



HAL
open science

Microclimate estimation under different coffee-based agroforestry systems using full-sun weather data and shade tree characteristics

Isabelle Merle, Rogelio Villarreyna-Acuña, Fabienne Ribeyre, Olivier Roupsard, Christian Cilas, Jacques Avelino

► **To cite this version:**

Isabelle Merle, Rogelio Villarreyna-Acuña, Fabienne Ribeyre, Olivier Roupsard, Christian Cilas, et al.. Microclimate estimation under different coffee-based agroforestry systems using full-sun weather data and shade tree characteristics. *European Journal of Agronomy*, 2022, 132, pp.126396. <10.1016/j.eja.2021.126396>. <hal-03473219>

HAL Id: hal-03473219

<https://hal.inrae.fr/hal-03473219v1>

Submitted on 5 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

23 In Central America, coffee is mainly grown in agroforestry systems. This practice modifies
24 the microclimate, which, in turn, influences coffee growth and development. However, modeling
25 these microclimate modifications is a challenge when trying to predict the development of a
26 disease in the understory crop, based on variables usually monitored in weather stations exposed
27 to full sunlight. Furthermore, critical variables for plant disease development, such as leaf
28 wetness duration and leaf temperatures, are generally not measured by weather stations. In our
29 study, we sought to build models explaining daily minimum and maximum coffee leaf
30 temperatures, daily coffee leaf wetness duration, and minimum and maximum air temperatures in
31 agroforestry systems with a single shade tree species, which are common in Central America, and
32 which were characterized by shade tree height, canopy openness and light gap distribution. The
33 modeled variables were mainly explained by one or more meteorological variables provided by
34 reference weather stations exposed to full sunlight. The presence of shade trees resulted in a
35 buffer effect, reducing daily maximum air and leaf temperatures, and increasing daily minimum
36 air and leaf temperatures. Moreover, except for the daily minimum air temperature under shade,
37 shade tree characteristics affected these microclimatic variables. Indeed, the buffer effect on the
38 daily maximum air temperature increased with shade trees 7 m tall or over, whereas for extreme
39 leaf temperatures, this effect seemed to be further intensified by a dense and homogeneous
40 canopy. The tallest shade trees also tended to provide conditions that reduced coffee leaf wetness
41 duration. The coffee leaf stratum affected the daily maximum leaf temperature, with a top layer
42 intercepting radiation for the lower strata, but had no effect on the daily minimum leaf
43 temperature, detected at night. The models developed were simple equations allowing
44 interpretation of shade tree height, the effects of canopy characteristics on the microclimate and
45 were therefore useful for designing and managing agroforestry system. The more accurate models
46 could be incorporated into an early warning system for coffee pests and diseases in the region.

47
48 Keywords: daily extreme temperatures, daily coffee leaf wetness duration, modeling, shade tree
49 height, canopy openness, light gap distribution
50

51 INTRODUCTION

52
53 Agroforestry is a cropping practice that consists in combining one or more tree species with
54 a crop production based on annual or perennial plants. While the word agroforestry is recent, this
55 practice is traditional for certain crops, such as coffee. Since the 1970s, the modernization of
56 coffee cultivation has led to a significant conversion of traditional diversified agroforestry
57 systems into agroforestry systems with fewer tree species and even monoculture systems
58 (Perfecto et al. 1996; Jha et al. 2014). These modernized full-sun systems have increased yields
59 through the introduction of high-yielding varieties and increased use of chemical inputs that are
60 all the more useful since the crop is fully exposed to sunlight. However, production costs have
61 also increased significantly, which probably explains why coffee is still mainly grown under
62 shade in regions where smallholders are mostly represented, such as Central America (Fernandez
63 1984). In this area, more than 40 species of trees are used in coffee agroforestry systems (Dix et
64 al. 1999).

65 Agroforestry offers many benefits: food security through income diversification and self-
66 consumption of products from the farm (wood, fruit), improved coffee quality, reduction of
67 coffee production bienniality, biodiversity conservation including pollinators, regulation of
68 certain diseases and pests, improved soil water status, increased light use efficiency and carbon
69 sequestration (Perfecto et al. 1996; Muschler 2001; DaMatta 2004; Lin 2007; Jha et al. 2014;
70 Charbonnier et al. 2017; Avelino et al. 2018; Schnabel et al. 2018). This practice is therefore

71 considered to be an agroecological practice that promotes the resilience of agroecosystems (Hillel
72 and Rosenzweig 2010; Lasco et al. 2014). However, disadvantages to its use have also been
73 reported since shade trees compete with coffee plants for light, nutrients (Campanha et al. 2004;
74 Stigter 2015) and even for water under certain conditions (Padovan et al., 2015), thus hampering
75 blossoming and the achievement of high yields (DaMatta and Rena 2002). Agroforestry also
76 influences the dynamics of coffee diseases and pests in different directions, mainly through its
77 effects on the microclimate (Schroth et al. 2000; Staver et al. 2001; Avelino et al. 2011; Allinne
78 et al. 2016; Avelino et al. 2018). Most studies have demonstrated the overall effect of coffee-
79 based agroforestry systems on different microclimate variables (Butler 1977; Barradas and Fanjul
80 1986; Gutierrez and Vaast 2002; Morais et al. 2006; Siles et al. 2010; Pezzopane et al. 2011;
81 Coltri et al. 2019). Air, leaf and soil temperatures are buffered, leaf wetness is increased, wind
82 speed and solar radiation are reduced, rainfall is intercepted and redistributed, and raindrops have
83 a higher kinetic energy (Monteith et al. 1991; Stigter 2015; Vezy et al. 2018; Avelino et al.
84 2020). However, only a few studies have modeled how the microclimate is affected by different
85 characteristics of these agroforestry systems, such as planting density and shade tree height, or
86 canopy opening rate and light gap distribution (van Oijen et al. 2010a; Vezy et al. 2020). At
87 present, simulation models based on physical phenomena are available to simulate flows
88 involved in the major coffee growth mechanisms of photosynthesis, respiration and transpiration
89 (van Oijen et al. 2010a; Rodríguez et al. 2011; Charbonnier et al. 2013; Vezy et al. 2018, 2020),
90 and even coffee canopy temperatures under shade trees (Vezy et al., 2018). However, these
91 process models are based on physical phenomena whose descriptors, such as the global radiation
92 extinction coefficient of the trees and tree leaf area index (Taugourdeau et al. 2014), are difficult
93 to measure. Some studies developed simple equations to forecast minimum night crop
94 temperatures, with a view to predicting frost events (Georg 1978; Lhomme and Guillioni 2004),

95 but these models were still using complex parameters that were difficult to measure.
96 Alternatively, to process models that are useful for research but difficult to apply widely,
97 empirical equations using only easy-to-measure characteristics would offer several interesting
98 perspectives and allow large-scale applications. Indeed, in order to regulate the microclimate to
99 suit the seasonal needs of the crop and improve disease and pest management, practices such as
100 shade tree pruning could help to adjust these easy-to-measure characteristics when needed
101 (Niether et al. 2018). In addition, the ability to estimate the microclimate under different
102 agroforestry systems based on their characteristics and data from weather stations fully exposed
103 to sunlight would improve the accuracy of crop growth model predictions and pest and disease
104 forecasts (Merle et al. 2020), which would be an important achievement prior to their
105 introduction in a warning system (van Maanen and Xu 2003).

106 In our study, we investigated the relative importance of different simple agroforestry
107 system characteristics to explain the microclimate in the understory, considering meteorological
108 data provided by nearby weather stations fully exposed to sunlight. To that end, we set up six
109 trials at six sites in an altitudinal gradient, where the microclimate of several agroforestry systems
110 was recorded along with that of full sun conditions. We focused on different agroforestry systems
111 with a single shade tree species, which are common in Central America. Shade tree height,
112 canopy openness and light gap distribution were measured.

113

114

MATERIALS AND METHODS

115

116

Location of the studied coffee-based single-species agroforestry systems

117

118

This study was carried out in Costa Rica from July 2018 to January 2019 in seven coffee plantations distributed in a gradient ranging from 740 to 1400 m a.s.l. The selection of these

119 plantations was based on the possibility to establish a coffee plot fully exposed to sunlight used
120 as a reference and a minimum of two coffee plots in agroforestry systems with a single shade tree
121 species, considering a minimum plot radius of 20 m. Four plantations were selected in Cartago
122 province and three in San Jose province (Table 1).

123 The first plantation in Cartago province was located in Pavones at an altitude of 740 m a.s.l.
124 and included two plots with the Catimor coffee variety grown in agroforestry systems with a
125 single shade tree species, namely *Erythrina poeppigiana* and *Cordia alliodora*. The second site
126 was located in Palomo at an altitude of 770 m a.s.l. and included a plot planted with the Catimor
127 coffee variety grown in an agroforestry system with *C. alliodora*. Due to its altitude close to that
128 of the Pavones site and the availability of only one agroforestry system, this site was not studied
129 over the whole duration of the test (Fig. 1). The third plantation studied in Cartago province was
130 located near the town of El Guayabo at an altitude of 840 m a.s.l. and provided three plots with
131 the Catimor coffee variety cultivated in agroforestry systems with a single shade tree species,
132 namely *E. poeppigiana*, *Musa spp.* and *Gliricidia sepium*. The last plantation studied in this
133 province was located near the village of Cachí at an altitude of 1140 m a.s.l. and had two plots
134 with the Caturra coffee variety cultivated in agroforestry systems with the species *E. poeppigiana*
135 and *Musa spp* alone.

136 In the province of San José, two plantations were selected at altitudes of 1000 m a.s.l. and
137 1400 m a.s.l. near the town of San Marcos. In the 1000 m a.s.l. plantation, three plots were
138 studied: one plot with the Obata coffee variety grown in agroforestry systems based on *Vochysia*
139 *guatemalensis* and two plots with the Catuaí rojo coffee variety grown in agroforestry systems
140 based on *Musa spp.* and *E. poeppigiana* alone. Finally, the last site of the province of San José
141 was located near the town of Aserrí at an altitude of 1270 m a.s.l. and the plots studied were three
142 agroforestry systems with a single shade tree species, namely *Acrocarpus fraxinifolius*, *E.*

143 *poepigiana* and *Musa* spp. At this site, the Catimor variety was grown in the shaded plot with *A.*
144 *fraxinifolius* and the variety Catuaí rojo in the other two plots. Most of the studied shade tree
145 species are commonly found in agroforestry systems in Central America (Staver et al. 2001; van
146 Oijen et al. 2010b).

147

148 **Microclimatic data recording**

149 Since we had a total of 12 dataloggers, it was decided that a maximum of 2 to 3 sites could
150 be equipped simultaneously and that each site would have weather stations during three separate
151 21-day recording periods (Fig. 1). The three recording periods of 21 days carried out in the six
152 sites represent a total of approximately 380 days of recording. At the Palomo site, the weather
153 stations were installed for only one recording period as explained previously.

154 Each of the weather stations included eleven to twelve sensors connected to a Campbell
155 CR1000 or Campbell CR1000X (Campbell Scientific) datalogger to measure daily microclimatic
156 variables that are drivers of coffee leaf rust disease caused by *Hemileia vastatrix*, one of the most
157 harmful diseases of the coffee tree (Merle et al. 2020). The stations were placed in the center of
158 each plot and included an air temperature and relative humidity sensor positioned 1.5 meters from
159 the ground (HMP45C), four leaf wetness sensors 1.2 meters from the ground, oriented in four
160 opposite directions (Dielectric LWS) and six T-type thermocouples (copper/constantan) placed at
161 three different heights on two coffee plants. Each thermocouple was subdivided into four
162 secondary thermocouples placed in contact with leaf laminae on the underside of four leaves from
163 the same stratum (Miller 1971). The leaf temperature measurements were therefore an average of
164 four leaves. Only the stations located in the reference plots with full sun exposure had a rain
165 gauge placed above coffee trees 2 meters from the ground (TE525MM, accuracy 0.1 mm). The
166 dataloggers recorded data every five seconds and stored average, minimum and maximum values

167 every fifteen minutes. Data were retrieved from the dataloggers weekly using PC200W 4.5
168 Datalogger Support Software (Campbell Scientific).

169

170 **Characterization of plot shade tree height and canopy openness**

171 To account for shade tree growth due to seasonal microclimatic variations as well as
172 pruning practices, we chose to measure shade tree height and canopy openness above the coffee
173 plants, which vary along year, rather than focusing on seedling density (Table 1). We measured
174 the shade tree height with a clinometer. Canopy openness (%) was calculated by using
175 hemispherical photographs analyzed with Gap Light Analyzer software (Frazer et al. 1999). The
176 hemispherical photographs were taken using a GoPro camera placed above the coffee plants and
177 equipped with a fish eye lens allowing the capture of images with an ultra-wide angle (Fig. 2).
178 The software then estimated the percentage of canopy openness for different angles by manually
179 classifying the pixels with a software feature that manages the contrast level. Given that this
180 classification is arbitrary, it was operated by a single person (Weiss et al. 2004).

181

182 **Description of variables**

183 Given our objective of using the models in warning systems based on a network of weather
184 stations fully exposed to sunlight, we decided to work on daily variables, which is the most
185 common format used to process weather data. Leaf wetness duration and leaf temperatures are
186 important for predicting fungal foliar diseases (Magarey et al. 2005). However, leaf wetness and
187 leaf temperature are not usually measured in unshaded weather stations. For that reason, in
188 addition to modeling the microclimate in the understory of agroforestry systems as a function of
189 shade tree characteristics, we decided to model these microclimatic variables as a function of
190 others, usually recorded in weather stations. Specifically, we chose to develop five models for:

191 the daily leaf wetness duration (*HoursLW*), the minimum and daily maximum leaves
192 temperatures (*MinTleaf* and *MaxTleaf* respectively), the daily minimum and maximum air
193 temperatures under agroforestry systems (*MinTairShade* and *MaxTairShade* respectively). The
194 daily leaf wetness duration was calculated by averaging the duration per hour of the four leaf
195 wetness sensors, and then by summing these hourly durations. The daily minimum and maximum
196 leaves temperatures was calculated by averaging the values recorded by the two thermocouples of
197 each coffee stratum. The daily minimum and maximum air temperatures under agroforestry
198 systems was the values provided by the air temperature and relative humidity sensor placed in
199 these systems.

200 To explain these five microclimatic variables, we chose to use only variables usually
201 measured by the weather station networks of the region. Thus, we selected only the daily
202 minimum and maximum air temperatures (*MinTairSun* and *MaxTairSun* respectively), the daily
203 average relative humidity (*RHSun*) and the total daily precipitation (*RainfallSun*), provided by the
204 reference weather station that we had placed in the full sun exposed plot at each site.

205 The plots were classified according to a factor characterizing their agroforestry system,
206 named *classAgroforSyst*. It included eight modalities representing the combination of two levels
207 of canopy openness, two levels of light gap distribution, and two levels of shade tree height
208 (Table 2). A ninth modality, representing plots fully exposed to sunlight, was created for the
209 models explaining the variables *HoursLW*, *MinTleaf* and *MaxTleaf*. Canopy openness was
210 considered low when $<50\%$ and high when $\geq 50\%$. To characterize the level of light gap
211 distribution, we chose four lines of gap fractions from the zenith rather than the larger angle to
212 exclude the tops of neighboring coffee plants and only characterize the shade provided by the
213 trees (Fig. 2 C). As an estimation of light gap distribution, we then used the standard error of the
214 ratios of canopy openness and the area of the 80 gap-fractions included in the four lines. The

215 higher the standard error, the more irregular was the light gap distribution. To create two classes
216 for the variables of light gap distribution and shade tree height we used the *party* package
217 (Hothorn et al., 2006) in R 3.6.1 (R Development Core Team 2019), which builds a tree-based
218 regression by recursive binary partitioning (Table 2).

219 The *MinTleaf* and *MaxTleaf* variables had the particularity of being measured on three leaf
220 strata of the coffee plant. We studied the effect of coffee leaf strata in these two models
221 (*CoffeeLeafStratum: Bottom, Middle, Top*).

222

223 **Statistical analysis**

224 For each of the five variables *HoursLW*, *MinTleaf*, *MaxTleaf*, *MinTairShade* and
225 *MaxTairShade*, we first studied the distributions of the microclimatic variables to focus on
226 domains of definition with a sufficient number of observations. We then used the boosted
227 regression tree analysis to evaluate the linearity of relationships and obtain a relative ranking of
228 all the variables tested for each model (Table 2). This machine learning algorithm is increasingly
229 being used in ecological modeling due to the flexibility of regression trees, which enables
230 complex ecological responses to be modeled (Elith et al., 2008; Bhatt et al., 2013). The model
231 consisted of a linear combination of regression trees. The relative importance of each variable
232 was estimated using the number of times a variable was selected for splitting, weighted by the
233 squared improvement of the model following each splitting, and averaged over all regression
234 trees (Friedman, 2001; Williams et al., 2010). The linearity of the dependence is checked using
235 the partial dependence function showed the marginal effect of each variable on the count
236 response after averaging the effects of all the other variables (Bhatt et al., 2013).

237 The five dependent variables were then fitted to a Gaussian distribution using generalized
238 linear models (GLM) and keeping the independent variables with the greatest relative level of

239 influence only (Table 3), the sum of whose influences accounted for 95% of the dependent
240 variable. To compare factor modality effects, we used Tukey's multiple comparison post hoc test.

241 In order to assess the validity of the equations on an independent dataset, two plots were
242 excluded from the entire construction of the model (BRT and GLM), the plot of the site at the
243 altitude of 770 m, under shade provided by tall shade trees, and the plot of the banana
244 agroforestry system at the altitude of 1140 m. In these two plots, the predicted and observed
245 values were then compared using the root mean square error. The extreme values excluded from
246 the model building stage were similarly used for evaluation purposes. All the statistical analyses
247 were performed with R 3.6.1 (R Development Core Team 2019) and with an alpha level of 0.05.
248 Boosted regressions trees were constructed using the *gbm* package version 2.1.5 (Greenwell et al,
249 2019) and the *dismo* package (Hijmans et al., 2017). GLM were fitted using the *lme4* package
250 version 1.1-21 (Bates et al., 2015), and we carried out Tukey's multiple comparison post hoc test
251 using the *multcomp* package version 1.4-12 (Hothorn et al. 2020).

252

253

RESULTS

254

Description of the study microclimate and shade tree characteristics

256 Thanks to the altitudinal gradient, we could measure a wide range of microclimatic
257 conditions. On the total of 380 days of recording, we observed a good distribution of rainy days
258 with 120 days without rain, 80 days with rainfall between 0.1 and 1 mm, 58 days with rainfall
259 between 1 and 5 mm and 122 days with rainfall ranging from 5 to 103 mm (Fig. 1). In terms of
260 air temperature, we observed minimum and maximum temperatures ranging from 8.0 to 20.4 °C
261 and from 18.4 to 34.1 °C respectively (Table 2). The temperature of the coffee leaves varied from
262 7.3 to 20.4 °C for the minimum daily temperature and from 17.7 to 48.8 °C for the maximum

263 daily temperature. Regarding the leaf wetness duration, it varied from 0 to 24 hours per day with
264 an average duration of 17 hours (Annex).

265 Tree height in the agroforestry systems we studied ranged from 2.8 m to 26.5 m and canopy
266 openness from 12 to 90% depending on the tree species, date of establishment and pruning
267 applied. Indeed, during the study, a tree pruning was carried out in several plots that included *E.*
268 *poeppigiana* or *Musa* spp., increasing canopy openness, light gap distribution sometimes and
269 decreasing shade tree height (Table 1).

270

271 **Model of the daily minimum and maximum air temperatures under agroforestry** 272 **systems**

273 The results of the exploratory analysis carried out using the boosted regression tree
274 approach enabled us to classify, in order of importance, the variables tested in the models
275 explaining the daily minimum and maximum air temperatures in agroforestry systems
276 (*MinTairShade* and *MaxTairShade* respectively) (Table 3).

277 Considering only the variables with the highest level of influence and representing about
278 95% of the dependent variable, the only variable selected was *MinTairSun*, with a relative
279 importance rate of around 95%, and its effect on *MinTairShade* was significantly positive ($p <$
280 0.001) (Equation 1 whose parameter values are presented in table 4). The variables *MaxTairSun*,
281 *RHSun*, *RainfallSun* and *classAgroforSyst* had negligible effects.

282

283 Equation 1: $MinTairShade = \alpha_1 + \alpha_2 \times MinTairSun$

284

285 On the model definition domain, i.e. at minimum air temperatures in full sunlight between
286 12 and 20°C, the temperature of the air under shade is always higher than that in full sunlight
287 with a difference of less than 1°C.

288 The comparison of predicted and observed values gave root mean square errors of 0.46 on
289 the data used to build the model, 0.96 on the extreme data excluded from the data set and 0.71 on
290 the independent data set (Fig. 3A, C and E).

291
292 The exploratory analysis showed that the *MaxTairSun* variable described about 79% of the
293 *MaxTairShade* variable. The variables *MinTairSun* and *classAgroforSyst* represented together a
294 relative influence of around 17% and the other variables had importance levels below 5% (Table
295 3). These three independent variables were selected to build the *MaxTairShade* estimation model,
296 but *MinTairSun* did not show a significant effect ($p = 0.056$). Thus, *MaxTairSun* had a positive
297 effect ($p < 0.001$) and the effect of the factor *classAgroforSyst* illustrated a negative effect of
298 taller shade trees (Equation 2 whose parameter values are presented in table 4).

299
300 Equation 2: $MaxTairShade = \beta_1 + \beta_2 \times MaxTairSun + \beta_{3,classAgroforSyst}$

301
302 For this model, only a few cases, mainly for low maximum temperatures in agroforestry
303 systems based on short trees, showed a higher maximum air temperature under shade than in full
304 sunlight. Indeed, in the range of definition of this model, i.e. maximum air temperatures in full
305 sunlight from 23 to 33°C, only 25% of the values were found below 28°C. For very high
306 maximum air temperatures with full sun exposure, the maximum air temperature under shade
307 could be 4°C lower.

308 This model was less efficient in terms of prediction accuracy than the model of
309 *MinTairShade* estimation. Indeed, the root mean square error between predicted and observed
310 values used to build the model was 1.11 (Fig. 3B). In addition, the validation on extreme values,
311 excluded from the analysis, and on the independent dataset showed that predicted and observed
312 values were linked by root mean square errors of 1.22 and 1.23, respectively (Fig. 3D and F).

313

314 **Model of the daily minimum and maximum leaf temperature**

315 By using the boosted regression tree approach, we determined the relative importance of
316 the variables tested in the models explaining the daily minimum and maximum leaf temperatures
317 (*MinTleaf* and *MaxTleaf* respectively) (Table 3). *MinTleaf* was described mainly by *MinTairSun*,
318 then in decreasing order of importance by the variables *classAgroforSyst*, *MaxTairSun*, *RHSun*,
319 *RainfallSun*, and *CoffeeLeafStratum*. With respect to the *MaxTleaf* variable, the maximum value
320 of the full sun temperature (*MaxTairSun*) was the most important variable but, unlike the
321 *MinTleaf* variable, the following variables also had a major weight: *CoffeeLeafStratum*,
322 *classAgroforSyst*, *MinTairSun*, *RainfallSun* and *RHSun*.

323 Considering only the variables with the highest level of influence and representing about
324 95% of the dependent variable, we selected the variables *MinTairSun*, *classAgroforSyst*,
325 *MaxTairSun*, and *RHSun* for the model explaining *MinTleaf*. From these variables, the
326 subsequent model development phase resulted in the conservation of three variables that had a
327 significant effect on *MinTleaf*: *MinTairSun*, *RHSun* and *classAgroforSyst*.

328 Considering quantitative microclimatic variables, *MinTairSun* and *RHSun* had a positive
329 effect on *MinTleaf* ($p < 0.001$ and $p = 0.026$ respectively). In terms of factors, we found a
330 significant influence of *classAgroforSyst* showing a positive effect of all of the agroforestry
331 systems compared to the full sun exposure ($p < 0.001$). The result of the pair-wise comparison of

332 the different modalities of *classAgroforSyst* did not show a clear difference related to any of the
333 three characteristics: shade tree height, canopy openness and light gap distribution (Equation 3
334 whose parameter values are presented in table 4). However, agroforestry systems combining a
335 low canopy openness and a regular light gap distribution were responsible for a greater increase
336 in the daily minimum leaf temperature.

337

338 Equation 3: $MinTleaf = \gamma_1 + \gamma_2 \times MinTairSun + \gamma_3 \times RHSun + \gamma_{4,classAgroforSyst}$

339

340 To explain *MaxTleaf*, we selected all the tested variables because the least influential
341 variable had a relative influence of 8% (Table 3). In this model, the variables conserved for their
342 significant effect were *MaxTairSun* for its positive effect ($p < 0.001$), *RHSun* for its negative
343 effect ($p < 0.001$), *MinTairSun* for its negative effect ($p = 0.020$), and the factors
344 *CoffeeLeafStratum* ($p < 0.001$) and *classAgroforSyst* ($p < 0.001$). Conversely, the variable
345 *RainfallSun* did not have a significant effect ($p = 0.34$). We found significant differences between
346 the three modalities of *CoffeeLeafStratum* with a positive effect of the upper strata (Equation 4
347 whose parameter values are presented in table 4). The pair-wise comparison of the different
348 modalities of *classAgroforSyst* highlighted that the modality with short shade trees, high canopy
349 openness and a regular light gap distribution was not significantly different from the modality of
350 full sun exposure, unlike the other modalities.

351

352 Equation 4: $MaxTleaf = \delta_1 + \delta_2 \times MaxTairSun + \delta_3 \times MinTairSun + \delta_4 \times RHSun +$
353 $\delta_{5,classAgroforSyst} + \delta_{6,CoffeeLeafStratum}$

354

355 Under shade, the daily minimum leaf temperature was higher than in full sunlight, with a
356 difference of 0.18 to 1.04°C, while the daily maximum leaf temperature was often lower with a

357 difference of 1.62 to 4.91°C. According to the model generated, the leaves of the upper stratum
358 of the coffee plant had a maximum temperature 2°C higher than those of the intermediate
359 stratum, and 5.95°C higher than those of the lower stratum.

360 The minimum leaf temperature estimation model gave better prediction results with a root
361 mean square error of 0.67 between predicted and observed values (Fig. 4A) compared to 3.01 for
362 the maximum leaf temperature estimation model (Fig. 4B). The evaluation of these models on the
363 extreme values extracted from the definition domain also resulted in a better predictive accuracy
364 of the *MinTleaf* estimation model compared to the *MaxTleaf* estimation model, with root mean
365 square errors between predicted and observed values of 1.06 and 3.16 respectively (Fig. 4C and
366 D). The validation on the independent dataset illustrated the same trend with root mean square
367 errors of 0.72 for *MinTleaf* and 2.93 for *MaxTleaf* (Fig. 4E and F).

368

369 **Model of the daily leaf wetness duration**

370 The exploratory phase of the analysis revealed that the variable *HoursLW* was mainly
371 explained by the variables *RHSun*, *classAgroforSyst*, *MaxTairSun*, *RainfallSun* and *MinTairSun*
372 (Table 3).

373 The model building stage for *HoursLW* resulted in the conservation of four variables with a
374 significant effect. *RHSun* had a positive effect ($p < 0.001$), *MaxTairSun* had a negative effect ($p <$
375 0.001), *RainfallSun* had a weak positive effect ($p = 0.020$) and *classAgroforSyst* showed a
376 tendency of taller shade trees to decrease more the number of hours with leaf wetness than
377 systems with shorter shade trees. Indeed, among the agroforestry systems with smaller shade
378 trees, the system with a high canopy openness and an irregular light gap distribution was the only
379 one that showed a significant difference from the system with full sun exposure, whereas among
380 the agroforestry systems with taller shade trees, there was only one system showing no difference

381 with the system with full sun exposure (Equation 5 whose parameter values are presented in table
382 4).

383

384 Equation 5: $HoursLW = \varepsilon_1 + \varepsilon_2 \times RHSun + \varepsilon_3 \times MaxTairSun + \varepsilon_4 \times RainfallSun +$
385 $\varepsilon_{5,classAgroforSyst}$

386

387 In the agroforestry systems with tall trees, the leaf wetness duration was higher than in the
388 full sunlight systems, with a maximum difference of up to 2 hours.

389 A comparison of the model's predictions provided root mean square errors of 2.87 with the
390 data used for its construction (Fig. 5A), of 3.73 with the extreme values excluded from model
391 building (Fig. 5B), and 2.38 with the independent dataset (Fig. 5C). The model inaccuracy was
392 higher for non-rainy days since the RMSE was 3.50 versus 2.59 for rainy days.

393

394 **DISCUSSION**

395

396 The main drivers for predicting the microclimate in agroforestry systems were the variables
397 provided by weather stations located in full sunlight and nearby. However, except for the daily
398 minimum air temperature in these systems, the data provided by the stations in full sunlight were
399 not sufficient to predict the microclimate under shade. Indeed, different agroforestry systems in
400 terms of tree height, canopy openness or even regularity of light gap distribution showed
401 different effects on the microclimate. This could explain the different effects of agroforestry
402 systems on the development of coffee pests and diseases (Merle et al. 2019). Therefore,
403 predicting their development only using data from stations in full sunlight, without taking into

404 account the particularities of agroforestry systems, could lead to significant prediction
405 inaccuracies.

406

407 **Estimated daily minimum temperatures of air under shade and of coffee leaves**

408 The daily minimum coffee leaf temperature and air temperature under shade were mainly
409 determined by the daily minimum air temperatures in full sunlight. Although this variable was
410 sufficient to predict the minimum daily air temperature under shade, the minimum daily
411 temperature of coffee leaves was explained by other microclimatic variables, but also by the
412 characteristics of the agroforestry systems. Indeed, the positive effect of the daily mean relative
413 humidity in full sunlight on the daily minimum leaf temperature may have been due to the fact
414 that relative humidity is lower on cloudless days and the absence of cloud leads to a greater
415 cooling of temperatures at night. The buffer effect we found for the presence of shade trees
416 compared to full sun exposure on the minimum temperature of coffee leaves has already been
417 observed (Morais et al. 2006; Soma 2015). We also found that agroforestry systems with a dense
418 and homogeneous canopy displayed a greater buffer effect, increasing the daily minimum coffee
419 leaf temperature. We suggest that this effect is due to the canopy uniformity preventing
420 exchanges with the outside air. The fact that the coffee leaf stratum had no effect on the daily
421 minimum leaf temperature was certainly due to the absence of radiation intercepted by the top
422 stratum at night when the minimum temperature was detected. In their definition domain, both
423 models showed that the minimum temperatures of air and coffee leaves were higher under
424 agroforestry systems with differences of around 1°C (Siles et al. 2010).

425

426 **Estimated daily maximum temperatures of air under shade and of coffee leaves**

427 The daily maximum temperatures of air under shade and of coffee leaves were mainly
428 explained by the daily maximum air temperature in full sunlight. With respect to the daily air
429 maximum temperature under shade, the strong overall buffering effect of trees on the maximum
430 air temperature under shade is well known (Barradas and Fanjul 1986; Jaramillo-Robledo and
431 Gómez-Gómez, 1989; Siles et al. 2010; López-Bravo et al. 2012; Sida et al. 2018). However, in
432 our study, it was mostly explained by one factor of agroforestry systems: shade tree height. Tall
433 trees made it possible to isolate a larger layer of air, which therefore heated up less easily than the
434 shallow layer of air delimited under short trees. This buffer effect was also observed in the case
435 of the daily maximum temperature of coffee leaves, but it seemed to be related both to the height
436 of the trees (Muschler 1998; Siles et al. 2010; Soma 2015; Vezy et al. 2018) and to the density
437 and regularity of the canopy. A dense canopy with a regular light gap distribution made it
438 possible to isolate a layer of air that was less easily heated than a system with an irregular canopy
439 openness (Renaud and Rebetez, 2009). This phenomenon resulted in a lower temperature of the
440 air surrounding the leaves. The upper coffee leaf stratum probably acted as a layer protecting the
441 lower ones from radiation (Siles et al. 2010; Ngao et al. 2017), thus reducing their daily
442 maximum temperature.

443 The weak negative effect of the daily minimum air temperature in full sunlight and the
444 negative effect of the relative humidity in full sunlight on the daily maximum leaf temperature
445 could be related to the fact that lower relative humidity induced stomatal closure that stopped
446 plant transpiration resulting in leaf heating (Lange et al. 1971). The effect of the minimum air
447 temperature in full sunlight on the daily maximum leaf temperature was possibly due to cloudy
448 days responsible for an increase in this minimum temperature and a decrease in the maximum
449 temperature because of a lower level of radiation.

450 These two models predicting maximum temperatures exhibited less accuracy than models
451 predicting minimum temperatures (Ferrez et al. 2011), doubtless because of the very
452 heterogeneous sunlight conditions interacting with the coffee leaf angle and orientation on the
453 plant (Miller 1971; Butler 1977). Another phenomenon that could partially explain this
454 inaccuracy is the increase or decrease in wind speed depending on the agroforestry system, which
455 are responsible for air conductance changes (Judd et al. 1996; Stigter et al. 2002; Pezzopane et al.
456 2011).

457

458 **Estimated daily leaf wetness duration**

459 The daily leaf wetness duration was mainly explained by a positive effect of the daily
460 average relative humidity in full sunlight, as described by other studies (Smith 1958; Shaw 1973;
461 Sentelhas et al. 2008). Actually, rainfall only showed a weak positive effect on the daily leaf
462 wetness duration, which can be attributed to three causes. The first cause is the nature of the
463 variable being measured, since daily rainfall is a sum of rainfall over 24 hours that does not
464 consider rain distribution. From that point, daily rainfall does not provide as much information as
465 average relative humidity on the duration of rainy periods during the day and therefore on leaf
466 wetness duration (Sentelhas et al. 2008). The other causes are related to tree effects on
467 precipitations in the understory, which reduces the effect of rains on leaf wetness, as rain
468 interception by shade trees (Siles et al., 2010) and the probable reduction of dew formation by
469 night under shade (Marrou et al. 2013), as minimum coffee leaf temperature is higher in this
470 condition. Leaf wetness is also under the influence of temperatures. The maximum air
471 temperature in full sunlight had a negative effect on the daily leaf wetness duration, indicating
472 that warmer conditions are conducive to leaf wetness drying. In addition, trees hinder leaf drying
473 by intercepting light (Charbonnier et al. 2013) and reducing wind speed (Stigter et al. 2002;

474 Pezzopane et al. 2011; Gagliardi et al. 2020). However, these effects that occur during the day,
475 seem secondary, as taller shade trees tended to decrease the daily leaf wetness duration compared
476 to full sun exposed plots. We verified, with the data at hand, that the reduction of dew formation
477 at night in the understory was a key factor reducing coffee leaf wetness. Coffee leaves took
478 longer to be wetted by dew under tall shade trees. The second effect of trees could be on wind.
479 Indeed, it has been shown that turbulence, which can enhance leaf drying, can be observed within
480 the canopy, particularly when windbreak solidity is high (Judd et al. 1996).

481 Our equation gave less accurate results probably because we used the daily average,
482 commonly provided by a weather station, rather than the number of hours of relative humidity
483 above 90%. In addition, it is possible that the absence of a very pronounced dry season during the
484 trial was responsible for a higher model inaccuracy for non-rainy days. Despite its inaccuracy,
485 our equation had the advantage of estimating the daily coffee leaf wetness duration in full
486 sunlight like Sentelhas et al. (2006), but also in agroforestry systems.

487

488 **CONCLUSION**

489

490 In our study, simple equations were developed to estimate five variables that are useful in
491 predicting the development of plant fungal diseases (Magarey et al. 2005) in plantations exposed
492 to full sunlight and in agroforestry systems. These models were based on (1) meteorological
493 variables commonly provided by reference weather stations located in full sunlight and (2) easily
494 measurable characteristics in agroforestry systems. Models estimating the daily maximum leaf
495 temperature and the daily leaf wetness duration did not show high accuracy, but highlighted the
496 importance of indicating the presence and height of shade trees to reduce estimation error. By
497 identifying tree height, canopy openness and light gap distribution as the main agroforestry

498 system factors influencing the studied microclimatic variables, our equations offer opportunities
499 to optimize agroforestry system design and management, for example, by carrying out pruning to
500 modify the canopy openness and the light gap distribution, and help manage coffee leaf rust. By
501 deciding to use only weather variables commonly provided by weather station networks, easy-to-
502 measure shade tree characteristics and to model daily variables, we sought to promote their use in
503 warning systems. However, incorporating meteorological variables such as wind and cloud cover
504 could improve the accuracy of the leaf wetness duration and maximum leaf temperature models
505 and are therefore variables that deserve to be more commonly measured by weather station
506 networks in the region. To evaluate the suitability of these equations for disease and pest
507 predictions under mono-specific shade in Central America, it would be valuable to compare
508 predictions given by pest and disease models using modeled microclimatic variables under shade
509 to predictions using models based on meteorological variables in full sun. Lastly, it would be
510 interesting to complete these results by carrying out such a study in diversified systems with
511 several shade tree species and incorporate these equations into a local disease warning system
512 that would improve prediction by considering the cropping system of each coffee producer.

513

514

ACKNOWLEDGEMENTS

515

516 For their valuable technical work, we thank Alejandra Barquero, Hugo Mendez and Steven
517 Cerdas. This work was developed as part of the “Programa Centroamericano de Gestión Integral
518 de la Roya del Café” (PROCAGICA) funded by the EU (DCI-ALA/2015/365-17). We thank the
519 Ernesto Illy Foundation and CIRAD (Centre de Coopération Internationale en Recherche
520 Agronomique pour le Développement) for their financial support and P. Biggins for reviewing
521 the English. We should like to thank in particular the coffee growers who were involved in the

522 project for their help, for allowing access to their plots and for their willingness to participate in
523 the trial we set up. Special thanks to Rogelio Villarreyña-Acuña, our dear friend and co-author,
524 who passed away while this article was being finalized.

525

526

LITERATURE CITED

527

528 Allinne, C., Savary, S., Avelino, J., 2016. Delicate balance between pest and disease injuries,
529 yield performance, and other ecosystem services in the complex coffee-based systems of
530 Costa Rica. *Agric. Ecosyst. Environ.* 222, 1–12.
531 <https://doi.org/10.1016/j.agee.2016.02.001>.

532 Avelino, J., Vílchez, S., Segura-Escobar, M.B., Brenes-Loaiza, M.A., Virginio Filho, E.M.,
533 Casanoves, F., 2020. Shade tree *Chloroleucon eurycyclum* promotes coffee leaf rust by
534 reducing uredospore wash-off by rain. *Crop Protect.* 129.

535 Avelino, J., Allinne, C., Cerda, R., Willocquet, L., Savary, S., 2018. Multiple-Disease System in
536 Coffee: From Crop Loss Assessment to Sustainable Management. *Annu. Rev. Phytopathol.* 56, 611–635. <https://doi.org/10.1146/annurev-phyto-080417-050117>.

538 Avelino, J., Ten Hoopen, G.M., Declerck, F.A.J., 2011. Ecological Mechanisms for Pest and
539 Disease Control in Coffee and Cacao Agroecosystems of the Neotropics. In: *Ecosystem
540 services from agriculture and agroforestry: measurement and payment*, Earthscan
541 Publications. pp. 91–117.

542 Barradas, V.L., Fanjul, L., 1986. Microclimatic characterization of shaded and open-grown coffee
543 (*Coffea arabica* L.) plantations in Mexico. *Agric. Forest Meteorol.* 38, 101–112.
544 [https://doi.org/10.1016/0168-1923\(86\)90052-3](https://doi.org/10.1016/0168-1923(86)90052-3).

545 Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models
546 Using lme4. *Journal of Statistical Software*, 67(1), 1–48. doi:10.18637/jss.v067.i01.

547 Bhatt, S., Gething, P.W., Brady, O.J., Messina, J.P., Farlow, A.W., Moyes, C.L., Drake, J.M.,
548 Brownstein, J.S., Hoen, A.G., Sankoh, O., Myers, M.F., George, D.B., Jaenisch, T., Wint,
549 G.R.W., Simmons, C.P., Scott, T.W., Farrar, J.J., Hay, S.I., 2013. The global distribution
550 and burden of dengue. *Nature* 496, 504.

551 Butler, D.R., 1977. Coffee Leaf Temperatures in a Tropical Environment. *Acta Bot. Neerl.* 26,
552 129–140. <https://doi.org/10.1111/j.1438-8677.1977.tb01106.x>.

553 Campanha, M.M., Santos, R.H.S., de Freitas, G.B., Prieto Martinez, H.E., Ribeiro Garcia, S.L.,
554 Finger, F.L., 2004. Growth and yield of coffee plants in agroforestry and monoculture

- 555 systems in Minas Gerais, Brazil. *Agroforest. Syst.* 63, 75–82.
556 <https://doi.org/10.1023/B:AGFO.0000049435.22512.2d>.
- 557 Charbonnier, F., Rounsard, O., le Maire, G., Guillemot, J., Casanoves, F., Lacoïnte, A., Vaast, P.,
558 Allinne, C., Audebert, L., Cambou, A., Clement-Vidal, A., Defrenet, E., Duursma, R.A.,
559 Jarri, L., Jourdan, C., Khac, E., Leandro, P., Medlyn, B.E., Saint-Andre, L., Thaler, P.,
560 Van den Meersche, K., Aguilar, A.B., Lehner, P., Dreyer, E., 2017. Increased light-use
561 efficiency sustains net primary productivity of shaded coffee plants in agroforestry
562 system. *Plant Cell Environ.* 40, 1592-1608.
- 563 Charbonnier, F., le Maire, G., Dreyer, E., Casanoves, F., Christina, M., Dauzat, J., Eitel, J.U.H,
564 Vaast, P., Vierling, L.A., Rounsard, O., 2013. Competition for light in heterogeneous
565 canopies: Application of MAESTRA to a coffee (*Coffea arabica* L.) agroforestry system.
566 *Agric. Forest Meteorol.* 181, 152–169. <https://doi.org/10.1016/j.agrformet.2013.07.010>.
- 567 Coltri, P.P., Pinto, H.S., do Valle Gonçalves, R.R., Junior, J.Z., Dubreuil, V., 2019. Low levels of
568 shade and climate change adaptation of Arabica coffee in southeastern Brazil. *Heliyon*
569 5:e01263. <https://doi.org/10.1016/j.heliyon.2019.e01263>.
- 570 DaMatta, F.M., 2004. Ecophysiological constraints on the production of shaded and unshaded
571 coffee: a review. *Field Crop Res.* 86, 99–114. <https://doi.org/10.1016/j.fcr.2003.09.001>.
- 572 DaMatta, F.M., Rena, A.B., 2002. Ecofisiologia de cafezais sombreados e a pleno Sol. In:
573 Zambolim, L. (ed), *O Estado da Arte de Tecnologias na Produção de Café*, Universidade
574 Federal de Viçosa, Viçosa. pp. 93-136.
- 575 Dix, M.E., Bishaw, B., Workman, S.W., Barnhart, M.R., Klopfenstein, N.B., Dix, A.M., 1999.
576 Pest management in energy- and labor-intensive agroforestry systems. In: Buck, L.E.,
577 Lassoie, J.P., Fernandes, E.C.M. (eds) *Agroforestry in sustainable agricultural systems*.
578 CRC Press, Boca Raton, USA, pp. 131–155.
- 579 Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. *Journal*
580 *of Animal Ecology* 77, 802– 813.
- 581 Fernandez, C.E., 1984. “Central America coffee rust project,” in *Coffee Rust in the Americas*.
582 Fulton, R. H., Ed. The American Phytopathological Society, St. Paul, MN, 84–92.
- 583 Ferrez, J., Davison, A.C., Rebetez, M., 2011. Extreme temperature analysis under forest cover
584 compared to an open field. *Agric. Forest Meteorol.* 151, 992–1001.
585 <https://doi.org/10.1016/j.agrformet.2011.03.005>.
- 586 Frazer, G.W., Canham, C.D., Lertzman, K.P., 1999. Gap Light Analyzer (GLA), Version 2.0:
587 Imaging software to extract canopy structure and gap light transmission indices from true-
588 colour fisheye photographs, users manual and program documentation. Copyright ©
589 1999: Simon Fraser University, Burnaby, British Columbia, and the Institute of
590 Ecosystem Studies, Millbrook, New York.

- 591 Friedman, J.H., 2001. Greedy function approximation: a gradient boosting machine. *Ann. Stat.*
592 1189–1232.
- 593 Gagliardi, S., Avelino, J., Bagny Beilhe, L., Isaac, M.E., 2020. Contribution of shade trees to
594 wind dynamics and pathogen dispersal on the edge of coffee agroforestry systems: A
595 functional traits approach. *Crop Protect.* 130.
- 596 Georg, J.G., 1978. Techniques of frost prediction. In: Bagdonas, A., Georg, J.C., Gerber, J.F.
597 (Eds.), *Techniques of Frost Prediction and Methods of Frost and Cold Protection*. WMO
598 No. 487, Technical Note No. 157, WMO, Geneva, pp. 2–45.
- 599 Greenwell, B., Boehmke, B., Cunningham, J., GBM Developers, 2019. gbm: Generalized
600 Boosted Regression Models. R package version 2.1.5. [https://CRAN.R-](https://CRAN.R-project.org/package=gbm)
601 [project.org/package=gbm](https://CRAN.R-project.org/package=gbm).
- 602 Gutierrez, P.S., Vaast, P., 2002. Comportamiento fisiológico del café asociado con *Eucalyptus*
603 *deglupta*, *Terminalia ivorensis* o sin sombra. *Agroforesteria en las Américas* 9, 44–49.
- 604 Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., 2017. dismo: Species Distribution Modeling. R
605 package version 1.1-4. <https://CRAN.R-project.org/package=dismo>.
- 606 Hillel, D., Rosenzweig C., 2010. *Handbook of Climate Change and Agroecosystems: Impacts,*
607 *Adaptation, and Mitigation*. ICP Series on Climate Change Impacts, Adaptation, and
608 *Mitigation: Volume 1*. Imperial College Press. 439pp.
- 609 Jha, S., Bacon, C.M., Philpott, S.M., Ernesto Méndez, V.E., Läderach, P., Rice, R.A., 2014.
610 Shade Coffee: Update on a Disappearing Refuge for Biodiversity. *BioScience* 64, 416–
611 428. <https://doi.org/10.1093/biosci/biu038>.
- 612 Judd, M.J., Raupach, M.R., Finnigan, J.J., 1996. A wind tunnel study of turbulent flow around
613 single and multiple windbreaks, part I: velocity fields. *Boundary-Layer Meteorol.* 80,
614 127–165. <https://doi.org/10.1007/BF00119015>.
- 615 Lange, O.L., Lösch, R., Schulze, E.D., Kappen, L., 1971. Responses of stomata to changes in
616 humidity. *Planta* 100, 76–86.
- 617 Lasco, R.D., Delfino, R.J.P., Espaldon, M.L.O., 2014. Agroforestry systems: helping
618 smallholders adapt to climate risks while mitigating climate change: Agroforestry
619 systems. *Wiley Interdiscip. Rev. Clim. Change* 5, 825–833.
620 <https://doi.org/10.1002/wcc.301>.
- 621 Lhomme, J.P., Guilioni, L., 2004. A simple model for minimum crop temperature forecasting
622 during nocturnal cooling. *Agric. Forest Meteorol.* 123, 55–68.
623 <https://doi.org/10.1016/j.agrformet.2003.11.001>.
- 624 Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate
625 extremes in coffee agriculture. *Agric. Forest Meteorol.* 144, 85–94.
626 <https://doi.org/10.1016/j.agrformet.2006.12.009>.

- 627 Magarey, R.D., Sutton, T.B., Thayer, C.L., 2005. A Simple Generic Infection Model for Foliar
628 Fungal Plant Pathogens. *Phytopathology* 95, 92–100. [https://doi.org/10.1094/PHYTO-95-](https://doi.org/10.1094/PHYTO-95-0092)
629 0092.
- 630 Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., Wery, J., 2013. Microclimate under agrivoltaic
631 systems: Is crop growth rate affected in the partial shade of solar panels? *Agric. Forest*
632 *Meteorol.* 177, 117-132.
- 633 Merle, I., Pico, J., Granados, E., Boudrot, A., Tixier, P., Virginio Filho, E.M., Cilas, C., Avelino,
634 J., 2019. Unraveling the complexity of coffee leaf rust behavior and development in
635 different *Coffea arabica* agro-ecosystems. *Phytopathology* 110, 418-427.
- 636 Merle, I., Tixier, P., Virginio Filho, E.M., Cilas, C., Avelino, J., 2020. Forecast models of coffee
637 leaf rust symptoms and signs based on identified microclimatic combinations in coffee-
638 based agroforestry systems in Costa Rica. *Crop Protect.* 130.
- 639 Miller, P.C., 1971. Sampling to Estimate Mean Leaf Temperatures and Transpiration Rates in
640 Vegetation Canopies. *Ecology* 52, 885–889. <https://doi.org/10.2307/1936038>.
- 641 Monteith, J.L., Ong, C.K., Corlett, J.E., 1991. Microclimatic interactions in agroforestry systems.
642 *Forest Ecol. Manag.* 45, 31–44. [https://doi.org/10.1016/0378-1127\(91\)90204-9](https://doi.org/10.1016/0378-1127(91)90204-9).
- 643 Morais, H., Caramori, P.H., Ribeiro, A.M.A., Gomes, J.C., Koguishi, M.S., 2006. Microclimatic
644 characterization and productivity of coffee plants grown under shade of pigeon pea in
645 Southern Brazil. *Pesq. agropec. bras.* 41, 763–770. [https://doi.org/10.1590/S0100-](https://doi.org/10.1590/S0100-204X2006000500007)
646 204X2006000500007.
- 647 Muschler, R.G., 2001. Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica.
648 *Agroforest. Syst.* 85, 131–139. <https://doi.org/10.1023/A:1010603320653>.
- 649 Muschler, R., 1998. Tree-crop Compatibility in Agroforestry: Production and Quality of Coffee
650 Grown under Managed Tree Shade in Costa Rica. PhD thesis, University of Florida,
651 Gainesville, Florida, USA, 219 pp.
- 652 Ngao, J., Adam B., Saudreau, M., 2017. Intra-crown spatial variability of leaf temperature and
653 stomatal conductance enhanced by drought in apple tree as assessed by the RATP model.
654 *Agric. Forest Meteorol.* 237–238, 340-354.
655 <http://doi.org/10.1016/j.agrformet.2017.02.036>, 2017.
- 656 Niether, W., Armengot, L., Andres, C., Schneider, M., Gerold, G., 2018. Shade trees and tree
657 pruning alter throughfall and microclimate in cocoa (*Theobroma cacao* L.) production
658 systems. *Ann. For. Sci.* 78: 38. <https://doi.org/10.1007/s13595-018-0723-9>.
- 659 Padovan, M.P., Cortez, V.J., Navarrete, L.F., Navarrete, E.D., Deffner, A.C., Centeno, L.G.,
660 Munguía, R., Barrios, M., Víchez-Mendoza, J.S., Vega-Jarquín, C., Costa, A.N., Brook,
661 R.M., Rapidel, B., 2015. Root distribution and water use in coffee shaded with *Tabebuia*
662 *rosea* Bertol. and *Simarouba glauca* DC. compared to full sun coffee in sub-optimal
663 environmental conditions. *Agrofor. Syst.* 89, 857-868.

- 664 Perfecto, I., Rice, R.A., Greenberg, R., Van der Voort, M.E., 1996. Shade Coffee: A
665 Disappearing Refuge for Biodiversity. *BioScience* 46, 598–608.
666 <https://doi.org/10.2307/1312989>.
- 667 Pezzopane, J.R.M., de Souza, P.S., Rolim, G.D.S., Gallo, P.B., 2011. Microclimate in coffee
668 plantation grown under *grevillea* trees shading. *Acta Sci. Agron.* 33, 201–206.
669 <https://doi.org/10.4025/actasciagron.v33i2.7065>.
- 670 R Development Core Team, 2019. R: A Language and Environment for Statistical Computing. R
671 Foundation for Statistical Computing, Vienna, Austria.
- 672 Renaud, V., Rebetez, M., 2009. Comparison between open-site and below-canopy climatic
673 conditions in Switzerland during the exceptionally hot summer of 2003, *Agric. Forest*
674 *Meteorol.*, 149, 873–880.
- 675 Ridgeway, G., 2007. “Generalized Boosted Models: A Guide to the gbm Package.” R package
676 vignette, URL <http://CRAN.R-project.org/package=gbm>.
- 677 Rodríguez, D., Cure, J.R., Cotes, J.M., Gutierrez, A.P., Cantor, F., 2011. A coffee agroecosystem
678 model: I. Growth and development of the coffee plant. *Ecol. Model.* 222, 3626–3639.
679 <https://doi.org/10.1016/j.ecolmodel.2011.08.003>.
- 680 Schnabel, F., Virginio Filho, E.M., Xu, S., Fisk, I.D., Roupsard, O., Haggard, J., 2017. Shade
681 trees: a determinant to the relative success of organic versus conventional coffee
682 production. *Agroforest. Syst.* 1–15 <https://doi.org/10.1007/s10457-017-0100-y>.
- 683 Schroth, G., Krauss, U., Gasparotto, L., Duarte Aguilar, J.A., Vohland, K., 2000. Pests and
684 diseases in agroforestry systems of the humid tropics. *Agroforest. Syst.* 50, 199–241.
- 685 Sentelhas, P.C., Dalla Marta, A., Orlandini, S., Santos, E.A., Gillespie, T.J., Gleason, M.L., 2008.
686 Suitability of relative humidity as an estimator of leaf wetness duration. *Agric. Forest*
687 *Meteorol.* 148, 392–400. <https://doi.org/10.1016/j.agrformet.2007.09.011>.
- 688 Sentelhas, P.C., Gillespie, T.J., Gleason, M.L., Monteiro, J.E.B.A., Pezzopane, J.R.M., Pedro
689 Junior, M.J., 2006. Evaluation of a Penman–Monteith approach to provide “reference”
690 and crop canopy leaf wetness duration estimates. *Agric. Forest Meteorol.* 141, 105–117.
691 <https://doi.org/10.1016/j.agrformet.2006.09.010>.
- 692 Shaw, R.H., 1973. Dew duration in central Iowa. *Iowa State J. Res.* 47, 219–227.
- 693 Sida, T.S., Baudron, F., Kim, H., Giller, K.E., 2018. Climate-smart agroforestry: *Faidherbia*
694 *albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia,
695 *Agric. Forest Meteorol.* 248, 339–347, <https://doi.org/10.1016/j.agrformet.2017.10.013>.
- 696 Siles, P., Harmand, J.M., Vaast, P., 2010. Effects of *Inga densiflora* on the microclimate of
697 coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa
698 Rica. *Agroforest. Syst.* 78, 269–286. <https://doi.org/10.1007/s10457-009-9241-y>.

- 699 Smith, L.P., 1958. The duration of surface wetness. *Proc. Int. Hortic. Congr.* 15, 478-484.
- 700 Soma, M., 2015. On the relationship between structure and canopy temperature in stands:
701 comparing Shaded and Full-Sun situations in a coffee agroforestry trial in Costa Rica.
702 CIRAD-CATIE, Agro ParisTech, Nancy.
- 703 Staver, C., Guharay, F., Monterroso, D., Muschler, R.G., 2001. Designing pest-suppressive
704 multistrata perennial crop systems: shade-grown coffee in Central America. *Agroforest.*
705 *Syst.* 53, 151–170.
- 706 Stigter, C.J., 2015. Agroforestry and micro-climate change. *Tree-Crop Interactions: Agroforestry*
707 *in a Changing Climate* CABI 119–145.
- 708 Stigter, C.J., Mohammed, A.E., Nasr Al-amin, N.K., Onyewotuc, L.O.Z., Oteng'i, S.B.B.,
709 Kainkwa, R.M.R., 2002. Agroforestry solutions to some African wind problems. *J. Wind*
710 *Eng. Ind. Aerod.* 90, 1101–1114. [https://doi.org/10.1016/S0167-6105\(02\)00224-6](https://doi.org/10.1016/S0167-6105(02)00224-6).
- 711 Taugourdeau, S., le Maire, G., Avelino, J., Jones, J.R., Ramirez, L.G., Quesada, M.J.,
712 Charbonnier, F., Gomez-Delgado, F., Harmand, J.M., Rapidel, B., Vaast, P., Rouspard,
713 O., 2014. Leaf area index as an indicator of ecosystem services and management
714 practices: An application for coffee agroforestry. *Agric. Ecosyst. Environ.* 192, 19-37.
- 715 van Maanen, A., Xu, X.M., 2003. Modelling plant disease epidemics. In: Xu, X., Bailey, J.A.,
716 Cooke, B.M. (eds) *Epidemiology of Mycotoxin Producing Fungi*. Springer Netherlands,
717 Dordrecht, pp. 669–682.
- 718 van Oijen, M., Dauzat, J., Harmand, J.M., Lawson, G., Vaast, P., 2010a. Coffee agroforestry
719 systems in Central America: II. Development of a simple process-based model and
720 preliminary results. *Agroforest. Syst.* 80, 361–378. [https://doi.org/10.1007/s10457-010-](https://doi.org/10.1007/s10457-010-9291-1)
721 [9291-1](https://doi.org/10.1007/s10457-010-9291-1).
- 722 van Oijen, M., Dauzat, J., Harmand, J.M., Lawson, G., Vaast, P., 2010b. Coffee agroforestry
723 systems in Central America: I. A review of quantitative information on physiological and
724 ecological processes. *Agroforest. Syst.* 80, 341–359. [https://doi.org/10.1007/s10457-010-](https://doi.org/10.1007/s10457-010-9294-y)
725 [9294-y](https://doi.org/10.1007/s10457-010-9294-y).
- 726 Vezy, R., le Maire, G., Christina, M., Georgiou, S., Imbach, P., Hidalgo, H.G., Alfaro, E.J., Blitz-
727 Frayret, C., Charbonnier, F., Lehner, P., Loustau, D., Rouspard, O., 2020. DynACof: A
728 process-based model to study growth, yield and ecosystem services of coffee agroforestry
729 systems. *Environmental Modelling & Software* 124, 104609.
- 730 Vezy, R., Christina, M., Rouspard, O., Nouvellon, Y., Duursma, R., Medlyn, B., Soma, M.,
731 Charbonnier, F., Blitz-Frayret, C., Stape, J.L., Laclau, J.P., Virginio Filho, E.D.,
732 Bonnefond, J.M., Rapidel, B., Do, F.C., Rocheteau, A., Picart, D., Borgonovo, C.,
733 Loustau, D., le Maire, G., 2018. Measuring and modelling energy partitioning in canopies
734 of varying complexity using MAESPA model. *Agric. Forest Meteorol.* 253–254, 203–
735 217. <https://doi.org/10.1016/j.agrformet.2018.02.005>.

- 736 Weiss, M., Baret, F., Smith, G.J., Jonckheere, I., Coppin, P., 2004. Review of methods for in situ
737 leaf area index (LAI) determination: Part II. Estimation of LAI, errors and sampling.
738 *Agric. Forest Meteorol.* 121, 37-53.
- 739 Williams, G.J., Aeby, G.S., Cowie, R.O.M., Davy, S.K., 2010. Predictive Modeling of Coral
740 Disease Distribution within a Reef System. *PLoS ONE* 5(2), e9264.
741 <https://doi.org/10.1371/journal.pone.0009264>.

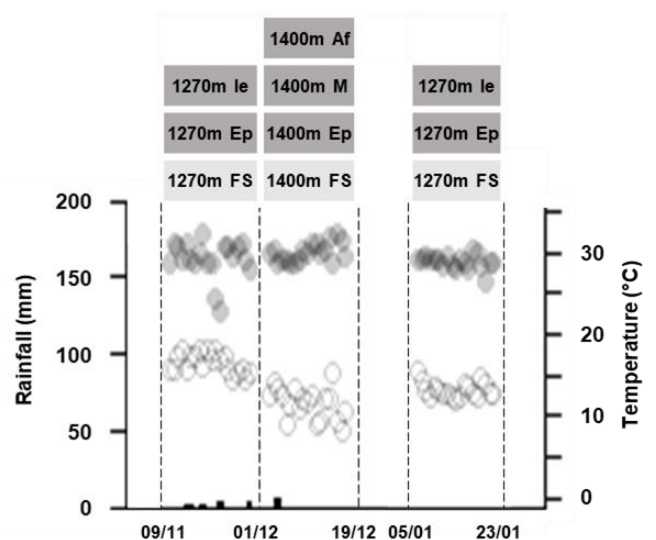
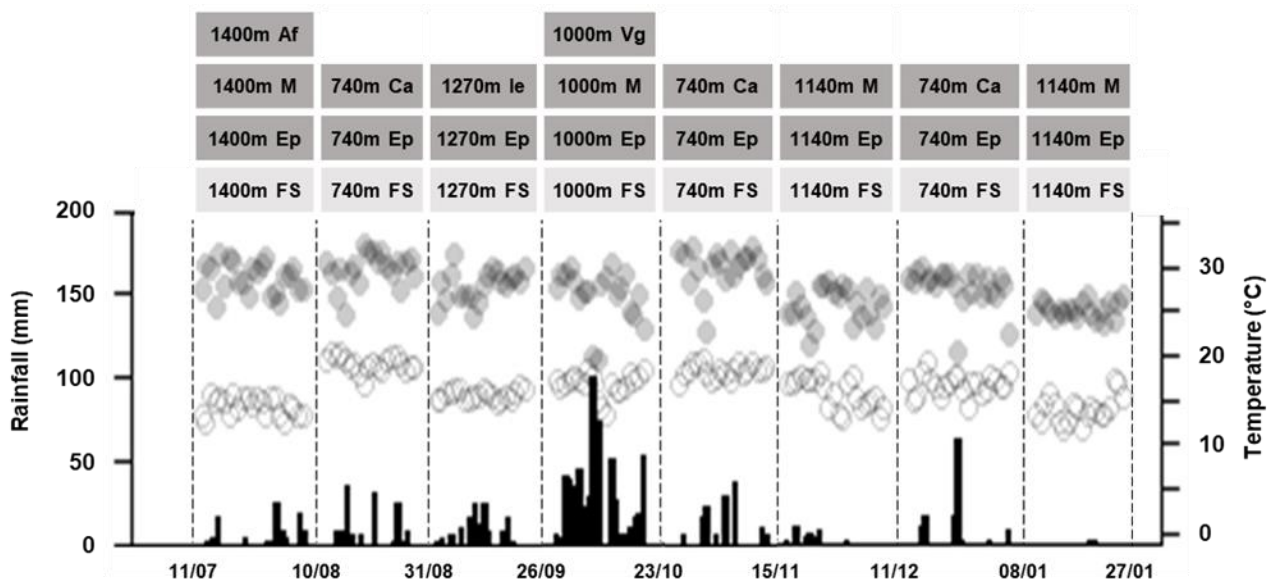
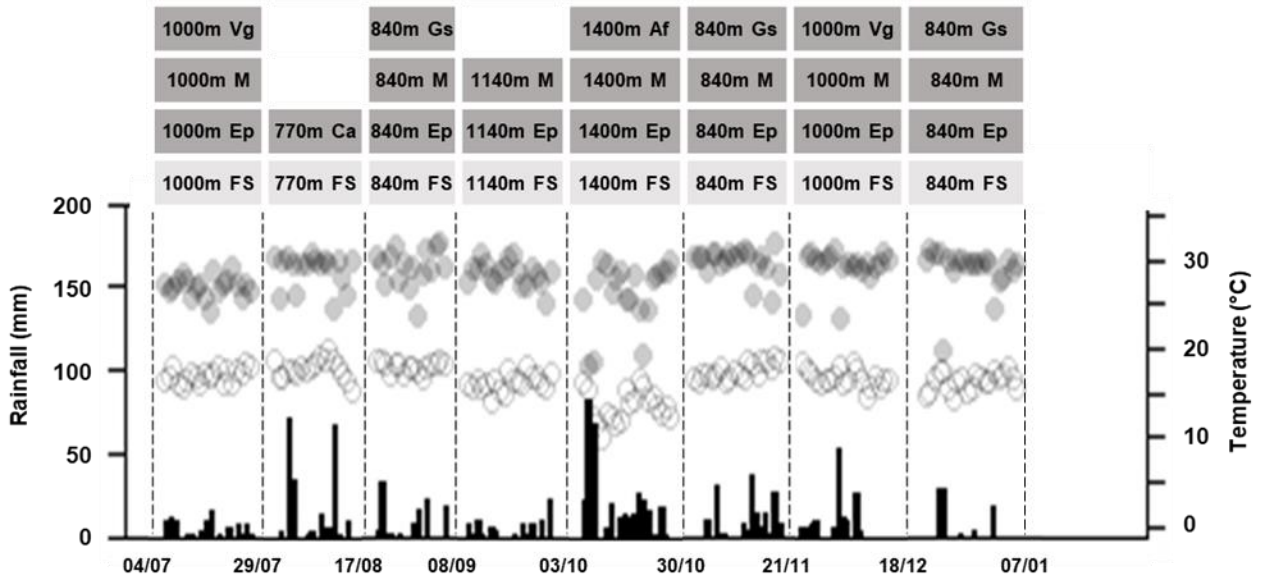


Fig. 1. Organization of the successive installations of weather stations on the plots of each site from July 2018 to January 2019 and data of daily rainfall (black bar plot), daily minimum temperature (empty dots) and daily maximum temperature (full dots) of the weather stations in the full sun reference plot.

Af = *Acrocarpus fraxinifolius*; Ca = *Cordia alliodora*; Ep = *Erythrina poeppigiana*; FS = Full sun; Gs = *Gliricidia sepium*; le = *Inga edulis*; M = *Musa* spp.; Vg = *Vochysia guatemalensis*.

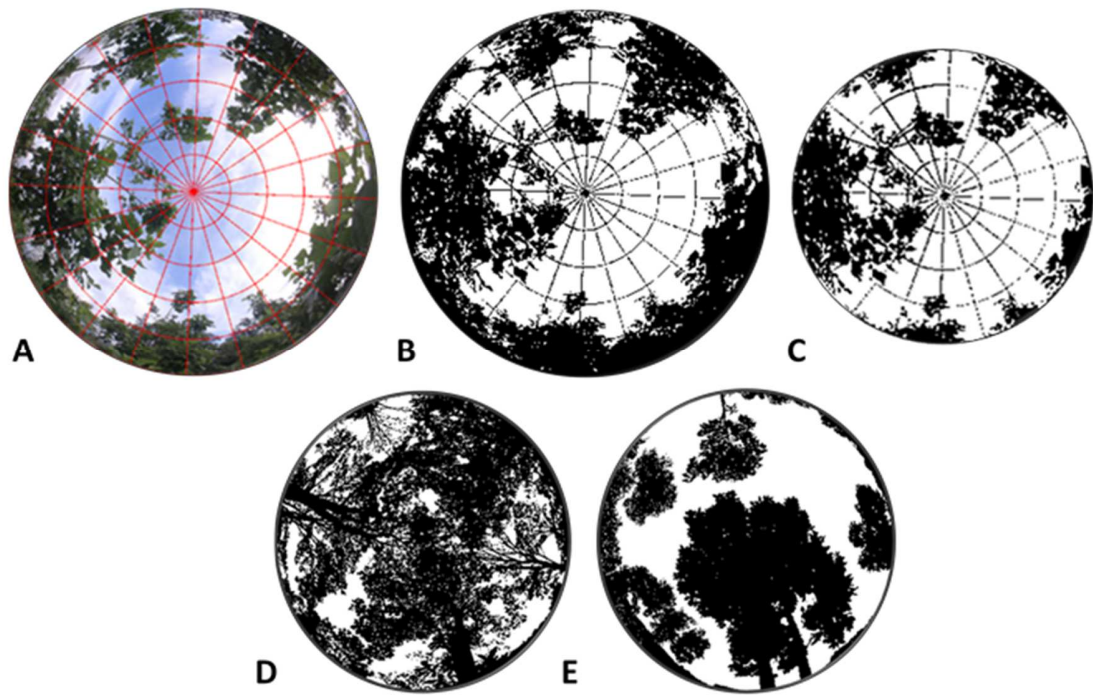


Fig. 2. Hemispherical photographs analyzed with Gap Light Analyzer software (A), which classified the pixels using the contrast level (B) to compute the canopy openness of four lines of gap fractions from the zenith (C). Examples of a regular light gap distribution (D) and an irregular light gap distribution (E).

Photographs by Rogelio Villarreyna-Acuña

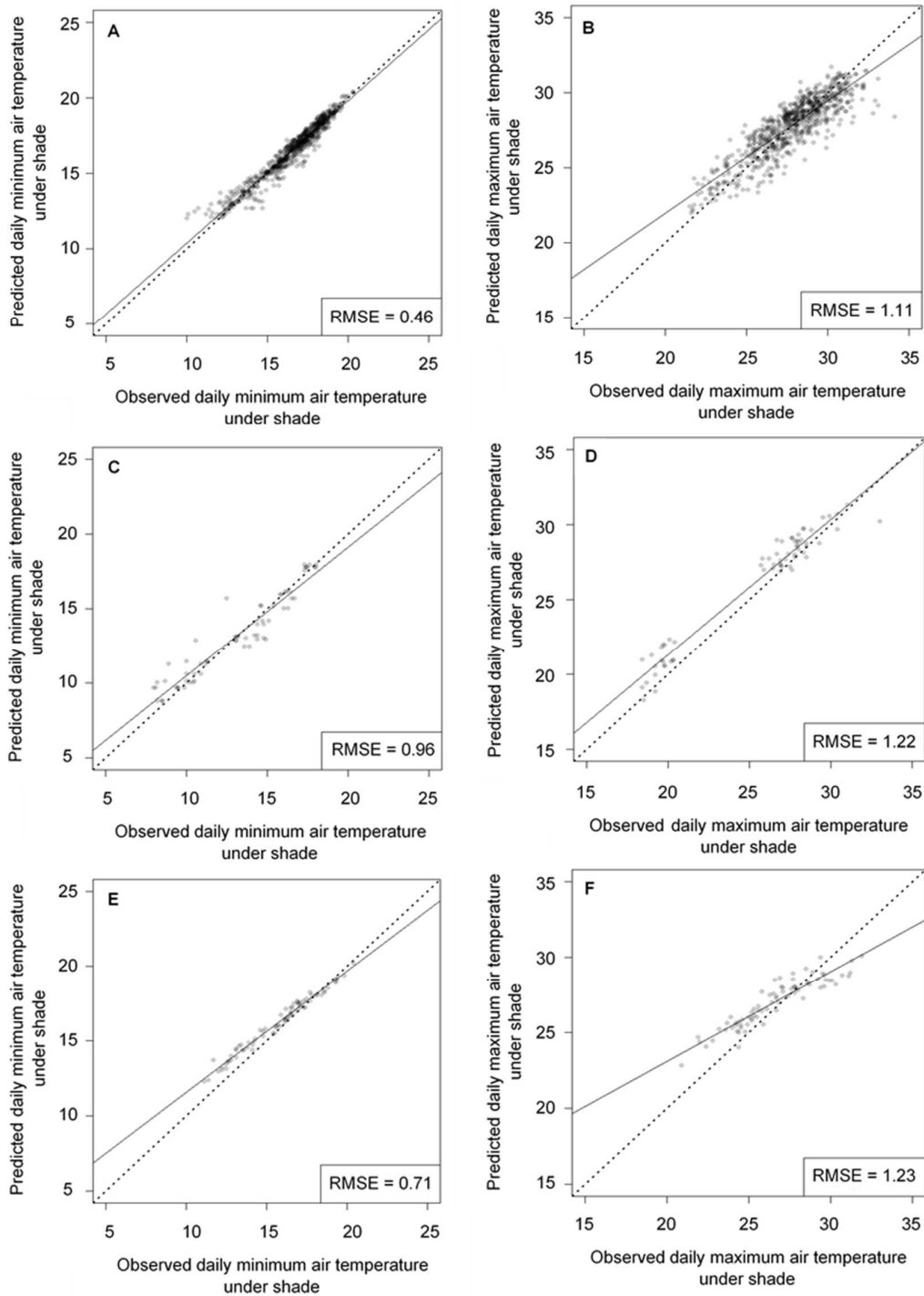


Fig. 3. Graphs illustrating predicted daily minimum and maximum air temperatures under shade as a function of the observed values on the dataset used to build the model (A and B), on the extreme values from the domain of definition excluded from the model building stage (C and D) and on the independent dataset including the site at an altitude of 770 m a.s.l. and the coffee plot with a banana agroforestry system at the site at an altitude of 1140 m a.s.l. (E and F); RMSE = root mean square error.

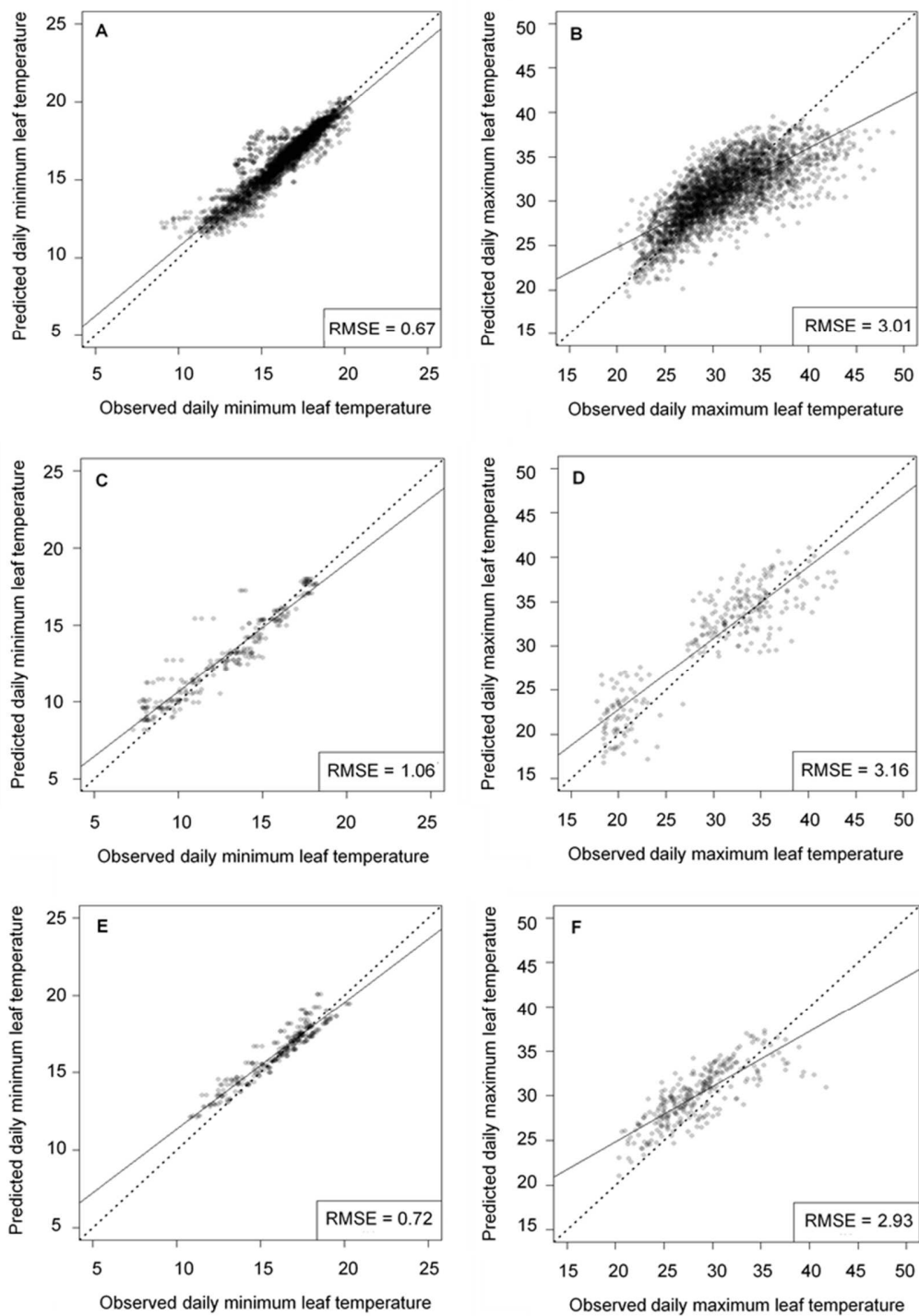


Fig. 4. Graphs illustrating predicted daily minimum and maximum leaf temperatures as a function of the observed values on the dataset used to build the model (A and B), on the extreme values from the domain of definition excluded from the model building stage (C and D) and on the independent dataset including the site at an altitude of 770 m a.s.l. and the coffee plot with a banana agroforestry system at the site at an altitude of 1140 m a.s.l. (E and F); RMSE = root mean square error.

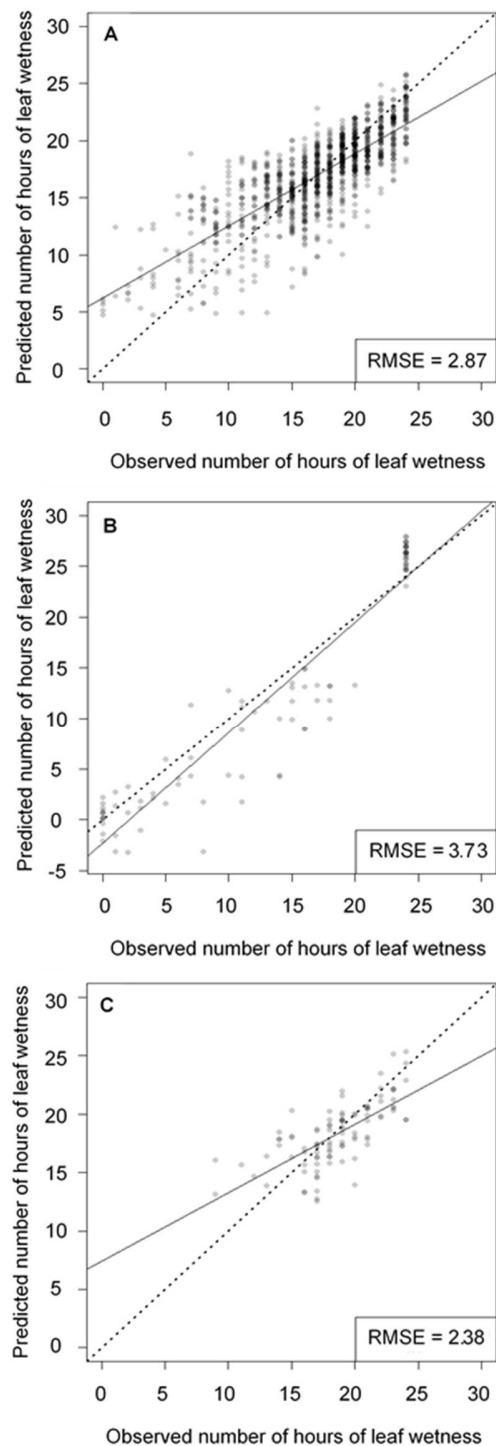


Fig. 5. Graphs illustrating predicted daily leaf wetness duration as a function of the observed values on the dataset used to build the model (A), on the extreme values from the domain of definition excluded from the model building stage (B) and on the independent dataset including the site at an altitude of 770 m a.s.l. and the coffee plot with a banana agroforestry system at the site at an altitude of 1140 m a.s.l. (C); RMSE = root mean square error.

TABLE 1. Studied coffee plots GPS data, altitude, shade tree species, shade tree height, canopy openness and light gap distribution (R=Regular and I=Irregular) during the three periods of recording (P1 = 1st period, P2 = 2nd period and P3 = 3rd period)

Site (Province)	GPS data	Altitude (m a.s.l.)	Shade tree species	Shade tree height (m)			Canopy openness (%)			Light gap distribution		
				P1	P2	P3	P1	P2	P3	P1	P2	P3
			-	-	-	-	-	-	-	-	-	-
Pavones (Cartago)	9°54'34'' N 83°37'55'' W	740	<i>Erythrina poeppigiana</i>	3.8	4.1	4.1	57	63	40	I	I	I
			<i>Cordia alliodora</i>	14.6	14.8	14.8	64	57	51	I	I	I
Palomo (Cartago)	9°59'27'' N 83°38'14'' W	770	-	-	-	-	-	-	-	-	-	-
			<i>C. alliodora</i>	18.5	-	-	56	-	-	I	-	-
El Guayabo (Cartago)	9°57'25'' N 83°39'50'' W	840	-	-	-	-	-	-	-	-	-	-
			<i>E. poeppigiana</i>	6.5	7.9	7.9	67	21	21	I	I	I
			<i>Gliricidia sepium</i>	4.8	5.5	12,5*	79	71	48	I	I	I
San Marcos (San Jose)	9°35'36'' N 84°01'29'' W	1000	<i>Musa spp.</i>	6.6	6.1	6.1	61	50	50	I	I	I
			-	-	-	-	-	-	-	-	-	-
			<i>E. poeppigiana</i>	5.8	2.8	3.5	74	90	59	I	R	I
Cachí (Cartago)	9°48'38'' N 83°49'20'' W	1140	<i>Musa spp.</i>	7.0	7.0	7.0	53	47	37	I	I	I
			<i>Vochysia guatemalensis</i>	10.5	10.8	10.9	36	32	27	I	I	I
			-	-	-	-	-	-	-	-	-	-
Aserri (San Jose)	9°46'8'' N 84°06'30'' W	1270	<i>E. poeppigiana</i>	6.8	7.2	7.2	16	12	27	R	R	R
			<i>Musa spp.</i>	6.9	6.2	6.2	37	44	46	I	I	I
San Marcos (San Jose)	9°39'29'' N 84°02'44'' W	1400	-	-	-	-	-	-	-	-	-	-
			<i>Acrocarpus fraxinifolius</i>	26.4	26.5	26.5	51	59	69	R	R	I
			<i>E. poeppigiana</i>	6.9	7.8	7.8	62	70	53	I	I	I
			<i>Musa spp.</i>	7.2	5.8	5.8	56	88	73	I	R	I

* change for a plot with older shade trees

TABLE 2

Description of the five microclimatic dependent variables and their tested independent variables, including microclimatic quantitative variables provided by a weather station exposed to full sunlight and plot characteristic factors

Variables	Description	Unit	Range
Dependent			
HoursLW	Daily number of hours of leaf wetness	-	[0; 24]
MinTleaf	Daily minimum leaf temperature	°C	[7.3; 20.4]
MaxTleaf	Daily maximum leaf temperature	°C	[17.7; 48.8]
MinTairShade	Daily minimum air temperature under agroforestry	°C	[8.0; 20.4]
MaxTairShade	Daily maximum air temperature under agroforestry	°C	[18.4; 34.1]
Independent			
Microclimatic quantitative variables			
MinTairSun	Daily minimum air temperature in full sunlight	°C	[8.1; 20.4]
MaxTairSun	Daily maximum air temperature in full sunlight	°C	[18.4; 32.7]
RHSun	Daily average relative humidity in full sunlight	%	[61; 100]
RainfallSun	Daily rainfall in full sunlight	mm	[0; 103]
Characteristic factors			
classAgroforSyst	Type of agroforestry system: Shade tree height \geq 7m, canopy openness \geq 50% and light gap distribution ($>$ 2.6) Shade tree height \geq 7m, canopy openness \geq 50% and light gap distribution (\leq 2.6) Shade tree height \geq 7m, canopy openness $<$ 50% and light gap distribution ($>$ 2.6) Shade tree height \geq 7m, canopy openness $<$ 50% and light gap distribution (\leq 2.6) Shade tree height $<$ 7m, canopy openness \geq 50% and light gap distribution ($>$ 2.6) Shade tree height $<$ 7m, canopy openness \geq 50% and light gap distribution (\leq 2.6) Shade tree height $<$ 7m, canopy openness $<$ 50% and light gap distribution ($>$ 2.6) Shade tree height $<$ 7m, canopy openness $<$ 50% and light gap distribution (\leq 2.6) Full sunlight (modality specific to HoursLW , MinTleaf and MaxTleaf)		
CoffeeLeafStratum	Coffee leaf stratum: Bottom; Middle; Top (specific to MinTleaf and MaxTleaf)		

TABLE 3

Relative levels of influence (%) of each independent variable on the dependent variables provided by the boosted regression tree analysis

Independent variables	Dependent variables				
	MinTairShade	MaxTairShade	MinTleaf	MaxTleaf	HoursLW
MinTairSun	95.3	9.2	84.2	9.3	6.3
MaxTairSun	1.4	78.6	2.8	30.0	7.8
RHSun	1.5	3.2	2.3	7.9	66.3
RainfallSun	0.6	2.2	1.8	6.1	7.1
classAgroforSyst	1.2	6.8	7.8	22.2	12.5
CoffeeLeafStratum	-	-	1.1	24.5	-

TABLE 4Description of the parameter estimates of the models *MinTairShade*, *MaxTairShade*, *MinTleaf*, *MaxTleaf* and *HoursLW*

		Models								
		MinTairShade		MaxTairShade		MinTleaf		MaxTleaf		HoursLW
Independent variables		Parameter value [±standard error]	Parameter value [±standard error] ^b	Parameter value [±standard error] ^b	Parameter value [±standard error] ^b	Parameter value [±standard error] ^b	Parameter value [±standard error] ^b	Parameter value [±standard error] ^b	Parameter value [±standard error] ^b	Parameter value [±standard error] ^b
Intercept		$\alpha_1 = 1.23$ [± 0.14]	$\beta_1 = 3.84$ [± 0.63]	-	$\gamma_1 = 0.28$ [± 0.21]	-	$\delta_1 = 18.6$ [± 1.64]	-	$\epsilon_1 = -37.07$ [± 2.69]	-
MinTairSun		$\alpha_2 = 0.94$ [± 0.0087]	-	-	$\gamma_2 = 0.92$ [± 0.0071]	-	$\delta_3 = -0.074$ [± 0.033]	-	-	-
MaxTairSun		-	$\beta_2 = 0.77$ [± 0.021]	-	-	-	$\delta_2 = 0.86$ [± 0.031]	-	$\epsilon_3 = -0.16$ [± 0.049]	-
RHSun		-	-	-	$\gamma_3 = 0.0058$ [± 0.0026]	-	$\delta_4 = -0.13$ [± 0.014]	-	$\epsilon_2 = 0.66$ [± 0.021]	-
RainfallSun		-	-	-	-	-	-	-	$\epsilon_4 = 0.023$ [± 0.0097]	-
classAgroforSyst ^a	A	-	$\beta_3 = 1.13$ [± 0.22]	b	$\gamma_4 = 0.62$ [± 0.039]	d	$\delta_5 = -2.79$ [± 0.]	b	$\epsilon_5 = -1.69$ [± 0.29]	a
	B	-	$\beta_3 = 0$	a	$\gamma_4 = 0.18$ [± 0.11]	ab	$\delta_5 = -4.01$ [± 0.47]	ab	$\epsilon_5 = -1.42$ [± 0.77]	ab
	C	-	$\beta_3 = 1.54$ [± 0.22]	c	$\gamma_4 = 0.76$ [± 0.038]	cf	$\delta_5 = -3.12$ [± 0.17]	b	$\epsilon_5 = -1.02$ [± 0.28]	a
	D	-	$\beta_3 = 0.77$ [± 0.24]	b	$\gamma_4 = 0.87$ [± 0.048]	ef	$\delta_5 = -4.91$ [± 0.22]	a	$\epsilon_5 = -1.95$ [± 0.37]	a
	E	-	$\beta_3 = 2.70$ [± 0.22]	e	$\gamma_4 = 0.58$ [± 0.033]	d	$\delta_5 = -1.65$ [± 0.15]	c	$\epsilon_5 = -1.81$ [± 0.26]	a
	F	-	$\beta_3 = 2.99$ [± 0.28]	e	$\gamma_4 = 0.56$ [± 0.071]	cd	$\delta_5 = 0.40$ [± 0.32]	d	$\epsilon_5 = -1.09$ [± 0.53]	ab
	G	-	$\beta_3 = 2.71$ [± 0.25]	e	$\gamma_4 = 0.52$ [± 0.064]	bd	$\delta_5 = -1.62$ [± 0.29]	c	$\epsilon_5 = 0.34$ [± 0.40]	b
	H	-	$\beta_3 = 2.46$ [± 0.29]	e	$\gamma_4 = 1.04$ [± 0.075]	e	$\delta_5 = -3.78$ [± 0.34]	ab	$\epsilon_5 = -0.49$ [± 0.56]	ab
	I	-	-	-	$\gamma_4 = 0$	a	$\delta_5 = 0$	d	$\epsilon_5 = 0$	b
CoffeeLeafStratum	Bottom	-	-	-	-	-	$\delta_6 = 0$	a	-	-
	Middle	-	-	-	-	-	$\delta_6 = 2.01$ [± 0.13]	b	-	-
	Top	-	-	-	-	-	$\delta_6 = 4.95$ [± 0.13]	c	-	-

^a: A: Shade tree height ≥ 7m, canopy openness ≥ 50% and irregular light gap distribution (> 2.6)

B: Shade tree height ≥ 7m, canopy openness ≥ 50% and regular light gap distribution (≤ 2.6)

C: Shade tree height ≥ 7m, canopy openness < 50% and irregular light gap distribution (> 2.6)

D: Shade tree height ≥ 7m, canopy openness < 50% and regular light gap distribution (≤ 2.6)

E: Shade tree height < 7m, canopy openness ≥ 50% and irregular light gap distribution (> 2.6)

F: Shade tree height < 7m, canopy openness ≥ 50% and regular light gap distribution (≤ 2.6)

G: Shade tree height < 7m, canopy openness < 50% and irregular light gap distribution (> 2.6)

H: Shade tree height < 7m, canopy openness < 50% and regular light gap distribution (≤ 2.6)

I: Full sun exposure

^b: by model and by factor, the modalities that do not share a letter are significantly different