1 # A comparison of ground-based methods for
2 # estimating canopy closure for use in phenology
3 # research

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18 ## Abstract

19 Climate change is influencing tree phenology, causing earlier and more prolonged
20 canopy closure in temperate forests. Canopy closure is closely associated with
21 understorey light, so shifts in its timing have wide-reaching consequences for ecological
22 processes in the understorey. Widespread monitoring of forest canopies through time is
23 needed to understand changes in light availability during spring in particular. Canopy
24 openness, derived from hemispherical photography, has frequently been used as a
25 proxy for understorey light. However, hemispherical photography is relatively resource
26 intensive, so we tested a range of inexpensive alternatives for monitoring variability in
27 canopy closure (visual estimation, canopy scope, smartphone photography, smartphone
28 photography with fisheye attachment; and image analysis with specialist hemispherical
29 photography software or with simpler, open access image analysis software).
30 Smartphone photography with an inexpensive fisheye lens attachment proved the most
31 reliable estimator of canopy closure. We found no significant difference in canopy
32 estimations from three widely-owned smartphone models with differing resolutions and
33 fields of view, and no significant effect of camera operator on the results. ImageJ, a free
34 image analysis software, detected canopy variability in a similar way to HemiView
35 specialist hemispherical photography software. We recommend a combination of
36 smartphone photography with fisheye attachment and analysis with ImageJ for
37 identifying changes in the timing of canopy closure (but not for estimating absolute
38 canopy closure). We discuss how large-scale citizen science using this approach could
39 generate meaningful and comparative data on the timings of canopy closure in different
40 forests, year-to-year.

41

1. Introduction

42

43 Climate change is affecting forest ecosystems around the globe, with changes in tree

44 phenology widely documented for temperate forests (Richardson et al., 2013; Roberts

45 et al., 2015; Vitasse et al., 2011). Growing season extensions have been observed for

46 many European tree species, most notably due to canopies coming into leaf earlier

47 (Menzel and Fabian, 1999; Menzel et al., 2006; Thompson and Clark, 2008). The

48 phenology of dominant canopy trees exerts strong influence on the understorey

49 environment, as canopy openness is highly related to available photosynthetically active

50 radiation (PAR) (Brusa and Bunker, 2014; Gonsamo et al., 2013; Promis et al., 2012),

51 influencing microclimate, soil respiration (Giasson et al., 2013; Yuste et al., 2004) and

52 understorey plant dynamics (Van Couwenberghe et al., 2011). Therefore, earlier canopy

53 closure and later senescence is likely to have wide-ranging impacts on the phenology

54 and life processes of understorey plants and wider forest biodiversity. Studies have

55 indicated threats to spring ephemeral herbs that utilise the period before canopy closure

56 for completing their life cycle (Kim et al., 2015). Many tree saplings depend on spring

57 sunlight prior to canopy closure for their growth and survival (Augspurger, 2008).

58 Understorey species that are shade tolerant or those with greater phenological plasticity

59 are likely to gain competitive advantage (De Frenne et al., 2011), and invasive species

60 could become more prevalent (Engelhardt and Anderson, 2011; Willis et al., 2010). As

61 canopy openness is a key determinant of ecological processes in the understorey,

62 effective methods for monitoring intra and inter-annual changes in the timing of canopy

63 closure/openness would be very useful, especially if they allowed data to be collected

64 across a variety of spatial scales, and with plenty of replication.

65 Canopy phenology has been extensively studied in recent years. Satellite remote

66 sensing has enabled data collection of forest leaf phenology at large spatial scales

67 (Boyd et al., 2011; Wang et al., 2016; White et al., 2009; Wu and Liu, 2013; Zhang et

68 al., 2005). These methods focus on deriving estimates of canopy green-up dates from

69 Normalised Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI)

70 data, for the purpose of tracking photosynthetic activity to assess forest productivity, gas

71 exchange and phenological feedbacks to the climate system (Richardson et al., 2013).

72 While remote sensing data is useful for identifying large-scale phenological trends, the

73 coarse resolution means that local variations between forest stands are often masked

74 (Fisher et al., 2006; White et al., 2014). Furthermore, loss of temporal resolution due to

75 atmospheric conditions (Cleland et al., 2007; White et al., 2014), and difficulties
76 separating greening of the understorey from canopy greening (Hamunyela et al., 2013),
77 can compromise the use of this data for identifying shifts in canopy closure timing.

78 A range of ground-based methods have been used to assess canopy structure and
79 understorey light environments at the forest-level. Direct measures of understorey light
80 are highly affected by sky conditions and accurate determination requires continuous
81 measurement over several days (Engelbrecht and Herz, 2001; Gendron et al., 1998). This
82 makes direct measurements inappropriate for phenology studies where the objective is
83 to assess variation through time. As an alternative, hemispherical photography and Plant
84 Canopy Analysers (PCAs) such as the LAI-2200, are commonly used to assess structural
85 attributes of forest canopies (Frazer et al., 1997; Gonsamo et al., 2013; Hale and
86 Edwards, 2002; Rich, 1990). Both instruments incorporate an extreme wide angle view
87 to measure gap fraction – defined as the proportion of unobstructed sky in a given region
88 of the projected image plane (Frazer et al., 1997) – at multiple zenith angles. For
89 estimating understorey light levels, particularly during spring, wide viewing angles are an
90 advantage as sunlight largely penetrates the canopy below the zenith. Using gap fraction
91 measurements, Leaf Area Index (LAI) and canopy openness can be determined.

92 LAI is the most widely used metric of canopy structure (Jonckheere et al., 2005; Weiss et
93 al., 2004), though it is also one of the most difficult to characterise accurately (Bréda,
94 2003). LAI is defined as one half the total green leaf area per unit ground surface area
95 (Chen and Black, 1992). Hemispherical photography and PCAs assess the whole canopy
96 as viewed from a single point, using gap fraction inversion principles and radiative transfer
97 theory respectively (Chen et al., 1997; Macfarlane et al., 2007; Woodgate et al., 2015).
98 As such, LAI derived from optical methods actually characterises 'Plant Area Index' (as
99 trunks and branches are included as well as leaves), and is highly related to understorey
100 light levels (Bréda, 2003; Jonckheere et al., 2004). However, both methods are costly,
101 particularly PCAs, which in addition to high instrument costs, require simultaneous
102 reference light readings outside the canopy. This is problematic in forests, as a wireless
103 set up or remote data loggers are needed, adding additional resource implications and
104 making the method impractical for large-scale use (Bréda, 2003). Furthermore, both
105 methods for estimating LAI assume that canopy elements are randomly distributed. In
106 reality, a degree of 'clumping' occurs both within and between plant canopies (Bréda,
107 2003; Chen et al., 1997; Ryu et al., 2010; Weiss et al., 2004). The degree of clumping

108   varies depending on forest type and structure, and also shows strong seasonal variation
109   according to the phenological stage (Ryu et al., 2010). Therefore accurate LAI estimation
110   requires determination of a clumping index for a given canopy at a given time of year, and
111   specialist equipment and/or software is required (Chianucci et al., 2015; Ryu et al., 2010).

112   Digital Cover Photography (DCP) using ordinary digital cameras can also be used to
113   estimate LAI following the method proposed by Macfarlane et al. (2007). This method has
114   a number of advantages as specialist equipment and software are not required, though a
115   number of steps are involved in analysis to calculate effects of foliage clumping
116   (Chianucci et al., 2014; Macfarlane et al., 2007). DCP has been successfully used to track
117   canopy development in phenological studies concerned with photosynthesis and gas
118   exchange (Ryu et al., 2012). However, the restricted viewing angle of DCP cover
119   photography is less appropriate for tracking the progress of canopy closure, where the
120   objective is to assess change in the relative timing of shading in the understorey. Although
121   LAI is highly related to understorey light (particularly where it is based on gap fraction at
122   multiple zenith angles) it is primarily used to quantify ecosphysiological attributes of forest
123   canopies (photosynthetic and transpiration rates) to study climate-biosphere interactions
124   (Bréda, 2003; Chen et al., 1997; Jonckheere et al., 2004; Macfarlane et al., 2007;
125   Woodgate et al., 2015). Where the aim is to track changes in relative canopy closure to
126   determine temporal variability in understorey light, canopy openness is a more
127   appropriate and straightforward metric to use (Brusa and Bunker, 2014).

128   Canopy openness is the proportion of the entire sky hemisphere that is unobstructed by
129   vegetation when viewed from a single point (Jennings et al., 1999), and is highly
130   correlated with understorey light (Brusa and Bunker, 2014; Gonsamo et al., 2013;
131   Pellikka, 2001; Promis et al., 2012; Roxburgh and Kelly, 1995; Whitmore et al., 1993).
132   Hemispherical photography has been widely used to assess canopy openness,
133   representing the sum of all gap fraction values, weighted according to zenith angle, and
134   multiplied by 100 to give a percent visible sky value (Frazer et al., 1997). The advent of
135   digital cameras and their increasing availability has made hemispherical photography
136   more widely available for forest science (Brusa and Bunker, 2014; Frazer et al., 2001;
137   Hale and Edwards, 2002; Inoue et al., 2004). However, cost and resource implications
138   still preclude many forest managers from using it as a monitoring tool. While
139   hemispherical photography does not require reference light readings to be made,
140   images must be taken under specific weather conditions – on dry, still days, without

141   direct sunlight, normally early or late in the day, or on a day with uniform overcast skies
142   (Rich, 1990). This places considerable constraint on when data can be collected. Once
143   images have been obtained, analysis can be time-consuming and expensive. Though
144   free specialist software programmes now exist that provide comparable results to
145   professional software (Promis et al., 2011), expertise is still required. Overall, the
146   technique is prohibitively expensive, in terms of cost and time, for phenology studies
147   that require high levels of replication.

148   A variety of cost-effective, rapid assessment alternatives to hemispherical photography
149   have been used to assess canopy openness, including photography without a fisheye
150   lens (Pellikka, 2001), the canopy scope (Brown et al., 2000), and simple visual
151   estimations (Jennings et al., 1999). These methods differ in their view zenith angle;
152   therefore canopy openness in this context is defined as the proportion of unobstructed
153   sky within the total area viewed. While these methods are used to characterise coarse-
154   level variation in canopy openness, their ability to detect fine-scale changes in canopies
155   through time needs to be assessed. Another option has emerged in the last few years
156   with the rise of smartphones that have high resolution cameras. Inexpensive fisheye
157   lens attachments for smartphones have recently become available for less than US$10.
158   Smartphone photography, if reliable, could provide an efficient means of collecting large
159   quantities of data on the timing of canopy closure using citizen science.

160   The use of citizen science has proven highly successful in other areas of phenological
161   research, including observational studies of plant bud-burst and leaf-out timing
162   (Collinson and Sparks, 2008; Jeong et al., 2013; Mayer, 2010). The widespread and
163   increasing ownership of smartphones means that many people now carry sophisticated
164   cameras, making them ideal citizen science tools. However, a considerable range of
165   makes and models exist. These vary in their camera specifications (e.g. resolution,
166   focussing capability and angle of view), which could affect canopy openness
167   estimations (Frazer et al., 2001; Inoue et al., 2004; Jennings et al., 1999). Therefore, for
168   this method to be practical for large-scale use, different makes and models of
169   smartphone need to give comparable estimations.

170   In this study, we compared canopy openness values (% visible sky) from hemispherical
171   photography, with estimates derived from visual estimation techniques and from
172   smartphone photography, with and without the use of a fisheye lens attachment. Data
173   were collected in winter, spring, summer and autumn, at fixed points across four

174   broadleaved woodlands in south-west England, to assess the extent that surrogate

175   methods can estimate variation in canopy openness. We then tested a basic means of

176   analysing hemispherical photos and smartphone fisheye photos to derive canopy

177   openness using non-specialist image analysis software. We did this by comparing

178   simple canopy openness values (% visible sky) derived from the free image-analysis

179   software, with weighted canopy openness values (% visible sky weighted as a function

180   of gap fraction zenith angle) from professional specialist software. Recognising that

181   different makes of smartphone camera might perform differently, we also compared

182   three popular smartphone cameras in a separate trial. The different phone cameras

183   were tested in broadleaved woodland under three levels of canopy density, and with

184   multiple camera operators, to test reproducibility under different canopy conditions and

185   with different users.

186   Our overall objectives were: a) to identify whether any of the proposed surrogate

187   methods provide reliable estimates of variation in canopy openness; b) to identify

188   whether non-specialist image analysis software can produce comparable estimates to

189   specialist software; c) to test whether different smartphone camera models and different

190   camera users yield similar canopy openness estimations. It is important to note that this

191   study was not concerned with identifying methods to closely represent absolute values,

192   since it has already been established that methods incorporating different view angles

193   tend to give different absolute estimates of canopy openness (Bunnell and Vales, 1990;

194   Cook et al., 1995). Our focus was to identify whether any of the alternative methods

195   could reliably identify relative differences in canopy openness to monitor canopy closure

196   timings, and promote data collection through large-scale citizen science.

197   ## 2. Methods

198   ### 2.1. Comparison of methods against hemispherical photography

199   Trials took place in 2014 at four woodlands in Devon, England. The suite of sites was

200   purposely chosen to represent a range of canopy/understorey light conditions, with

201   varying aspect, composition and structure (Table 1). Six fixed sample points or 'stations'

202   were randomly selected in each of the four woodlands. At each station, canopy

203   openness was estimated by a variety of methods in each season (related to leaf

204   phenology): winter (no canopy), spring (around 50% leaf-out), summer (full canopy) and

205   autumn (around 50% leaf-drop). All estimates were made concurrently for a woodland
206   within each season, and the four woodlands all estimated within a week of each other.

207   2.1.1. Hemispherical photography

208   Hemispherical photographs were taken in colour using a Nikon Coolpix 990 3.34 MP
209   camera with Nikon Fisheye Converter FC-E8 lens (Nikon Corporation, Tokyo, Japan).
210   The circular fisheye lens provides a 180° field of view in all directions. Images were
211   taken using the basic quality setting and stored in VGA-size, as canopy openness
212   estimates are not affected by resolution or size settings with this camera model (Inoue
213   et al., 2004).

214   Photos were taken without rain or direct sunlight entering the lens (Rich, 1989). The
215   camera was mounted on a tripod at 1.2 m above ground, and levelled using a circular
216   bubble level. Pictures were taken using the camera timer function to reduce movement
217   during image capture (Rich, 1989). Aperture and shutter settings were set to automatic,
218   and to minimise error from over-exposure (Brusa and Bunker, 2014; Hale and Edwards,
219   2002), exposure was checked using the histogram function in the camera playback
220   facility, following the method outlined by Beckschafer et al. (2013). Where over-
221   exposure was apparent, exposure settings were manually lowered to -2.0 EV, the
222   minimum limit on this camera.

223   Images were analysed in HemiView Canopy Analysis Software v.2.1 (Delta-T Devices,
224   Cambridge, UK). The Coolpix 900 lens settings in HemiView were selected to correct
225   for lens distortion (Hale and Edwards, 2002). Various options exist for classifying a
226   photograph into "sky" and "not sky" (binarization), using image analysis software
227   (Glatthorn and Beckschafer, 2014; Zhao and He, 2016). In HemiView, it is only possible
228   to use manual thresholding of black and white pixels, so we followed this method, which
229   has been widely used in other studies (Bertin et al., 2011; Capdevielle-Vargas et al.,
230   2015; Hale and Edwards, 2002; Machado and Reich, 1999; Zhang et al., 2005). Each
231   photograph was individually processed to obtain the best contrast between vegetation
232   and the background sky, by visual comparison with the original photograph (Rich,
233   1990). A decision was made, based on visual assessment during threshold setting,
234   whether each photo should be included in the analysis. If it was not possible to gain a
235   good contrast between sky and vegetation across the whole image, that photo was
236   excluded. Canopy openness—in HemiView, "% visible sky"— was then derived for each

237   image by the software. In HemiView this value represents a weighted canopy openness

238   score based on gap fraction zenith angles (Rich et al., 1999).

239   Following analysis in HemiView, photos were also analysed using ImageJ (Rueden,

240   2016). Photos were converted to 8-bit binary black ("not sky") and white ("sky") images

241   in ImageJ. Following the same procedure as we used for photos in HemiView, the

242   manual thresholding function in ImageJ was used to individually process each image

243   and obtain the best contrast between vegetation and background sky. This was done

244   with reference to the original photograph (Rich, 1990). Hemispherical photos consist of

245   a circular image inside a rectangular frame. As ImageJ is not designed specifically for

246   such images, it cannot automatically exclude the framing pixels as is possible in

247   HemiView. Therefore to calculate canopy openness (the proportion of pixels classified

248   as sky) excluding the frame, we first calculated the number of pixels in a reference

249   image containing only open sky. We then used the 'batch measure function' to calculate

250   white (sky) pixels for all images, and calculated the canopy openness as a proportion of

251   the circular hemispherical image, excluding the framing pixels.

252   2.1.2. Smartphone photography with fisheye lens

253   Photos were taken using a Sony Xperia L smartphone camera (Android Version 5.0)

254   with magnetic fisheye lens attachment (Skimn FE-12 180° fisheye lens). Images were

255   taken at 5 MP using a 16:9 aspect ratio – the camera's default settings. Using these

256   settings, the fisheye lens gave a 125° x 75° field of view. The smartphone was held

257   level, with the wider view orientated east-to-west when taking photos of the canopy, to

258   ensure comparable images were obtained for each season. Photographs were taken in

259   manual mode, with exposure lowered to -2.0 EV, the minimum limit on the camera.

260   Images were stored as high quality JPEGs, between 2–3 MB in size.

261   Smartphone fisheye photos were analysed in HemiView and ImageJ and visible sky

262   values were calculated, following the same procedures outlined for hemispherical photo

263   analysis. Lens equation coefficients relating zenith angles and radial distance were

264   calculated from a calibration curve constructed from measurements taken from

265   reference photographs. The resulting lens correction function ($y = 1.2213x -$

266    $1.396x^2 + 1.0855x^3 - 0.2761x^4$) was used by HemiView to adjust the calculations to correct

267   for lens distortion.

268   2.1.3. Smartphone photography without a fisheye lens

269 Smartphone photos were also taken of the canopy without the fisheye lens attachment,

270 giving a 70° x 40° field of view. Photos were taken of the canopy directly overhead (with

271 the wider view orientated east-west), and of the canopy facing in three different

272 bearings from the station – at 60°, 180° and 300° (with the camera positioned in a

273 landscape orientation at a at a 45° angle from the horizontal). All photos were taken

274 using the same settings as the photos with fisheye lens attachment, and exposure

275 settings were manually adjusted as previously described. Photographs were then

276 analysed using ImageJ, following the same procedure for binarization, to derive a

277 canopy openness estimation based on % visible sky. Two sets of canopy openness

278 estimates were derived from these photos: one based solely on the overhead canopy

279 photo, and one calculated as an average from all four photographs to incorporate a

280 wider area of view.

281 2.1.4. Non-photographic methods

282 Canopy openness was estimated visually on a simple percentage scale. Two sets of

283 canopy openness estimates were derived, one based solely on an overhead estimation,

284 and another based on an average of four estimations: one directly overhead, and at

285 three different bearings from the station (60°, 180° and 300°) at a 45° angle from the

286 horizontal.

287 Brown et al. (2000) proposed a canopy scope to aid in the visual estimation of canopy

288 openness. The scope consists of a simple Perspex sheet with a grid of twenty-five dots,

289 spaced 3cm apart in a 5x5 array. A 20cm length of string is attached to the corner, and

290 ensures the scope is held at a constant distance from the eyes when making

291 estimations. Canopy openness was estimated by focussing the scope on the largest

292 canopy gap visible from the station, and counting the number of dots coinciding with

293 sky. This number was then multiplied by four to obtain a percentage estimate. Brown et

294 al. (2000) found a close correlation between largest gap canopy openness and total

295 canopy openness, but acknowledged that for woodlands with several similar sized

296 canopy gaps, the largest gap estimate may not give an accurate representation. Two

297 alternative estimates were made: one by pointing the canopy scope at the canopy

298 directly overhead; and another by taking the mean of four canopy scope estimates

299 (using the overhead estimate and estimates made from viewing the canopy at bearings

300 of 60°, 180° and 300° from north, at an approximately 45° angle from the horizontal).

301 2.1.5. Statistical analysis

302 We used linear regression to compare canopy openness derived from hemispherical

303 photographs in HemiView, against each surrogate method. We first compared data from

304 all seasons and sites together to assess which methods were able to estimate broad

305 changes in canopy openness. We then compared methods on a season-by-season

306 basis across the four sites, to understand whether methods were capable of estimating

307 finer-scale variation in canopy openness. We also conducted method comparisons on a

308 site-by-site basis using data from all four seasons, to assess whether methods

309 performed well across the different woodlands.

310 For methods that performed consistently well across the comparisons, Analysis of

311 Covariance (ANCOVA) was used to test whether the methods estimated canopy

312 openness in similar ways under different conditions, with seasons and sites as

313 covariates. A Tukey-Kramer test was used to explore differences that were found

314 between seasons or sites. All statistical analyses were carried out in R 3.3 (R Core

315 Team, 2016).

316 **2.2.   Comparison of smartphone models and operators**

317 2.2.1. Field imagery

318 A second trial comparing smartphone models and phone users took place in mixed

319 deciduous woodland at Mount Edgcumbe Estate, Cornwall (approximately 50°35'N and

320 4°16'W), during summer when trees were in full leaf. Three sampling locations or

321 'stations' were selected at the site, using visual assessment, to represent a 'closed',

322 'intermediate' and 'open' overhead canopy. We tested two popular Smartphone

323 cameras – the iPhone 5 and Samsung Galaxy S4 – against the Sony Xperia used in the

324 previous trials, to assess the comparability of canopy openness estimates. Photos taken

325 with the iPhone 5 had a resolution of 8 MP and an aspect ratio of 16:9, providing a 61° x

326 48° field of view. Photos taken with the Samsung Galaxy S4 had a resolution of 9.6 MP

327 and aspect ratio of 16:9, providing a 57° x 34° field of view. Photos were stored as high

328 quality JPEGS, between 2–3 MB in size.

329 Twenty-two volunteers consecutively took an overhead photograph of the canopy with

330 each camera, at each of the three stations. All photos were taken within a half-hour

331 period. Volunteers were instructed to hold the phone at an estimated level position and

332 take a photo of the canopy above, but were not told to orientate the phone in a

333 particular direction, as we were interested to see the extent that individual user
334 operation affected consistency in the results. Photos were analysed in ImageJ following
335 the procedure outlined above.

336 2.2.2. Statistical analysis

337 The Aligned Rank Transform (ART) procedure in the R package ARTool (Kay and
338 Wobbrock, 2016), followed by separate ANOVA using R 3.3 (R Core Team, 2016), was
339 used to assess the effects of phone user, phone model and canopy treatment on
340 canopy openness values. The ART procedure is an appropriate way to analyse
341 datasets which are not normally distributed, and is described in more detail by
342 Wobbrock et al. (2011). We performed *post hoc* contrasts using estimated marginal
343 means with the emmeans package (Lenth, 2017).

344 **3. Results**

345 **3.1. Hemispherical photography with HemiView v other methods**

346 All hemispherical photos taken were suitably exposed in relation to sky conditions, for
347 inclusion in the analysis, while four smartphone fisheye photos and six smartphone
348 photos without the fisheye lens attachment were eliminated due to overexposure, out of
349 96 photos in each case.

350 Analysis of hemispherical photography with ImageJ produced reliable estimates of
351 canopy openness values derived from analysis with HemiView (Table 2, Figs 1A and
352 1D). With photos from spring, summer and autumn combined into a single ANCOVA
353 analysis, the slope of the relationship was no different for all three seasons (Fig. 1D
354 ANCOVA $F_{2,66} = 2.55$, $p = 0.09$). However, the intercepts of the relationships were
355 significantly different (Fig. 1D ANCOVA $F_{2,68} = 8.09$, $p < 0.001$), with summer values
356 estimated relatively lower than those of spring and autumn (Tukey-Kramer Test,
357 summer v spring $p = 0.004$, summer v autumn $p < 0.001$, spring v autumn $p = 0.864$).

358 None of the other methods closely estimated absolute canopy openness values derived
359 from hemispherical photography, but all smartphone photographic methods reliably
360 estimated relative differences in canopy openness across all seasons for all sites (Table
361 2, Figs 1B and 1C). The slopes of these relationships, which were all >1, indicate that
362 smartphone fisheye photography results in higher estimates of canopy openness than
363 hemispherical photography, and that the estimates differ more at higher values of

364 canopy openness. During winter, when there were very high levels of canopy openness

365 (*mean* = 37%, *sd* = 5%), smartphone fisheye photos did not correspond reliably to

366 hemispherical photography (Table 2). This was also true for all other methods tested,

367 and since winter is not a season where canopy change is expected and therefore not

368 relevant to our aims, winter data were excluded from the rest of the analyses. Non-

369 photographic methods (canopy scope and simple visual estimations) were much poorer

370 estimators of change in canopy openness across all seasons and sites (Table 2).

371 Smartphone with fisheye lens estimates taken in different seasons had similar slope

372 relationships (Fig. 1E ANCOVA $F_{2,66}$ = 0.31, p = 0.73; Fig.1F $F_{2,66}$ = 0.64, p = 0.53), but

373 they varied in intercept (Fig 1E, ANCOVA $F_{2,64}$ = 33.56, p < 0.001; Fig. 1F $F_{2,64}$ = 48.73,

374 p < 0.001). For smartphone photographs analysed with HemiView canopy analysis

375 software, spring and autumn intercepts were not significantly different (Tukey-Kramer p

376 = 0.796), but both were significantly different from summer (p < 0.001 in each case).

377 The same photographs analysed with ImageJ had different intercepts for each of the

378 three seasons (spring v autumn p = 0.020, spring v summer p < 0.001, summer v

379 autumn p < 0.001).

380 Since smartphone fisheye photography and ImageJ analysis reliably estimated variation

381 in canopy openness, we tested whether the methods performed consistently between

382 different sites (Fig. 2). Hemispherical imagery analysed with ImageJ showed similar

383 slope relationships across all sites (Fig. 2A; ANCOVA $F_{3,64}$ = 1.17, p = 0.33), but

384 significant differences in intercept (ANCOVA $F_{3,67}$ = 4.75, p = 0.005). The intercept of

385 Hardwick was different from Hunshaw and Whitleigh (Tukey-Kramer Test, p = 0.018

386 and p = 0.007), though all other intercepts were not different (p = 0.288 to 1.000).

387 Smartphone with fisheye photography, whether analysed with HemiView or ImageJ,

388 resulted in different slope relationships for Hardwick compared to the other sites (Fig.

389 2B, ANCOVA $F_{3,60}$ = 4.10, p = 0.010; Fig. 2C, $F_{3,60}$ = 7.07, p < 0.001). As canopy

390 openness increased, the estimates for Hardwick differed less from the hemispherical

391 standard than the other sites. The intercepts of the other sites did not differ (Fig. 2B,

392 ANCOVA $F_{2,46}$ = 0.91, p = 0.41; Fig. 2C, $F_{2,46}$ = 0.54, p = 0.59).

393 **3.2. Comparison of smartphone models and operators**

394 The three canopy treatments (closed, intermediate and open) were clearly different from

395 each other in terms of canopy openness, but it did not matter which phone model or

396   user took the photos (Fig. 3; Aligned Rank Transform + ANOVA, $p_{canopy} < 0.0001$, p_{user}

397    $= 1.00$ and $p_{model} = 0.50$). However, variability in estimation of canopy openness

398   increased markedly as canopy openness increased. For the closed canopy, standard

399   deviations of the estimates ranged from 0.79–1.46% canopy openness, but were much

400   greater for the open canopy (7.42–12.43%).

4. Discussion

402   Our results showed that smartphone photographic methods estimated variation in

403   canopy closure effectively, but rapid visual estimation methods did not. Basic visual

404   estimations of canopies are known to lack consistency, varying considerably due to

405   weather conditions (Jennings et al., 1999) and observer biases (Vales and Bunnell,

406   1988). The canopy scope is more a quantitative visual estimation method, allowing for

407   greater consistency and has been shown to have low between-observer bias (Brown et

408   al., 2000), so is potentially more suitable for citizen science. However, while the canopy

409   scope can distinguish quite different degrees of canopy openness (Brown et al., 2000),

410   it lacked the fine resolution needed to distinguish between similar canopies, and

411   therefore is less suitable for monitoring changes through time.

412   Smartphone photographic methods have now become a cost effective and practical

413   alternative to visual estimation. Simple photographs using a smartphone camera without

414   a lens attachment were sufficient for assessing the degree of variation in canopies

415   across a whole season, but did not pick up fine-scale variations (i.e. between similar

416   canopies within a season) compared with hemispherical photography. This is

417   unsurprising, as their narrow angle of view means they are essentially providing an

418   estimate of canopy cover directly overhead, as opposed to canopy closure across a

419   range of zenith angles (Chianucci et al., 2014; Jennings et al., 1999). With the addition

420   of an inexpensive fisheye lens attachment, smartphone photographs were able to pick

421   up finer variations in canopy openness in spring, summer and autumn, which would be

422   important for monitoring seasonal dynamics.

423   As anticipated, smartphone fisheye photography gave higher canopy openness

424   estimations than hemispherical photography, due to its narrower field of view. With

425   hemispherical photography, an image taken within a forest will typically include a ring of

426   tree trunks and shrubs around the periphery, with low gap fractions in the outer portions

427   of the image (at larger zenith angles) (Chen et al., 1997). Although incorporating a

428 greater field of view than non-fisheye photos, smartphone fisheye photos still omit the
429 largest zenith angles containing most of the lower trunks and shrub layer. In its field of
430 view, the gaps in a canopy contribute more to the overall image. Similarly, twigs and
431 foliage have higher prominence in images. As smartphone fisheye photography misses
432 gaps at larger zenith angles, it would not be a suitable method for detailed studies of
433 canopy structure or plant growth. However, the method is suitable for monitoring timing
434 of canopy closure, and its narrower field of view could actually make it a superior
435 method for identifying leafing activity early in spring.

436 We found canopy structure affected the relationship between hemispherical
437 photography and smartphone photography, meaning that canopy openness values must
438 be converted to proportions of total canopy closure to be correctly interpreted. Where
439 the overhead canopy was uniformly closed, the difference between canopy openness
440 estimations from smartphone fisheye photos and hemispherical photos was lower –
441 both sets of images show a closed canopy with few gaps. In more open situations, the
442 difference between the two sets of estimations was greater. Similarly where stand
443 density was higher and the height of the tree canopy was lower (e.g. at Hardwick Wood,
444 Table 1), the difference between canopy openness values from the two methods was
445 smaller. Canopy height is known to effect openness estimations when the field of view
446 is reduced (Jennings et al., 1999; Pellikka, 2001).

447 Due to the influence of canopy structure on canopy openness values, we propose this
448 method is appropriate for monitoring relative change in canopies through time. In order
449 to compare the timing and rate of canopy closure across different forest locations we
450 can standardize along a proportional scale of canopy closure, where 0% represents the
451 winter canopy value prior to budburst, and 100% represents the summer canopy value
452 once the canopy is fully in leaf. We note that canopies are dynamic, and small-scale
453 fluctuations occur through summer. Therefore the summer canopy value would be
454 determined from the point where the canopy reaches 'adjustment stability' (Margalef,
455 1969), after which only small changes of less than 2% canopy closure are observed.
456 The progress of canopy closure can then be plotted through time from 0–100%, and a
457 logistic growth model can be fitted to characterise the phenological pattern (Richardson
458 et al., 2006; Zhang et al., 2003). An example using smartphone fish-eye photography is
459 provided in Supplementary Material.

460   In terms of photo analysis, we found that ImageJ is a reasonable alternative to

461   professional specialist software such as HemiView, for deriving relative canopy

462   openness values. It is clear that ImageJ overestimates values from HemiView to some

463   degree, so again, this method would not be suitable for studies where absolute values

464   were needed. The distortion of a hemispherical or fisheye lens causes the central part

465   of the image, towards the zenith, to appear larger than peripheral elements towards the

466   horizon (Herbert, 1987). Canopy openness derived from HemiView is based on a

467   weighted gap fraction that takes into account the zenith angle of canopy gaps, and

468   corrects for a given lens distortion (Promis et al., 2011). In contrast, canopy openness

469   derived from ImageJ is simply the percentage visible sky across the image. However,

470   values from ImageJ still consistently and reliably estimated relative differences in

471   canopy openness in our study.

472   ImageJ has the benefits of being free, open access and relatively straightforward to use.

473   It is not necessary to provide specifications of the fisheye lens to use it. Image

474   binarization is still required, which can be time consuming. The manual thresholding

475   technique used in this study would not be suitable for analysing large quantities of

476   citizen science data. Many citizen science projects have successfully utilised internet

477   crowd-sourcing applications (Kosmala et al., 2016) to involve the public in processing

478   and classifying large numbers of images, so a similar approach could be used to

479   binarize canopy photos, with multiple people classifying pixels for the same image to

480   reduce error (Inoue et al., 2011). However, new methods for automatic thresholding of

481   photos would improve efficiency (Brusa and Bunker, 2014; Glatthorn and Beckschafer,

482   2014; Inoue et al., 2004), and auto-thresholding plug-ins for ImageJ (Glatthorn and

483   Beckschafer, 2014) could provide a viable option.

484   In terms of practicalities, smartphone fisheye photography is suitable for widespread

485   use as part of citizen science projects, and if managed properly is a game-changer in

486   terms of data quantity. The good agreement between smartphone models and users

487   suggests the method can be reliably applied by citizen scientists. The three phone

488   models tested varied in resolution and field of view, but still produced comparable

489   results. While some variation was evident between photos taken with the same phone,

490   under the same canopy conditions, there was no overall effect of phone user on canopy

491   openness values. Variation between photos taken with the same phone was greatest at

492   higher levels of canopy openness. This is not surprising, as under the dense canopy,

493 gaps were small and uniformly distributed, whereas the open canopy comprised a very

494 large central gap bordered by canopy. Small variation in camera positioning could

495 therefore result in compositional differences between photographs. This could lead to

496 significant differences in estimates, as has been observed with other methods for

497 estimating canopy openness (Jennings et al. 1999). Therefore, we recommend that for

498 best results camera position is standardised by installation of fixed camera mounts

499 (University of New Hampshire, 2017) for citizen scientists to place their smartphones on

500 in order to take repeat photographs of particular parts of the canopy.

501 The quality of photos obtained from smartphone fisheye photography is sufficient to

502 obtain reliable data. The high resolution available with smartphone cameras is a clear

503 advantage. Resolution is known to be an important factor influencing the quality of

504 canopy openness measures from hemispherical photography (Brusa and Bunker, 2014;

505 Woodgate et al., 2015), and in this study the smartphone camera resolution was

506 superior to that of the hemispherical camera (with nearly 2,000,000 more pixels). It has

507 also been noted that higher resolution images are less vulnerable to thresholding errors

508 during image processing and analysis (Macfarlane et al., 2007). Some blurring was

509 evident towards the perimeter of the smartphone fisheye photos, but this is also

510 apparent with hemispherical photos (Frazer et al., 2001). Blurring from motion caused

511 by holding the camera to capture images could also influence image quality (Woodgate

512 et al., 2015). The use of fixed mounts for phone cameras would help alleviate this

513 problem, as well as utilising the camera's timer function or earphone controls to

514 remotely operate the camera shutter.

515 As with hemispherical photography, there are several logistical issues associated with

516 the use of smartphone photography, relating to sky conditions and image exposure. The

517 effects of over-exposure and the importance of taking photos under uniform sky

518 conditions has been emphasised in many studies (Beckschafer et al., 2013; Brusa and

519 Bunker, 2014; Rich, 1990; Woodgate et al., 2015; Zhang et al., 2005). In this study, a

520 small proportion of smartphone photos had to be excluded due to over-exposure. While

521 smartphone photographs were taken at -2.0 EV, the lowest exposure setting available,

522 Beckschafer et al. (2013) showed that over-exposure can still occur at -2.0 EV under

523 bright skies. This can also be a problem with hemispherical photography, as the Nikon

524 Coolpix 990 had the same limits for exposure compensation. The histogram function

525 allows a definitive check as to whether photos are over-exposed, and more advanced

526   cameras allow for lowering below -2.0 EV (Beckschafer et al., 2013). We emphasise
527   again that the smartphone fish-eye photography method would not be suitable for
528   detailed studies of canopy structure or growth where small differences between sites
529   must be detected, and therefore consistent exposure is paramount (Leblanc, 2005).
530   However, to track the progress of canopy closure through time and compare trends in
531   the timing of this phenological event over large spatial scales, a small degree of noise in
532   the data is acceptable. The example in Supplementary Material demonstrates that the
533   phenological process of canopy closure can be clearly modelled using this method.
534   While the limits of exposure settings on smartphone cameras may mean some photos
535   have to be discarded, the greater number of images obtained by utilising a citizen
536   science approach should increase the number of suitable images that can be included
537   in a study. Where possible citizen scientists should be encouraged to take photos early
538   or late in the day, which is when sky conditions are generally most appropriate, and
539   coincides with times when people are likely to be available to collect imagery.

540   ## 5. Conclusions

541   Smartphone fisheye photography, with relatively simple image analysis, offers a
542   practical method for comparing changes in the timing of canopy closure across different
543   forests year on year, and may even be more suited to this task than hemispherical
544   photography. Using this approach, trends in proportional changes in canopy closure
545   could be identified across different spatial and temporal scales using citizen science.
546   Further research is required to assess the temporal resolution of image capture needed
547   to represent canopy changes adequately.

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773

774 **Tables**

775

Site	Size (ha)	Stand density (trees/ha)	Average tree height (m)	Aspect	Dominant canopy species	Dominant shrub layer species
Hardwick Wood (50°22'N, 4°4'W)	22	1360	16	Flat	*Acer pseudoplatanus, Fraxinus excelsior*	*Acer pseudeoplatanus, Ulmus* sp.
Hunshaw Wood (50°55'N, 4°7'W)	18	556	30	S	*Quercus robur* with *Fagus sylvatica* sub-canopy	*Corylus avellana, Sorbus aucuparia*
Newton Mill (50°52'N, 4°15'W)	25	456	35	NE	*Quercus robur*	*Corylus avellana, Fagus sylvatica*
Whitleigh Wood (50°25'N, 4°8'W)	20	1111	27	N	*Quercus robur* and *Betula pendula*	*Corylus avellana, Fagus sylvatica, Acer pseudoplatanus*

776 Table 1. Site descriptions of woodlands used to compare methods for estimating

777 canopy openness. All sites were located in Devon, England.

Method	All seasons		Spring		Summer		Autumn		Winter	
	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p
Hemispherical photo (ImageJ)	0.96	<0.001	0.85	<0.001	0.77	<0.001	0.94	<0.001	0.69	<0.001
Smartphone fisheye photo (HemiView)	0.89	<0.001	0.83	<0.001	0.67	<0.001	0.79	<0.001	0.05	0.300
Smartphone fisheye photo (ImageJ)	0.84	<0.001	0.74	<0.001	0.76	<0.001	0.66	<0.001	0.08	0.170
Smartphone photo (overhead)	0.85	<0.001	0.57	0.002	0.43	<0.001	0.69	<0.001	0.04	0.380
Smartphone photo (average of 4)	0.81	<0.001	0.15	0.410	0.60	<0.001	0.72	<0.001	0.02	0.490
Canopy scope (overhead)	0.51	<0.001	0.24	0.240	0.01	0.170	0.41	<0.001	0.00	0.820
Canopy scope (largest gap)	0.52	<0.001	0.2	0.029	0.20	0.030	0.33	0.003	0.00	0.850
Canopy scope (average of 4)	0.55	<0.001	0.31	0.005	0.18	0.040	0.55	<0.001	0.00	0.910
Visual estimation (overhead)	0.39	<0.001	0.01	0.740	0.05	0.280	0.31	0.005	0.06	0.260
Visual estimation (average of 4)	0.52	<0.001	0.03	0.460	0.20	0.029	0.51	<0.001	0.04	0.350

778   Table 2. Proportion of variation explained (R^2) and statistical significance (p) for

779   relationships between hemispherical photography analysed with HemiView and

780   alternative methods. Relationships were considered separately for each season, as well

781   as across all seasons together.

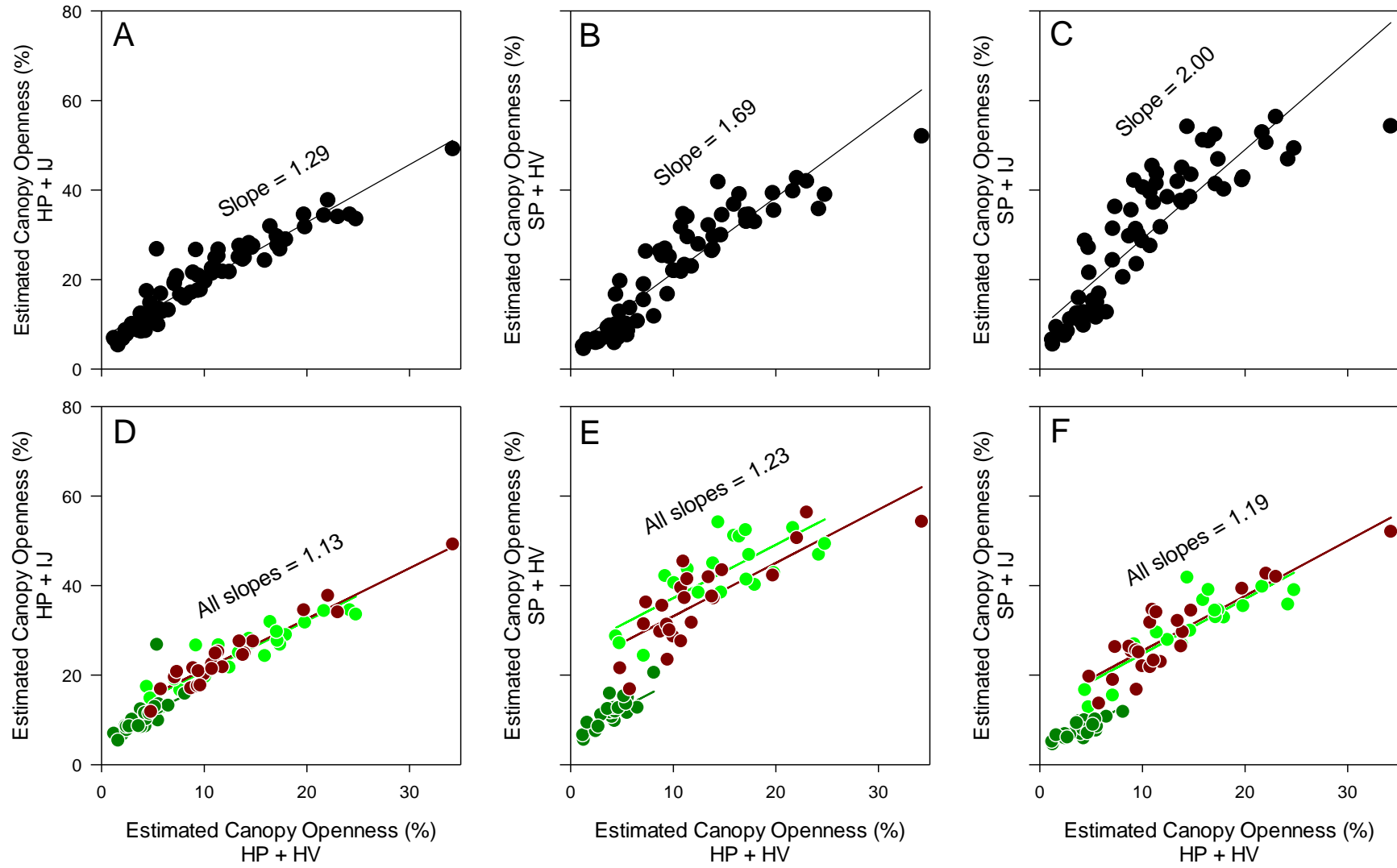| Method	Hardwick		Hunshaw		Newton Mill		Whitleigh	
	R^2	p	R^2	p	R^2	p	R^2	p
Hemispherical photo (ImageJ)	0.97	<0.001	0.85	<0.001	0.98	<0.001	0.81	<0.001
Smartphone photo fisheye (HemiView)	0.95	<0.001	0.86	<0.001	0.86	<0.001	0.86	<0.001
Smartphone photo fisheye (ImageJ)	0.84	<0.001	0.80	<0.001	0.81	<0.001	0.86	<0.001
Smartphone photo (overhead)	0.88	<0.001	0.78	<0.001	0.68	<0.001	0.85	<0.001
Smartphone photo (average of 4)	0.92	<0.001	0.93	<0.001	0.70	<0.001	0.85	<0.001
Canopy scope (overhead)	0.47	0.002	0.08	0.260	0.68	<0.001	0.19	0.072
Canopy scope (largest gap)	0.42	0.004	0.22	0.049	0.73	<0.001	0.12	0.160
Canopy scope (average of 4)	0.39	0.005	0.25	0.034	0.75	<0.001	0.16	0.100
Visual estimation (overhead)	0.42	0.004	0.1	0.200	0.60	<0.001	0.01	0.630
Visual estimation (average 4)	0.47	0.002	0.2	0.063	0.67	<0.001	0.01	0.740

782 Table 3. Proportion of variation explained (R^2) and statistical significance (p) for

783 relationships at each woodland site between estimates of canopy openness from

784 hemispherical photography analysed with HemiView versus estimates from other

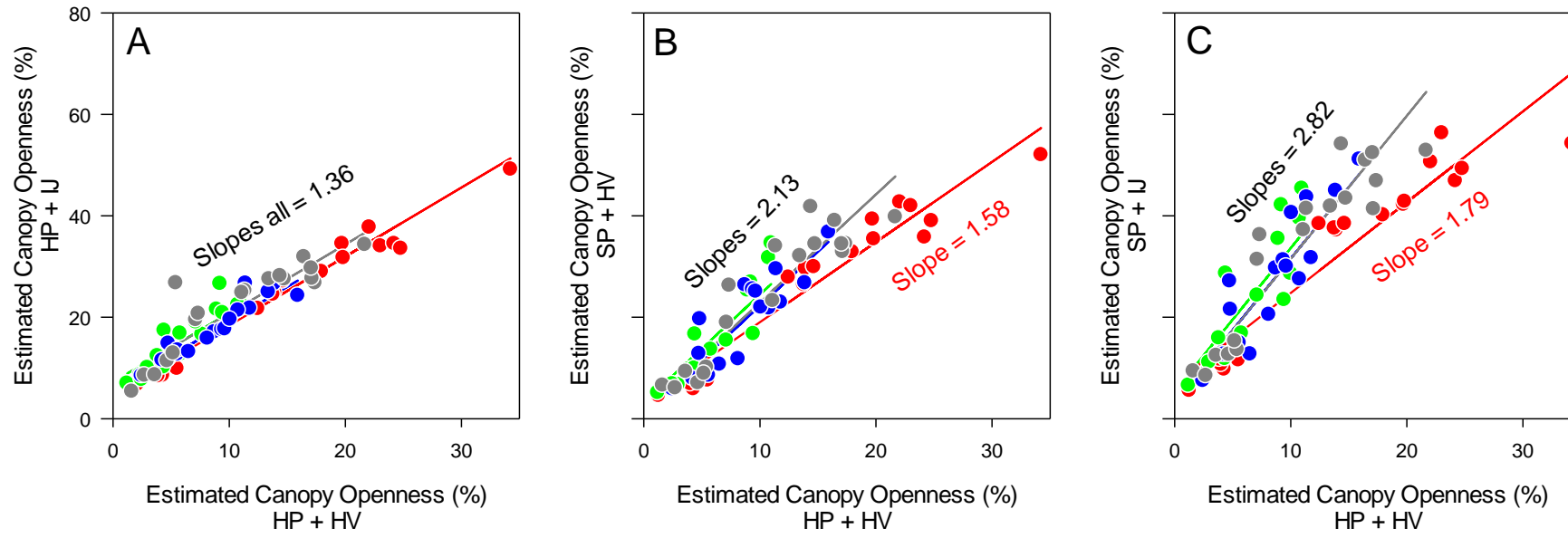785 methods. Photographs were included from spring, summer and autumn, but not winter.

Figures

Fig. 1. Canopy openness estimates from hemispherical photography with HemiView (HP+HV) compared with estimates from hemispherical photography with ImageJ (HP+IJ), smartphone fisheye photography with HemiView (SP+HV), and smartphone fisheye photography with ImageJ (SP+IJ). **Figs A–C.** Overall relationships across all seasons. R^2 and statistical significance of these relationships is presented in Table 2. **Figs D–F.** Separate relationships for each growing season (light green = spring, dark green = summer, dark red = autumn).

Fig. 2. Site canopy openness estimates from hemispherical photography with HemiView (HP+HV) compared with estimates from **(A)** hemispherical photography with ImageJ (HP+IJ), **(B)** smartphone fisheye photography with HemiView (SP+HV), and **(C)** smartphone fisheye photography with ImageJ (SP+IJ). R^2 and statistical significance of these relationships is presented in Table 3. Relationships are shown for each site (red = Hardwick, green = Hunshaw, blue = Newton Mill, grey = Whitleigh).

Fig. 3. Comparison of estimates of canopy openness using three different models of smartphone in three canopy densities. Every canopy density x phone combination was based on 22 photographs, each taken by a different user. The median is shown as a horizontal line, the box represents values within the 25–75% quartiles, and the error bars show the minimum and maximum values. Means sharing a letter were not significantly different according to *post hoc* contrasts using estimated marginal means.
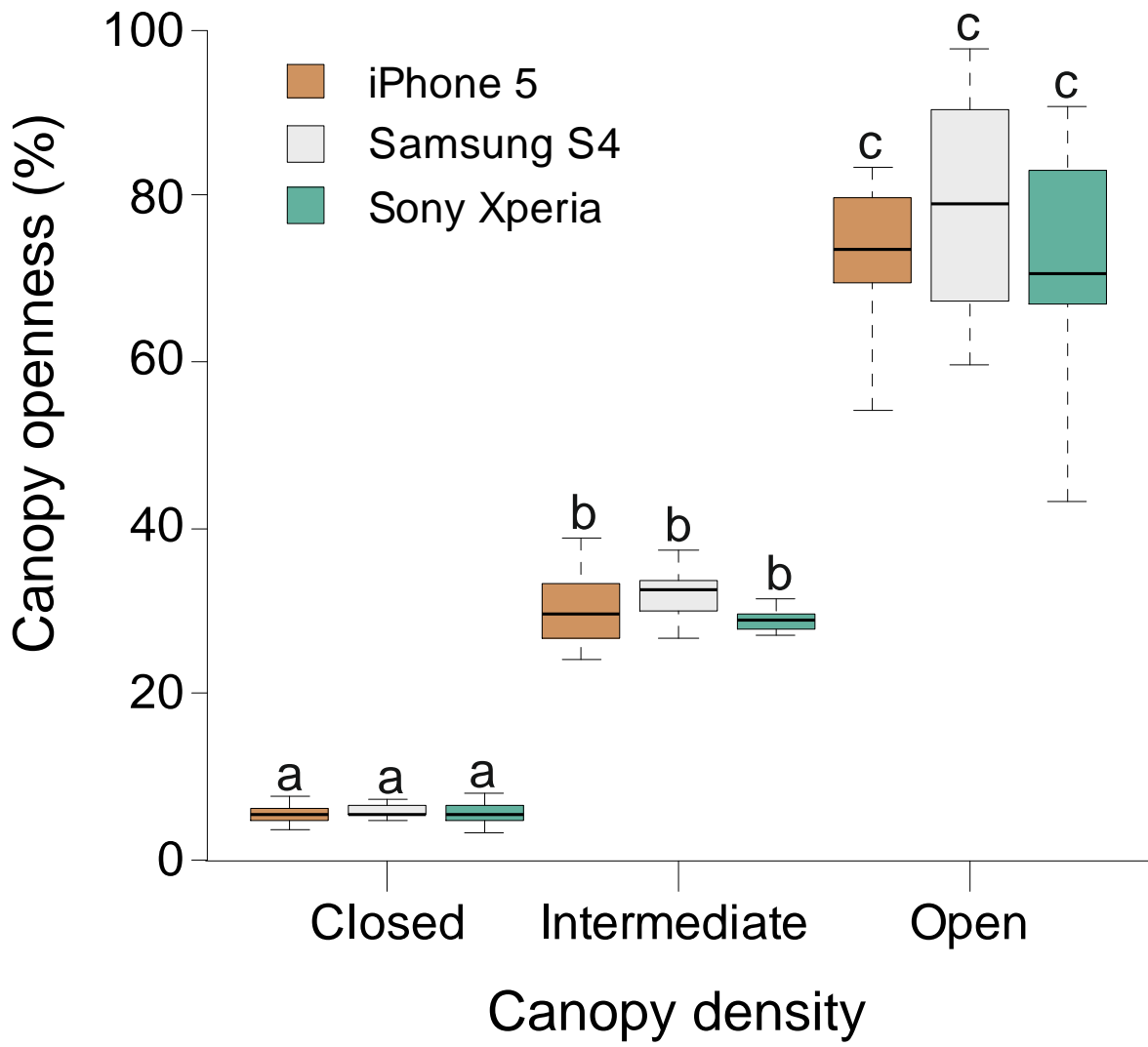
806   Fig. 1

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809   Fig. 2

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