indirect, Direct and Global Site Factor (“sm” for
 532 smartphone outputs). For the fixed effects, “x” indicates the smartphone HP parameter used in the model, and OV is the overstorey type.

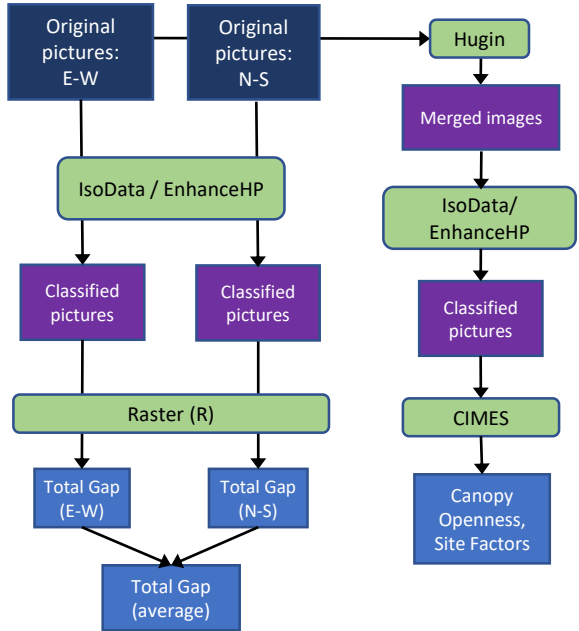
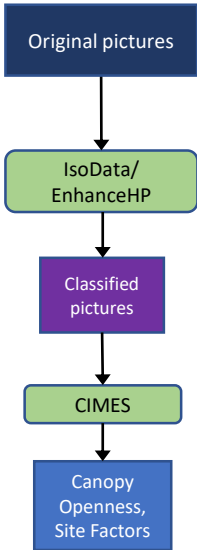
	CO ~ TG			CO ~ COsm			ISF ~ ISFsm			DSF ~ DSFsm			GSF ~ GSFsm		
	Value	St. Err	p-value	Value	St. Err	p-value	Value	St. Err	p-value	Value	St. Err	p-value	Value	St. Err	p-value
Fixed Effects															
(Intercept)	0.025	0.010	0.013	0.032	0.009	0.001	0.042	0.012	0.000	0.049	0.011	0.000	0.049	0.011	0.000
x	0.275	0.082	0.001	0.309	0.118	0.009	0.355	0.095	0.000	0.764	0.046	0.000	0.292	0.104	0.002
x:OV(douglas)	0.197	0.080	0.014	0.386	0.120	0.002	0.347	0.094	0.000	-	-	-	0.376	0.107	0.001
x:OV(sitka)	0.228	0.081	0.005	0.437	0.112	0.000	0.341	0.086	0.000	-	-	-	0.384	0.097	0.000
x:OV(larch)	0.398	0.083	0.000	0.694	0.118	0.000	0.471	0.090	0.000	-	-	-	0.542	0.101	0.000
x:OV(pine)	0.267	0.081	0.001	0.610	0.113	0.000	0.487	0.088	0.000	-	-	-	0.560	0.096	0.000
Random Effects															
(Intercept)	Standard Deviation			Standard Deviation			Standard Deviation			Standard Deviation			Standard Deviation		
Forest	0.018			0.012			0.008			0.000			0.009		
Stand (in Forest)	0.011			0.012			0.019			0.038			0.019		
Residual	0.020			0.020			0.031			0.034			0.028		

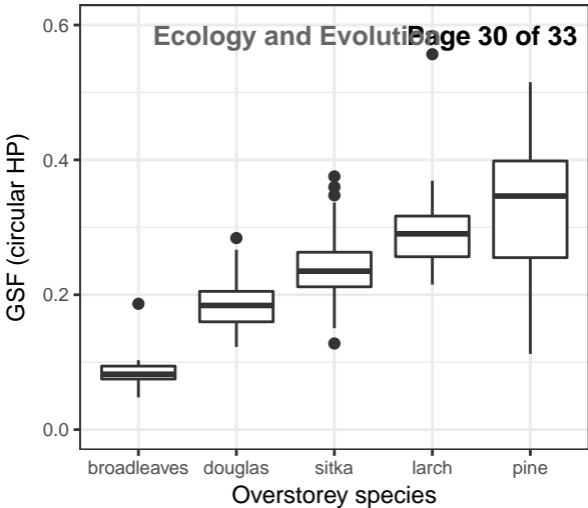
533

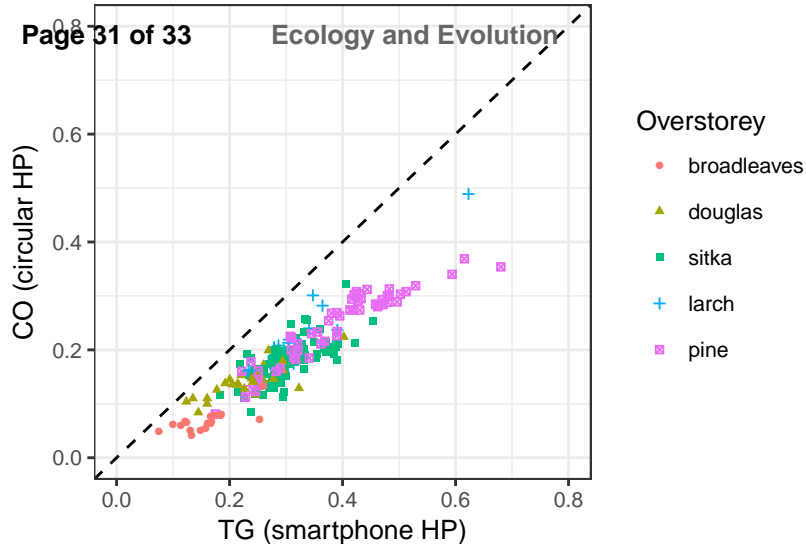


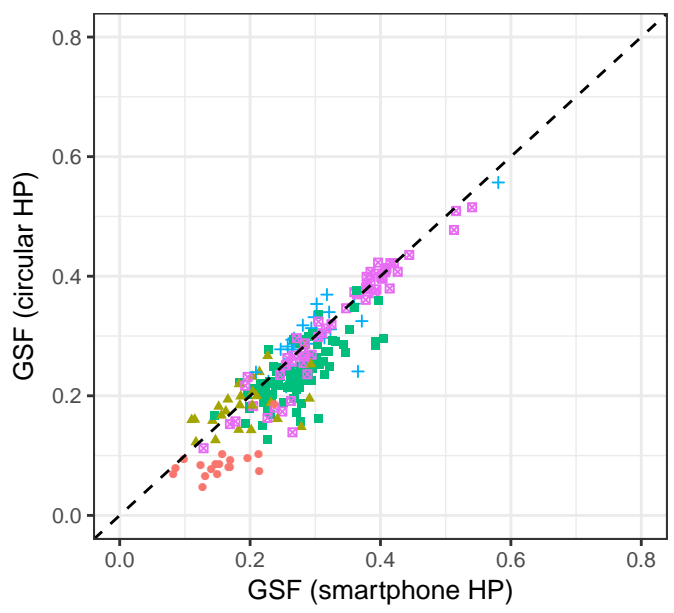
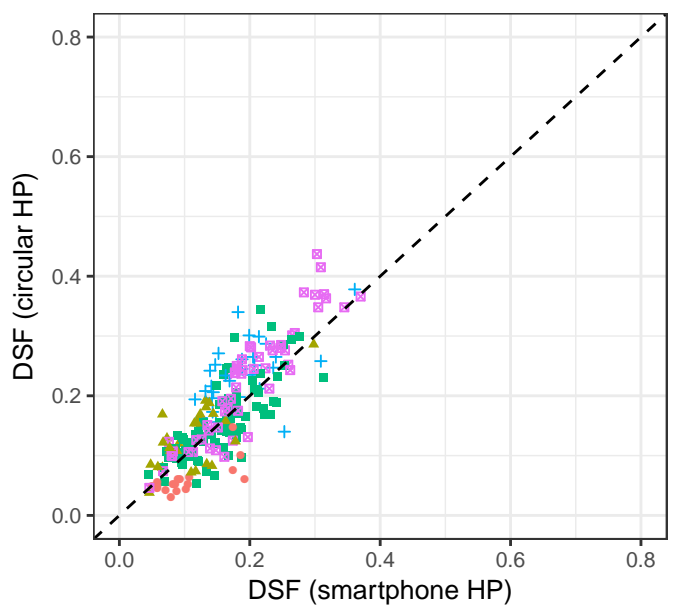
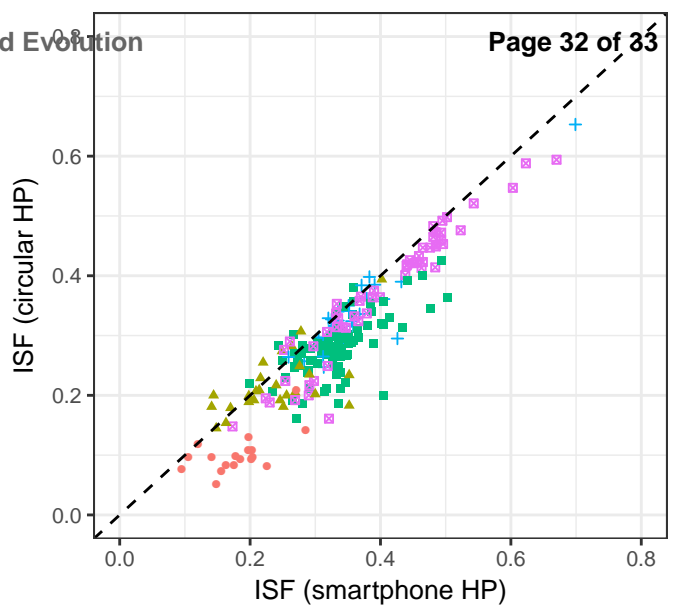
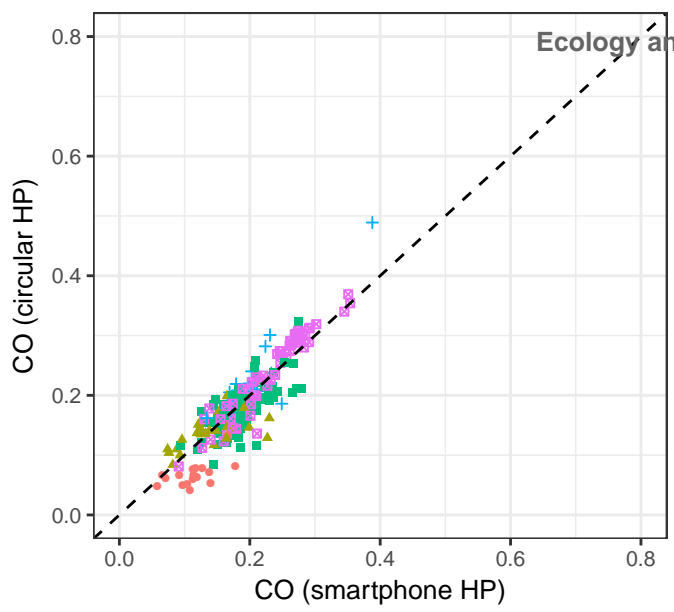
Circular hemispherical images with a full-frame camera (left) versus diagonal smartphone hemispherical images (right). Adapted from Schneider et al. (2009).

78x33mm (300 x 300 DPI)

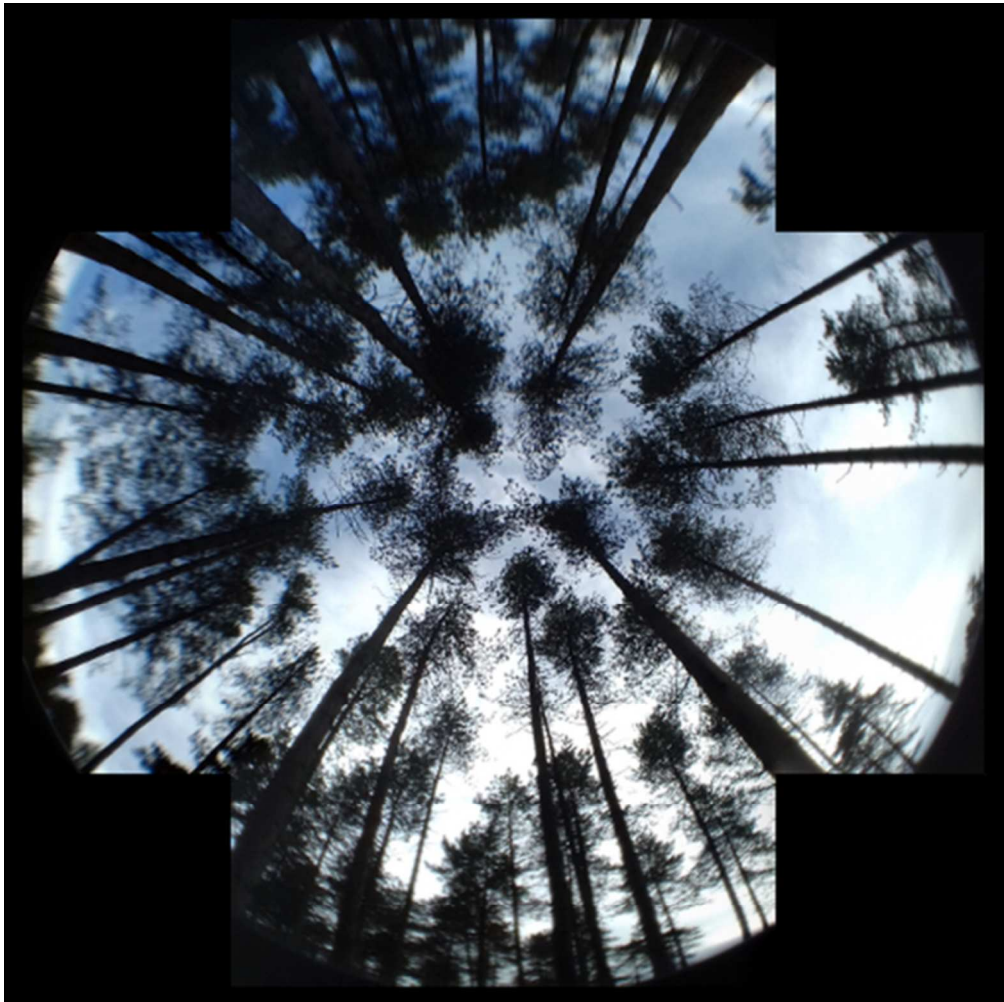








Overstorey • broadleaves ▲ douglas ■ sitka + larch ■ pine



Graphical abstract image

86x86mm (200 x 200 DPI)