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► **To cite this version:**

Oriana Ovalle-Rivera, Marcel van Oijen, Peter Läderach, Olivier Roupsard, Elias de Melo Virginio Filho, et al.. Assessing the accuracy and robustness of a process-based model for coffee agroforestry systems in Central America. *Agroforestry Systems*, 2020, 94 (5), pp.2033-2051. 10.1007/s10457-020-00521-6 . hal-02911641

**HAL Id: hal-02911641**

**<https://hal.inrae.fr/hal-02911641>**

Submitted on 29 Nov 2021

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## Article (refereed) - postprint

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Ovalle-Rivera, Oriana; Van Oijen, Marcel; Läderach, Peter; Roupsard, Olivier; de Melo Virginio Filho, Elias; Barrios, Mirna; Rapidel, Bruno. 2020. **Assessing the accuracy and robustness of a process-based model for coffee agroforestry systems in Central America.**

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**This is a post-peer-review, pre-copyedit version of an article published in *Agroforestry Systems*, 94 (5). 2033-2051. The final authenticated version is available online at:**

**<https://doi.org/10.1007/s10457-020-00521-6>.**

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# 1 **Assessing the accuracy and robustness of a process-based model for coffee** 2 **agroforestry systems in Central America**

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15

16 **Abstract:** Coffee is often grown in production systems associated with shade trees that provide different  
17 ecosystem services. Management, weather and soil conditions are spatially variable production factors.  
18 CAF2007 is a dynamic model for coffee agroforestry systems that takes these factors as inputs and simulates  
19 the processes underlying berry production at the field scale. There remain, however, uncertainties about  
20 process rates that need to be reduced through calibration.

21 Bayesian statistics using Markov chain Monte Carlo algorithms is increasingly used for calibration of  
22 parameter-rich models. However, very few studies have employed multi-site calibration, which aims to reduce  
23 parameter uncertainties using data from multiple sites simultaneously. The main objectives of this study were  
24 to calibrate the coffee agroforestry model using data gathered in long-term experiments in Costa Rica and  
25 Nicaragua, and to test the calibrated model against independent data from commercial coffee-growing farms.  
26 Two sub-models were improved: calculation of flowering date and the modelling of biennial production

27 patterns. The modified model, referred to as CAF2014, can be downloaded at  
28 <https://doi.org/10.5281/zenodo.3608877>.

29 Calibration improved model performance (higher  $R^2$ , lower RMSE) for Turrialba (Costa Rica) and  
30 Masatepe (Nicaragua), including when all experiments were pooled together. Multi-site and single-site  
31 Bayesian calibration led to similar RMSE. Validation on new data from coffee-growing farms revealed that  
32 both calibration methods improved simulation of yield and its bienniality. The thus improved model was used  
33 to test the effect of N fertilizer and shade in different locations on coffee yield.

34

35

36 **Key words:** Agroforestry systems, Bayesian calibration, *Coffea arabica*, Modelling, Yield

37

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39

## 40 **Declarations**

41 **Acknowledgments:** This study was part of the PCP Agroforestry Systems with Perennial Crops, a scientific  
42 partnership platform led by CATIE and CIRAD in Central America. We greatly acknowledge CATIE and its  
43 partners and CIRAD for facilitating the data required for the calibration of this model, and the farm owners for  
44 granting us access to their farms and records. We also thank the reviewers of the original manuscript whose  
45 comments have led to considerable improvements in the presentation.

46 **Funding:** This study was funded by the Caf Adapt project, Fontagro/RF-1027. It was implemented as part of  
47 the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) with the support  
48 from CGIAR Fund Donors and through bilateral funding agreements. For details, please visit  
49 <https://ccafs.cgiar.org/donors>. Coffee-Flux Observatory, Llano Bonito and CATIE agroforestry trial were also  
50 supported by SOERE F-ORE-T from Ecofor, Allenvi and the French national research infrastructure ANAEE-  
51 F (<http://www.anaee-france.fr/fr/>), the European project CAFNET (EuropAid/121998/C/G), the Ecosfix  
52 project (ANR- 2010-STRA-003-01), the CIRAD-SAFSE project, the MACACC project (ANR-13-AGRO-  
53 0005) and the CATIE-PROCAGICA-IICA-UE project. MvO acknowledges support from BBSRC through  
54 GCRF project SEACAF (BB/S01490X/1).

55 **Conflicts of interest/Competing interests:** None.

56 **Ethics approval:** Not applicable.

57 **Consent to participate:** Not applicable.

58 **Consent for publication:** Not applicable.

59 **Availability of data and material:** Requested for data should be addressed to EdMVF and MB.

60 **Code availability:** The coffee agroforestry model CAF2014 can be downloaded from  
61 <https://doi.org/10.5281/zenodo.3608877>.

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63

## 64 Introduction

65

66 Process-based dynamic models have been used for over 50 years to explore the effect of variation of  
67 environmental variables or agricultural practices on agronomic or environmental indicators, like crop yields  
68 or N leached to aquifers (de Wit, 1965; Bunn et al., 2014; Makowski et al., 2014). Due to their ability to explore  
69 a wide range of options, dynamic models can be used to represent and optimize management decisions for  
70 increased outputs (Dogliotti et al. 2005). Models are frequently used to assess the effect of future climate  
71 change on crop yields, as they are able to represent conditions that are difficult to observe currently. However,  
72 to simulate the impacts of future conditions adequately, scientists have to evaluate very carefully the adequacy  
73 of their models for a wide variety of current conditions, including production situations to which the models  
74 were not specifically calibrated.

75 Agroforestry systems combine crops with trees in the same field. As such, they can represent a solution  
76 to the challenge of producing food for a growing global population while preserving the resources used for  
77 this production, as well as other ecosystem services provided to societies, such as provision of clean water,  
78 control of soil erosion, and control of pests and weeds. For certain crops at least, production under shade trees  
79 can be as good or better than in full sun (Jose, 2009). The trees in agroforestry systems may produce goods  
80 like timber, firewood or fruits (Cerda et al., 2014), or medicine. But they are also known to protect natural  
81 resources from exhaustion, by working as safety nets for nutrients, or by mobilizing them better from the soil  
82 (Van Noordwijk et al., 1996), to regulate climate both locally and globally (Vaast et al., 2015), or to protect  
83 soil surface from crusting, runoff and erosion (Villatoro-Sánchez *et al.*, 2015).

84 Agroforestry systems have been used by farmers only in a limited number of cases. Such cases include  
85 perennial crops, naturally adapted to growth and reproduction as understory crops, like coffee and cocoa grown  
86 under humid climates in the tropics. They also include other crops, like dry cereals in dry climates, when soil  
87 fertility and soil water balance are enhanced by some perennial shrubs, like *Guiera senegalensis* or *Piliostigma*  
88 *reticulatum* (Kizito *et al.*, 2012; Yelemou *et al.*, 2013; Hernandez *et al.*, 2015) or where crops and trees explore  
89 distinct niches, as is the case for *Faidherbia albida* in West Africa (Roupsard et al., 1999). The case of coffee  
90 and cocoa, though, is particular, as those crops are mostly cultivated in agroforestry systems (Jha et al., 2014).

91 Success in the combined provision of goods and services by agroforestry systems depends on delicate  
92 equilibria between the plant species involved, which can oscillate between competition and facilitation  
93 depending on the species involved, their management, or the environmental conditions (Jose, 2009; De  
94 Beenhouwer *et al.*, 2013; Taugourdeau *et al.*, 2014). No combination of crop and tree species exists that can  
95 be used everywhere. Scientific knowledge has been produced for a few decades now on the processes  
96 underlying these combined provisions. Some of this research has been done on experimental sites, where long-  
97 term experiments have produced a wealth of information (Imbach *et al.*, 1989; Hagggar *et al.*, 2011). However,  
98 even nowadays when interest in agroforestry is high, such experiments are few, as they require large areas of  
99 land (due to border effects of tree plantations) over long times (typically 15-30 years).

100 Dynamic models can be used to explore the ability of agroforestry systems to provide ecosystem  
101 services. Agroforestry models can be somewhat artificially sorted into two types. Some, of a generic nature,  
102 focus on the interactions between species, like WaNuLCAS (Van Noordwijk and Lusiana, 1998). Others are  
103 more focused on a particular crop and try to estimate the effects of shade trees on its productivity (Zuidema *et*  
104 *al.*, 2005; Rahn *et al.*, 2018). These models, whatever their type, are useful for testing hypotheses on  
105 interactions between species under different environmental conditions, and for testing the impact of  
106 environmental change scenarios on the productivity and other ecosystem services provided by agroforestry  
107 systems. They have also proven useful to elicit and nurture fruitful participatory processes between farmers  
108 and researchers on the technical management of cropping systems (Carberry *et al.*, 2004; Whitbread *et al.*,  
109 2010; Meylan *et al.*, 2014).

110 Dynamic crop models simulate phenology along full crop cycles. Rodríguez *et al.* (2011) proposed a  
111 physiologically-based full sun coffee dynamic growth and yield model, working from coffee organ (fruiting  
112 node) to whole coffee-plant and validated in two extreme latitudinal conditions for coffee cropping, with a  
113 special effort to accurately simulate the bud, flower and fruit phenology. This model proved to be efficient at  
114 early stages of the coffee cycle (0-5 years old). Recently, Vezy *et al.* (2020) incorporated the reproductive  
115 modules of Rodríguez *et al.* (2011), including reproductive cohorts to best distribute the fruit carbon demand  
116 along the year and scaled them up to simulate ecosystem services (multi-objective calibration) of a whole  
117 agroforestry field for full rotations, but the model was parameterized and tested for only one site so far. Indeed,  
118 another model existed previously for the simulation of coffee production at the field scale in full sun and

119 agroforestry systems, CAF2007 (van Oijen *et al.*, 2010b). It was built to simulate coffee plantations in Central  
120 America, but has not been thoroughly parameterized based on agroforestry trials, nor tested in commercial  
121 plantations, so its use has been limited so far.

122 Adequate parameterization of agroforestry models is a complex task. Numerous processes are closely  
123 interrelated, so it is difficult to parameterize one process without having previously parameterized other  
124 connected processes. Measurements on diverse processes in coffee agroforestry systems have been carried out  
125 in experiments and in commercial plantations for some years now (van Oijen *et al.*, 2010a; Hagggar *et al.*, 2011;  
126 Charbonnier *et al.*, 2013; Meylan *et al.*, 2013; Taugourdeau *et al.*, 2014; Gagliardi *et al.*, 2015; Padovan *et al.*,  
127 2015; Villatoro-Sánchez *et al.*, 2015; Defrenet *et al.*, 2016). This parameterization, necessary as it is to use a  
128 model with reasonable confidence, cannot be done everywhere. To avoid parameterizing the model again and  
129 again depending on its intended use, we need to assess the robustness of the parameterization process itself: to  
130 do that, we can compare site-specific and multi-site calibrations in their ability to reproduce the same sets of  
131 data (Van Oijen *et al.* 2013).

132 The measurements made to parameterize the agroforestry models concern complex processes,  
133 measurement methods are frequently delicate and their results often come with significant uncertainties. These  
134 uncertainties need to be taken into account in the parameterization process. Methods for including probability  
135 distributions for measurements, parameters and outputs do exist, based on Bayesian statistics, and these  
136 methods have proven their suitability to complex processes and related models (Van Oijen *et al.*, 2005; Van  
137 Oijen 2017). Bayesian calibration has been implemented in different models for specific sites. Multi-site  
138 calibration is a relatively new method for calibration of process-based models such as the VSD model, which  
139 simulates chemical solution of soil and nitrogen pools in natural and semi-natural ecosystems (Reinds *et al.*,  
140 2008), the BASFOR forest model (Van Oijen *et al.*, 2013), and the BASGRA\_N grassland model (Höglind *et*  
141 *al.*, 2020). We followed the procedure described by Van Oijen *et al.* (2005) which makes it possible to calibrate  
142 the parameters that influence the model processes based on data measured in the field while accounting for  
143 uncertainties in measurements and modelling.

144 This paper reports how the CAF2007 coffee agroforestry model was modified (and renamed to CAF2014),  
145 parameterized using data gathered over the course of several years at multiple sites, validated under  
146 commercial conditions for coffee in Central America, and applied to address challenges associated with the



147 management of coffee tree plantations regarding the effect of shade and fertilization dose and distribution at  
148 different sites and altitudes in Costa Rica and Nicaragua.

149

150

## 151 **2. Materials and methods**

### 152 **2.1 Study area**

153 The study was carried out in the coffee-growing regions of Nicaragua and Costa Rica. The climatic conditions  
154 in these coffee growing regions have been analyzed and clustered in four different climatic zones shown in  
155 Figure 1, mainly related to the rainfall-temperature combinations from the WorldClim historical weather data  
156 base (Läderach et al. 2017).

157 *Climatic zone 1* is characterized by cold and dry weather with an annual average precipitation of 1,544  
158 mm and a mean annual temperature of 20°C. These conditions were only found in Nicaragua. *Climatic zone 2*  
159 is cold and humid with an annual average precipitation of 2,503 mm and a mean annual temperature of 19°C,  
160 present in both countries in some of the best producing regions, Jinotega and Matagalpa in Nicaragua and  
161 Tarrazú in Costa Rica. *Climatic zone 3* is characterized by being hot and humid with an annual average  
162 precipitation of 2,886 mm and a mean annual temperature of 23°C, mostly present in Costa Rica (Turrialba)  
163 and marginally in Nicaragua. *Climatic zone 4* is dry and hot, with an annual average precipitation of 1,688 mm  
164 and an annual mean temperature of 23°C, mainly present in Nicaragua (Masatepe, the oldest coffee producing  
165 region in Nicaragua, is a typical example of it), and almost restricted to the Nicoya peninsula in Costa Rica.

### 166 **2.2 Sites used for model calibration**

167 Twelve sites were used for calibration, representing three of the four climatic zones (Table 1). The sites were  
168 located at four different locations:

- 169 a. The CATIE long-term agroforestry experiment in Turrialba, Costa Rica (six sites - Zone 3) planted in  
170 2000: Six of the calibration sites were located in the canton of Turrialba in the province of Cartago in  
171 Costa Rica, at 600 m above sea level. Hagggar et al. (2011) described this location as one of low altitude

172 with humid weather. Six sites were selected for calibrating the model with different intensities of  
173 management (quantities of fertilizers and other inputs), different densities and species of shade tree.

174 b. The Llano Bonito coffee-growing farm in San Pablo de León Cortés in Tarrazú, Costa Rica (single site -  
175 Zone 2): The calibration site was located at a coffee-growing farm in the region of Los Santos at 1,620 m  
176 above sea level near the central mountain range in Costa Rica. The selected farm has shade predominantly  
177 from *Erythrina* trees and some from musaceae (Meylan, 2012). The coffee field was gradually replanted  
178 conform local farming practice.

179 c. The Coffee-Flux observatory at the Aquiares farm in Cartago, Costa Rica (single site - Zone 3): The final  
180 Costa Rican calibration site was at the Aquiares farm which is located 10 km northwest of Turrialba at an  
181 average altitude of 1,100 m above sea level. 98% of the selected site area is cultivated with the Caturra  
182 coffee cultivar with shade from tall free-growing *Erythrina* trees (no pruning or thinning). The general  
183 management practices varied from year to year. The data for calibration in Aquiares were obtained from  
184 Charbonnier 2013, Taugourdeau *et al.*, 2014, Defrenet *et al.*, 2016 and Kinoshita *et al.*, 2016.

185 d. The CATIE long-term coffee agroforestry trial in the low and dry zone in Masatepe, Nicaragua (four sites  
186 – Zone 4). The sites were located in the Pacific Center for Training and Regional Services (UNICAFE)  
187 with two repetitions planted in 2000. The sites were planted with the Pacas coffee variety (genetically very  
188 similar to the Caturra variety) with different management intensities. Two sites were in the shade  
189 predominantly from *Inga edulis* trees and two other sites were in full sun (Table 1).

190

### 191 **2.3 Field data used for calibration**

192 Seventeen variables were used for calibrating the model. These were variables that the model calculated and  
193 for which also measurements were available, but not all variables at all sites, as data had been collected  
194 primarily for other purposes. Information was available about coffee productivity at all sites, but data on  
195 average soil carbon content were only collected at 92% of the sites (Table 2). Data on the content of carbon in  
196 the above-ground portion of the coffee plants were available for 50% of sites. The leaf area indices of the  
197 coffee and shade trees as well as the content of carbon in the trunk and coffee leaves were measured more  
198 rarely.

199        Additionally, we had access to historical data on coffee flowering dates in the agroforestry trial in  
200 Turrialba. From prior simulations, we knew that flowering date was not predicted accurately. We used these  
201 data to modify the subroutine of the model that calculates the onset of flowering, which is essential as all other  
202 phenological stages are based on this flowering date (see next section).

## 203 **2.4 From CAF2007 to CAF2014**

### 204 *2.4.1 Original version of the model*

205 CAF2007 is a basic dynamic process model for simulating managed coffee full sun or agroforestry fields at a  
206 daily time step (van Oijen *et al.*, 2010b). Two vegetation layers are distinguished: shade tree and coffee.  
207 CAF2007 was designed to assist in taking decisions associated with management strategies such as fertilizer  
208 dose, shade tree density and species, pruning and thinning schedule. The model is also able to simulate the  
209 response of the system to environmental change (climate, atmospheric CO<sub>2</sub>). The model simulates growth,  
210 yield and other services associated with specific tree species, taking into account the main processes occurring  
211 in plants and soil. These include the processes that contribute to the C-, N- and water-balance of the system.  
212 The model is generic by nature but it has thus far been calibrated only for the edapho-climatic conditions,  
213 coffee and tree genotypes and management conditions that are typical of Central America.

214        The model takes into consideration environmental inputs including radiation, precipitation,  
215 temperature, [CO<sub>2</sub>], water, and nitrogen. The behavior of the simulated agroforestry system is constrained by  
216 soil properties, weather conditions, and individual site management. CAF2007 simulates the effects of shade  
217 trees on coffee through competition for light, water, and nutrients, and it takes into account the contribution of  
218 pruning and thinning to organic matter in the litter layer (van Oijen *et al.*, 2010b).

219        The model has 104 parameters, 70 of which are calibrated. Prior information for estimating parameter  
220 values was obtained from reviews of literature (van Oijen *et al.*, 2010a) including dissertations, project reports,  
221 data collections, and interviews with farmers. We now describe two modifications of the model, which led to  
222 a new model version that we refer to as CAF2014.

### 223 *2.4.2 Model modifications for flowering*

224 In the original model, flowering was triggered by daily rainfall exceeding a certain threshold, set at 10 mm by  
225 default, as soon as it occurred in the calendar year (Van Oijen 2010b). We modified this to better simulate  
226 actual flowering dates in regions where flowering is grouped and occurs after a significant period of water  
227 shortage: flowering now starts on the first day of the year on which the product of the amount of daily rainfall  
228 and the Julian day is greater than 1,000. This means that it can take 100 days after January 1 for flowering to  
229 occur with a daily rainfall of 10 mm to induce flowering or just 10 days of 100 mm rain. We used multi-annual  
230 time-series of flowering dates observed at the Aquiares farm experiment to check the ability of this new routine  
231 to improve the simulation of coffee flowering dates (Figure 2). The modification reduced RMSE for flowering  
232 date from 41.5 to 26.0. Further increases in prediction quality may be achievable, but it would require the  
233 writing of a new, complex model that takes into account soil water content, temperature and day length. We  
234 considered that the model in its new form was sufficiently accurate for our purposes, and consistent with our  
235 limited knowledge on the triggering of coffee flowering.

#### 236 2.4.3 *Model modifications for biennial production*

237 In current full sun and moderate shade systems, years with high yields and low leaf-area index (LAI) tend to  
238 alternate with years with low yields but high LAI (Carvalho et al. 2020). The original CAF2007 model did not  
239 simulate a biennial pattern of coffee productivity. To incorporate this widely occurring phenomenon, the sink  
240 strength of the coffee beans is now inversely related to previous year's sink strength. This small change leads  
241 to biennial variation of simulated coffee yields which matches observations as shown in Figure 3. In the  
242 absence of data on bean sink strength, the inclusion of this modification in the model was not tested  
243 independently of the whole model.

#### 244 2.4.4 *Initialization and inputs of CAF2014*

245 We refer to the model formed by modifying the flowering and bean sink algorithms of CAF2007 as CAF2014.  
246 This new model version is freely downloadable from <https://doi.org/10.5281/zenodo.3608877>, and a  
247 description of model structure can be found in a paper by Rahn et al. (2018), who carried out a parameter  
248 sensitivity analysis of CAF2014 for application in Uganda and Tanzania. To run the model, the initial values  
249 of state variables must be specified, as must be the site management practices and weather conditions. Data to

250 meet these model information requirements were compiled for each of the experimental sites and coffee-  
251 growing farms in the study.

- 252 • Model initialization. Four values of initial carbon content in different plant parts are needed for shade trees,  
253 and four values for coffee trees. Seven initial values (primarily the contents of N and C) are needed for the  
254 soil.
- 255 • Management. Three parameters for coffee management (first day of pruning, pruning interval, and pruned  
256 biomass fraction), six for shade tree management (first day of pruning, pruning interval, pruned biomass  
257 fraction, thinning data, thinned biomass fraction, and initial tree density), and two for soil fertility  
258 management (date of application and dose of soil fertilizer).
- 259 • Weather. Six daily variables: minimum and maximum temperature ( $^{\circ}\text{C}$ ), wind speed ( $\text{m s}^{-1}$ ), global  
260 radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ), atmospheric vapour pressure (kPa), and precipitation ( $\text{mm d}^{-1}$ ).

261

## 262 **2.5 Bayesian calibration**

263 The values of model parameters are generally poorly constrained and the consequences of these uncertainties  
264 for model outputs must be quantified. We can represent such parameter uncertainties of process-based models  
265 by means of prior probability distributions, and use measurements on the model's output variables to calibrate  
266 the model within a Bayesian framework (Kennedy & O'Hagan 2001, Van Oijen et al. 2005, Van Oijen 2017).

### 267 *2.5.1 Selection and prioritization of parameters to be calibrated*

268 Some parameters values were known or directly measurable. These included geographic parameters and other  
269 parameters well documented in scientific literature. We did not include these parameters in the model  
270 calibration. Also not included in the calibration were parameters that had no significant impact on the results  
271 of the model, as shown in a sensitivity analysis by Remal (2009). Therefore, only those parameters were  
272 calibrated that had a significant impact on the results of the model and were not measured directly. Depending  
273 on each site, the number of parameters ranges from 63 to 67: 26 tree parameters, 13-17 soil parameters  
274 (depending on whether there was information available from a soil analysis at the site), and 24 coffee

275 parameters. The sites with the largest number of calibration parameters were those for which there was no  
276 initial soil analysis available.

### 277 2.5.2 *Bayesian calibration*

278 Every Bayesian calibration begins by assigning a *prior* probability distribution to the model's parameters. The  
279 prior distribution for CAF2014 consisted of wide beta probability distributions based on literature review and  
280 other information (Van Oijen et al. 2010a). The calibration itself consists of using data on model output  
281 variables to update the parameter distribution, by application of Bayes' Theorem. We assumed independent  
282 measurement errors, represented by zero-centered Gaussian probability distributions with a coefficient of  
283 variation of 0.3. After all data are used, the updated distribution is referred to as the *posterior* parameter  
284 distribution. The method that we used for the calibration was Markov chain Monte Carlo sampling (MCMC)  
285 by means of the Metropolis algorithm (Robert & Casella 1999, Van Oijen et al. 2005). The R-code for the  
286 Metropolis algorithm is provided together with CAF2014 code at <https://doi.org/10.5281/zenodo.3608877>.  
287 The algorithm produces a representative sample from the posterior parameter distribution by a walk through  
288 'parameter space'. Each proposed next step of the walk, i.e. each proposed new parameter vector, is accepted  
289 or rejected based on the product of the prior probability for that parameter vector and the *likelihood* of the data  
290 given CAF2014's outputs for the parameter vector. In this way, Bayesian calibration combines prior  
291 information with new data. For the calibrations reported here, we used Markov chains of length 100,000. Trace  
292 plots of the chains – showing how parameters values changed over the 100,000 iterations, were inspected to  
293 assess convergence visually. Based on this, an initial burn-in phase of 10,000 iterations was discarded from  
294 the final sample.

295

### 296 2.5.3 *Types of calibration*

297 We carried out both *single-site and multi-site* calibrations (Reinds et al. 2008). In the single-site calibrations,  
298 all calibrated parameters were considered to be site-specific. A separate MCMC was thus run for each site of  
299 Table 1, leading to twelve different site-specific posterior parameter distributions. In multi-site calibrations,  
300 data from multiple sites were used simultaneously in one MCMC, and posterior parameter estimates were  
301 assumed to apply to all sites involved. Two types of multi-site calibration were carried out: '*cluster*' calibration

302 using subsets of sites close to each other (this was done for Turrialba and for Masatepe) and ‘generic’  
303 calibration which included all twelve sites of Table 1. Therefore a total of 15 different calibrations were carried  
304 out:

- 305 • 12 single-site calibrations (one for each site),
- 306 • 2 cluster calibrations (a six-site calibration for Turrialba and a four-site calibration for Masatepe),
- 307 • 1 generic calibration (for all twelve sites simultaneously).

308

#### 309 2.5.4 Calibration evaluation

310 To estimate the goodness of fit of the model to data, the root mean square error (RMSE) was calculated for the  
311 mode of the posterior parameter distribution. The number of measurements observed vs. the number of  
312 simulated measurements was taken into account. The RMSE is defined as the square root of the sum of the  
313 squared differences between observed and simulated values divided by the total number of values. Values  
314 close to zero indicate a good model fit to the data.

$$315 \quad \text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}},$$

316 where  $n$  = number of observations in the sample,  $X_{obs,i}$  = values observed for the "i"-th instance, and  $X_{model,i}$   
317 = are the values modelled for the "i"-th instance.

318 The validity of the RMSE value is limited in that this indicator assumes that data measured are accurate,  
319 which is contradictory to the Bayesian calibration principle that affirms that all values, including measured  
320 data, are associated with an uncertainty represented by a distribution of probabilities. The interpretation of  
321 RMSE must therefore be taken with some caution; in our study, we will focus on its use for the detection of  
322 systematic bias in the modelling outputs and possible correction.

## 323 2.6 Sites used for model validation

324 For validation purposes, information was compiled from non-experimental sites in Nicaragua (Table 3) where  
325 yield and climatic data could be collected accurately. Historical data were compiled from farmer-surveys and  
326 climatic data from weather stations near the farms for running the model. These included input data for driving

327 the model such as weather, management of coffee plants, trees and soil as well as data on coffee yields to  
328 compare with model outputs.

329 One site was taken from each farm, planted with the Caturra coffee variety where shade comes  
330 predominantly from Inga trees using different coffee tree management practices. The coffee-growing farms  
331 were located in three climatic zones:

- 332 - Climatic zone 2 (cold and humid) was represented by the Solingalpa farm located in Jinotega. The farm  
333 has steep slopes (25%) planted with the Caturra coffee variety. Shade comes predominantly from guaba  
334 (*Psidium sp.*) trees with selective management practices.
- 335 - El Rosal farm is in Climatic zone 4 (dry and hot). It is located in Carazo department in Nicaragua, and  
336 represented by the "Las Negras" site. This site has shade predominantly from Erythrina trees with presence  
337 of the Catrenic coffee variety and management of shade and coffee trees.
- 338 - Lastly, the Hammonia and La Pinedita farms in the department of Matagalpa in Nicaragua represented  
339 Climatic zone 1 (dry and cold), to further challenge the robustness of model predictions.

340

## 341 **2.7 Sensitivity analysis**

342 To assess model behaviour under a wider range of conditions than were present in the study sites, we analysed  
343 the sensitivity of the calibrated model to various management options regarding fertilization and shade. The  
344 calibration sites differed in many respects (weather, shade management, fertilizer use etc.), so cannot be  
345 compared directly. The sensitivity analysis standardized fertilization to analyse shade response differences  
346 between sites (Table 5), and it standardized shade management to analyse fertilization impact differences  
347 (Table 6).

348

## 349 **3. Results**

350 The study results were first broken down into individual and multi-site calibrations using the modified model.  
351 The model was then validated using information of coffee-growing farms located in different climate clusters.  
352 We finally ran simulations of coffee-growing sites with the calibrated model, as a preliminary assessment of  
353 the capacity of the model to evaluate different management practices and site conditions.



### 354 **3.1 Calibration of the CAF2014 model**

355 In the first stage, the calibration was performed separately for each of the twelve sites listed in Table 1 (single  
356 site calibrations), then for Turrialba and Masatepe (cluster calibrations) and lastly, for the set of all sites  
357 (generic calibration). For each calibration, 100,000 MCMC iterations were carried out. Figure 3 shows  
358 examples of model simulations after cluster calibration for two of sites in Turrialba with different levels of  
359 fertilization and shade.

#### 360 *3.1.1 Single-site calibration*

361 Measured production data were available for between 10 and 11 years for all sites, with the exception of Llano  
362 Bonito (only two years). Maximum measured production values of coffee beans dry matter in Turrialba,  
363 AQUIARES, and Masatepe were 5.74, 4.3, and 5 tons DM cherry  $y^{-1}$ , respectively. The single-site calibrated model  
364 simulated maximum production values in Turrialba, AQUIARES, and Masatepe of 5.81, 4.8, and 2.27,  
365 respectively.

366 Figure 4 shows simulated coffee production compared against measured production and the relevant  
367 determination coefficients ( $R^2$ ) for each of the calibrated sites. We can globally observe that all Turrialba  
368 experiments were adequately simulated, with acceptable  $R^2$ , ranging from 0.54 to 0.71. More importantly,  
369 there seems to be no clear bias, overestimations and underestimations seem to compensate each other. On the  
370 other hand, although low production levels in Masatepe were correctly estimated, high productions are not,  
371 and this is particularly clear in the full sun intensive management site, where the best production was measured  
372 at 5 tons  $ha^{-1}$ , in 2005-2006, while the production simulated did not exceed 2.3 tons  $ha^{-1}$ . In AQUIARES the  
373 model overestimates most harvests on average by 0.7 t DM cherry  $ha^{-1} y^{-1}$ . It has, however, a good fit with an  
374  $R^2$  value of 0.71 (Figure 4).

375 A comparison of the individually calibrated and uncalibrated sites (Fig. 5) indicates that the RMSE for  
376 coffee production (t DM cherry  $ha^{-1} y^{-1}$ ) improves at the majority of the calibrated sites with an improvement  
377 in RMSE that ranges from 0.22 to 1.84. Several sites in Turrialba exhibit a good fit with low RMSE. Llano  
378 Bonito exhibits a high RMSE from the calibration of the coffee production. This is due to the low number of  
379 measured production data. This is also the case for sites in full sun with high conventional management  
380 practices in Turrialba and Masatepe before calibration, but RMSE was greatly reduced by calibration.

### 381 3.1.2 *Multi-site calibration (by cluster and generically)*

382 Figure 5 shows the RMSE for model simulations of coffee production in t DM cherry ha<sup>-1</sup> y<sup>-1</sup>, for each of the  
383 sites, after different calibration efforts: (1) no calibration, (2) generic calibration, (3) cluster calibration, (4)  
384 single-site calibration. The highest RMSE values are found in the case of no calibration, confirming that a  
385 calibrated model fits measured data better. On average, RMSE improves by 0.91.

386 The progression of RMSE from generic via cluster to individual calibration is uneven: it generally  
387 decreases but this evolution is not systematic: at Aquiares, surprisingly, the single-site calibration shows higher  
388 RMSE than generic calibration, but both calibrations show rather low RMSE.

389 Coefficients of determination (R<sup>2</sup>) for cluster and generic calibrations are shown in Figure 6. Turrialba  
390 and Masatepe exhibit a similar R<sup>2</sup> value of 0.54-0.56. Some of the high harvest values simulated at both sites  
391 are underestimated. Generic calibration yields an R<sup>2</sup> of 0.64. The underestimations of the model at high  
392 productivity remain, but are not systematic.

393 Table 4 shows average coffee production as simulated following the three types of calibration. There  
394 were no significant differences versus measured production for any site with the exception of the Masatepe-3,  
395 the Nicaraguansite in full sun with high fertilization.

396

### 397 **3.2 Validation of the CAF2014 model**

398 Production simulations using the generically calibrated model exhibit low RMSE values and a good  
399 determination coefficient. Figure 7 shows an R<sup>2</sup> of 0.55 for the four validation farms, whose data had not been  
400 used for any model calibration. The model underestimated some of the high harvests, while the other harvests  
401 exhibit a good fit.

402 As the results from generic calibration were shown to perform adequately for calibration sites, without  
403 any dramatic increase in RMSE compared to cluster calibration or single-site calibration, we decided to use  
404 the generically calibrated model for the following simulations.

### 405 **3.3 Additional simulations using the generically calibrated CAF2014 model**

406 Simulations were carried out with the generically calibrated model to show the effect of shade and fertilization  
407 at different sites and altitudes in Costa Rica and Nicaragua (Tables 5, 6). The results reveal that production  
408 varies depending on the altitude and weather conditions at each site. Production in a hot and dry area  
409 (Masatepe) is lower in the sun than in the shade, in contrast to the wetter conditions (Turrialba and Llano  
410 Bonito) where shade reduces production (Table 5). But shade has a positive effect on productivity in the drier  
411 conditions. In contrast, in the more humid Costa Rican areas, production decreases by 10 to 22% in the shade  
412 from *Inga edulis* trees. The model simulations show that this is due to the fact that the tree crown diameter  
413 grows at a faster rate in humid zones than in dry zones.

414 Two virtual experiments were run to explore fertilization effects, the most expensive input in coffee  
415 production in Central America (Meylan *et al.*, 2013), related to dose and fractionation (Table 6). The dose  
416 that simulates the largest production in three fractions is 300 kg N ha<sup>-1</sup> y<sup>-1</sup>. At higher doses, the production did  
417 not increase anymore; most of this additional N was lost. Simulations using different fractionation of this  
418 fertilization rate showed that the effects of higher fractionations were real (with one exception), but minimal,  
419 probably less than the labour cost of an additional application. The days of N application were optimized in  
420 each experiment.

421

## 422 **4. Discussion**

423

424 We started from CAF2007, a simple dynamic model of coffee agroforestry systems (van Oijen *et al.*, 2010b),  
425 and modified the algorithms for two processes that were simulated inaccurately, i.e. blossoming date and  
426 biennial oscillation of cherry production. We then proceeded to calibrate the new model, CAF2014 using  
427 measurements from contrasting environmental conditions and management regimes. A Bayesian method was  
428 used for the calibration, for a total of 12 experimental sites. We found few differences between calibrations  
429 performed for each site separately (leading to site-specific estimates for coffee, tree and soil parameters), by  
430 cluster (Turrialba- and Masatepe-specific parameters), or generically for the complete dataset. The generically  
431 calibrated model was able to account for most of the variation in independent yield data from commercial  
432 plantations, the model was thus considered to be robust. We finally found that the modelled effects of N

433 fertilization were not as strong as expected, and the effects of shade depended mainly on local humidity.

434

#### 435 **4.1 Single-site vs. multi-site model calibration**

436 Single-site and multi-site calibrations revealed that the model exhibits very similar fits regardless of whether  
437 it is calibrated for a single site, for clusters, or for all sites together. The RMSE values are very similar at any  
438 of the sites regardless of the procedure, and always lower than the RMSE values of the uncalibrated model.  
439 This result is encouraging because it suggests that parameter values for coffee ecophysiology have limited  
440 variability in the studied region, which facilitates broadscale model application across Costa Rica and  
441 Nicaragua without a need for additional calibration. The finding is consistent with the narrow genetic base of  
442 cultivated *Coffea arabica* in the Western hemisphere (Sousa et al. 2017). The RMSE values for shaded sites  
443 for coffee production in Costa Rica and Nicaragua (t DM cherry ha<sup>-1</sup> y<sup>-1</sup>) were low and the R<sup>2</sup>-values were  
444 high. Strong model performance for these sites may have been aided by the availability of good information  
445 on initial constants, site management, and *a priori* distribution of parameters. A remarkable feature of the  
446 calibrated model is that it accounts very well for the very high interannual variability in yields that was  
447 observed on all sites. Model predictions always accounted for more than 50% of interannual variation, and for  
448 about half the sites this reached about 70% (Figures 4 and 6). So the calibrated model can reproduce patterns  
449 of alternating high- and low-yielding years, i.e. alternate bearing (see also Figure 3). The absolute values of  
450 yield were underestimated in some years with high yields, in particular for Masatepe (e.g. Figure 4i). This site  
451 is in Climatic zone 4, which is dry and hot, so CAF2014 may be overestimating the impacts of water deficiency.  
452 The calibrated model also had a relatively high RMSE-value for the Llano Bonito site where shade was  
453 provided by *Erythrina poeppigiana* trees that were pollarded twice or thrice each year (see Figure 5). CAF2014  
454 uses allometric equations to establish the relationship between tree branch biomass and crown area – and this  
455 relationship may conceivably be disrupted by the frequent pollarding. Quick re-growth of branches of this tree  
456 species after pollarding is generally observed, initiated by rapid mobilization of reserves from trunks (Nygren  
457 *et al.*, 1993). A new, *Erythrina*-specific tree submodel would be required to model the pollarding response,  
458 possibly based on the earlier work by Nygren *et al.* (1993, 1996). This is considered for future modifications  
459 of the model.

460

## 461 **4.2 Model testing against independent data and sensitivity analysis**

462 Our tests against independent data from three of the climatic zones corroborated that the model behaves well  
463 under different management and biophysical conditions (Fig. 7). The tests were carried out using the posterior  
464 mode from generic calibration; no site-specific information was used to adjust parameter values. Overall, the  
465 comparison of model estimates and production rates at commercial farms showed the same qualities and  
466 defects as the calibration results. The model correctly estimated low production rates, but underestimated high  
467 production rates. It is possible that the control of weeds, pests and diseases as well as the reliability of the data  
468 themselves differed between the experimental calibration sites and the commercial testing sites, but detailed  
469 information on the growing conditions at the commercial farms is lacking. Nevertheless, the model again  
470 ranked high- and low-yielding years for the most part correctly, leading to an  $R^2$  value of 0.55 (Fig. 7). It thus  
471 seems that the alternate bearing pattern of coffee may largely be explained from factors that were present in  
472 the model, i.e. interannual variation in weather conditions and the negative lag-effects of high reproductive  
473 sinks on sink strengths in succeeding years – conform theories of carbon allocation in woody plants (Génard  
474 *et al.*, 2008). The flowering date, the modelling of which was modified in CAF2014, also affects the balance  
475 between the sources and sinks of carbohydrates, as allocation patterns change dramatically after flowering. We  
476 note however that our new implementation of biennial sink patterns was not highly mechanistic, so there  
477 remains significant scope for model improvement. This is complicated because of the difficulty of measuring  
478 sink strength directly and because of the complicated interannual dynamics of reserves in perennial woody  
479 plants. It does constitute an important research question because alternate bearing is a phenomenon common  
480 to a large number of species of fruit trees (Monselise and Goldschmidt, 1982). In future model development,  
481 CAF2014 may benefit from incorporating the equations of Rodriguez *et al.* (2011) for the dynamics of cohorts  
482 of reproductive organs and reserve compartment, as was done by Vezy *et al.* (2020) in their DynACof model.  
483 That would constitute a more mechanistic simulation of sink competition between leaf and reproductive  
484 compartments than we attempted here, but it would increase model complexity. Moreover, the method still  
485 needs independent testing across sites in multiple climatic zones (only one site was used by Vezy *et al.* 2020)  
486 and Bayesian multi-site calibration following the approach that we developed here.

487

488 Our findings suggest that our model can be used in Central America, because the calibrations at experimental  
489 sites exhibited a good and relatively robust fit, which was confirmed through validation. Moreover, the  
490 sensitivity analysis provided plausible conclusions with respect to management: least yield loss from shading  
491 at low altitude ((Table 5) and little benefit from fertilizer above 200 kg N ha<sup>-1</sup> y<sup>-1</sup>, both of which are consistent  
492 with the literature (e.g. Beer et al. 1998, Meylan et al. 2017). The calibrated model may thus become a useful  
493 tool for various stakeholders, such as farms and policymakers, to support decisions regarding issues like  
494 climate change, fertilization efficiency, use of tree species for shade, and other management practices. The  
495 model can also provide estimates of other ecosystem services, including water-, carbon- and nitrogen-retention,  
496 but the quality of model predictions for those variables requires additional data to allow further testing of the  
497 model beyond the yield estimates that we focused on here.

498

## 499 **5. Conclusions**

500 We were able to calibrate the CAF2014 coffee agroforestry model for farms in Costa Rica and Nicaragua that  
501 span different climatic zones, soils, shading practices and management conditions. Interannual variability was  
502 well accounted for by the model. Whereas simulation of coffee production (t DM cherry ha<sup>-1</sup> year<sup>-1</sup>) using the  
503 original model underestimated production, the modified and calibrated model showed realistic production  
504 rates, decreasing RMSE and increasing R<sup>2</sup>. Simulations were improved for coffee production in three climatic  
505 zones, including one that had not been included for calibration. However, the model still underestimates very  
506 high production rates at some sites. Coffee models implemented thus far have allowed providing an assessment  
507 of the niche-range over which the species is distributed and comparing the ability of crops to face climate  
508 changes in the future. The calibrated CAF2014 model makes it possible to simulate coffee production yields  
509 in agroforestry systems, thus enabling estimates of the costs and benefits of implementing the system as well  
510 as the impacts of climate change, elevated CO<sub>2</sub>, fertilization and pruning of coffee plants and trees - estimates  
511 that empirical suitability models are not able to provide (Ovalle-Rivera *et al.*, 2015). The model may thus be  
512 used as a tool for exploring different adaptation scenarios in the face of current and future problems of coffee

513 growers, as shown in our preliminary study of the effects of N fertilizer and shade in different locations on  
514 coffee productivity.

515

516

## 517 **References**

518 Beer, J., Muschler, R., Kass, D., Somarriba, E., 1998. Shade management in coffee and cacao plantations. *Agrofor. Syst.*  
519 38, 139–164.

520 Bunn C, Läderach P, Ovalle Rivera O, Kirschke D, 2014. A bitter cup: climate change profile of global production of  
521 Arabica and Robusta coffee. *Climatic Change* 129: 89–101 DOI 10.1007/s10584-014-1306-x

522 Carberry, P., Gladwin, C., Twomlow, S., 2004. Linking simulation modelling to participatory research in smallholder  
523 farming systems. In: Delve, R.J., Probert, M.E. (Eds.), *Modelling nutrient management in tropical cropping*  
524 *systems*. ACIAR Proceedings No. 114, pp. 32-46.

525 Carvalho, H.F., Galli, G., Ferrao, L.F.V., Nonato, J.V.A., Padilha, L., Maluf, M.P., de Resende Jr, M.F.R., Guerreiro  
526 Filho, O., Fritsche-Neto, R., 2020. The effect of bienniality on genomic prediction of yield in arabica coffee.  
527 *Euphytica* 216, 101: 1-16.

528 Cerda, R., Deheuvels, O., Calvache, D., Niehaus, L., Saenz, Y., Kent, J., Vilchez, S., Villota, A., Martinez, C., Somarriba,  
529 E., 2014. Contribution of cocoa agroforestry systems to family income and domestic consumption: looking  
530 toward intensification. *Agrofor Syst* 88, 957-981.

531 Charbonnier, F., 2013. *Mesure et modélisation des bilans de lumière, d'eau, de carbone et de productivité primaire nette*  
532 *dans un système agroforestier à base de caféier au Costa Rica*. Université de Lorraine, Nancy, France, p. 230.

533 Charbonnier, F., Roupsard, O., le Maire, G., Guillemot, J., Casanoves, F., Lacoïnte, A., Vaast, P., Allinne, C., Audebert,  
534 L., Cambou, A., Clement-Vidal, A., Defrenet, E., Duursma, R.A., Jarri, L., Jourdan, C., Khac, E., Leandro, P.,  
535 Medlyn, B.E., Saint-Andre, L., Thaler, P., Van den Meersche, K., Aguilar, A.B., Lehner, P., Dreyer, E., 2017.  
536 Increased light-use efficiency sustains net primary productivity of shaded coffee plants in agroforestry system.  
537 *Plant Cell and Environment* 40, 1592-1608.

538 De Beenhouwer, M., Aerts, R., Honnay, O., 2013. A global meta-analysis of the biodiversity and ecosystem service  
539 benefits of coffee and cacao agroforestry. *Agr Ecosyst Environ* 175, 1-7.

540 de Wit, C.T., 1965. *Photosynthesis of leaf canopies*. Agricultural Research Report, 663. Wageningen University,  
541 Wageningen.

542 Dogliotti, S., van Ittersum, M.K., Rossing, W.A.H., 2005. A method for exploring sustainable development options at  
543 farm scale: a case study for vegetable farms in South Uruguay. *Agr Syst* 86, 29-51.

544 Gagliardi, S., Martin, A.R., Virginio Filho, E.d.M., Rapidel, B., Isaac, M.E., 2015. Intraspecific variation in leaf traits  
545 along a shade tree biodiversity gradient in coffee (*Coffea arabica*) agroforestry systems of Costa Rica. *Agr*  
546 *Ecosyst Environ* 200, 151-160.

547 Génard, M., Dauzat, J., Franck, N., Lescourret, F., Moitrier, N., Vaast, P., Vercambre, G., 2008. Carbon allocation in fruit  
548 trees: from theory to modelling. *Trees* 22, 269-282.

549 Hagggar, J., Barrios, M., Bolaños, M., Merlo, M., Moraga, P., Munguia, M., Ponce, A., Romero, S., Soto, G., Staver, C.,  
550 Virginio, E., 2011. Coffee agroecosystem performance under full sun, shade, conventional and organic  
551 management regimes in Central America. *Agrofor Syst* 82, 285-301.

552 Hernandez, R.R., Debenport, S.J., Leewis, M., Ndoeye, F., Nkenmogne, K.I.E., Soumare, A., Thuita, M., Gueye, M.,  
553 Miambi, E., Chapuis-Lardy, L., Diedhiou, I., Dick, R.P., 2015. The native shrub, *Piliostigma reticulatum*, as an  
554 ecological "resource island" for mango trees in the Sahel. *Agriculture Ecosystems & Environment* 204, 51-61.

555 Höglind, M., Cameron, D., Persson, T., Huang, X., Van Oijen, M. 2020. BASGRA\_N: A model for grassland  
556 productivity, quality and greenhouse gas balance. *Ecological Modelling* 417: 108925.  
557 <https://doi.org/10.1016/j.ecolmodel.2019.108925>.

558 Imbach, A., Fassbender, H., Beer, J., Borel, R., Bonnemann, A., 1989. Sistemas agroforestales de Café (*Coffea arabica*)  
559 con Laurel (*Cordia Alliodora*) y Café con Poro (*Erythrina poeppigiana*) en Turrialba, Costa Rica. VI. Balances  
560 hidricos e ingreso con lluvias y lixiviacion de elementos nutritivos. *Turrialba* 39, 400-414.

561 Jha, S., Bacon, C.M., Philpott, S.M., Mendez, V.E., Laderach, P., Rice, R.A., 2014. Shade coffee: Update on a  
562 disappearing refuge for biodiversity. *BioScience* 64, 416-428.

563 Jose, S., 2009. Agroforestry for ecosystem services and environmental benefits: An overview. *Agrofor Syst* 76, 1-10.

564 Kennedy, M.C., O'Hagan, A. 2001. Bayesian calibration of computer models. *Journal of the Royal Statistical Society:*  
565 *Series B (Statistical Methodology)* 63: 425-64.

566 Kizito, F., Dragila, M.I., Sene, M., Brooks, J.R., Meinzer, F.C., Diedhiou, I., Diouf, M., Lufafa, A., Dick, R.P., Selker,  
567 J., Cuenca, R., 2012. Hydraulic redistribution by two semi-arid shrub species: Implications for Sahelian agro-  
568 ecosystems. *J Arid Environ* 83, 69-77.

569 Läderach, P., Ramirez-Villegas, J., Navarro-Racines, C., Zelaya1, C., Martinez-Valle, A., Jarvis, A., 2017. Climate  
570 change adaptation of coffee production in space and time. *Clim. Ch.* 141: 47-62.



571 Meylan, L., 2012. Design of cropping systems combining production and ecosystem services: developing a methodology  
572 combining numerical modeling and participation of farmers. *Fonctionnement des Ecosystèmes Naturels et*  
573 *Cultivés*. Montpellier Supagro, Montpellier, p. 145.

574 Meylan, L., Gary, C., Allinne, C., Ortiz, J., Jackson, L., Rapidel, B. 2017. Evaluating the effect of shade trees on provision  
575 of ecosystem services in intensively managed coffee plantations. *Agric Ecosys Env* 245: 32-42.

576 Meylan, L., Merot, A., Gary, C., Rapidel, B., 2013. Combining a typology and a conceptual model of cropping system to  
577 explore the diversity of relationships between ecosystem services: The case of erosion control in coffee-based  
578 agroforestry systems in Costa Rica. *Agr Syst* 118, 52-64.

579 Meylan, L., Sibelet, N., Gary, C., Rapidel, B., 2014. Combining a numerical model with farmer participation for the  
580 design of sustainable and practical agroforestry systems. IIIrd World Congress of Agroforestry. ICRAF, Delhi,  
581 India, 10-14 Feb 2014.

582 Monselise, S.P., Goldschmidt, E.E., 1982. Alternate bearing in fruit trees. *Horticultural Reviews*. John Wiley & Sons,  
583 Inc., pp. 128-173.

584 Nygren, P., Kiema, P., Rebottaro, S., 1996. Canopy development, CO<sub>2</sub> exchange and carbon balance of a modeled  
585 agroforestry tree. *Tree Physiol* 16, 733-745.

586 Nygren, P., Rebottaro, S., Chavarria, R., 1993. Application of the pipe model-theory to nondestructive estimation of leaf  
587 biomass and leaf-area of pruned agroforestry trees. *Agrofor Syst* 23, 63-77.

588 Ovalle-Rivera, O., Läderach, P., Bunn, C., Obersteiner, M., Schroth, G., 2015. Projected shifts in *Coffea arabica*  
589 suitability among major global producing regions due to climate change. *PLoS ONE* 10, e0124155.

590 Padovan, M.P., Cortez, V.J., Navarrete, L.F., Navarrete, E.D., Barrios, M., Munguía, R., Centeno, L.G., Deffner, A.C.,  
591 Vílchez, J.S., Vega, C., Costa, A.N., Brook, R.M., Rapidel, B., 2015. Root distribution and water use in a coffee  
592 shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* DC. compared to full sun coffee in sub-optimal  
593 environmental conditions. *Agrofor Syst* 89, 857-868.

594 Rahn E et al., Vaast, P., Läderach, P., van Asten, P., Jassogne, L., Ghazoul, J. 2018 Exploring adaptation strategies of  
595 coffee production to climate change using a process-based model. *Ecol Model* 371:76–89.

596 Reinds, G.J., Van Oijen, M., Heuvelink, G.B.M., Kros, H., 2008. Bayesian calibration of the VSD soil acidification model  
597 using European forest monitoring data. *Geoderma* 146, 475-488.

598 Remal, S., 2009. Conceptual and numerical evaluation of a plot scale, process-based model of coffee agroforestry systems  
599 in Central America: CAF2007. *Production Végétales Durables*. SupAgro, Montpellier, p. 40.

600 Rodríguez, D., Cure, J.R., Cotes, J.M., Gutierrez, A.P., Cantor, F., 2011. A coffee agroecosystem model: I. Growth and  
601 development of the coffee plant. *Ecol Model* 222, 3626-3639.

602 Rouspard, O., Ferhi, A., Granier, A., Pallo, F., Depommier, D., Mallet, B., Joly, H.I., Dreyer, E., 1999. Reverse phenology  
603 and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese west  
604 Africa. *Funct Ecol* 13, 460-472.

605 Sousa, T.V., Caixeta, E.T., Alkimim, E.R., de Oliveira, A.C.B., Pereira, A.A., Zambolim, L., Sakiyama, N.S., 2017.  
606 Molecular markers useful to discriminate *Coffea arabica* cultivars with high genetic similarity. *Euphytica* 213,  
607 75: 1-15.

608 Taugourdeau, S., le Maire, G., Avelino, J., Jones, J.R., Ramirez, L.G., Quesada, M.J., Charbonnier, F., Gómez-Delgado,  
609 F., Harmand, J.-M., Rapidel, B., Vaast, P., Rouspard, O., 2014. Leaf area index as an indicator of ecosystem  
610 services and management practices: an application for coffee agroforestry. *Agr Ecosyst Environ* 192, 19-37.

611 Vaast, P., Harmand, J.-M., Rapidel, B., Jagoret, P., Deheuvels, O., 2015. Coffee and cocoa production in agroforestry—  
612 A climate-smart agriculture model. In: Torquebiau, E. (Ed.), *Climate Change and Agriculture Worldwide*.  
613 Editions Quae, Paris, France, pp. 209-224.

614 Van Noordwijk, M., Lawson, G., Soumaré, A., Groot, J.J.R., Hairiah, K., 1996. Root distribution of trees and crops:  
615 competition and/or complementarity. In: Ong, C.K., Huxley, P.W. (Eds.), *Tree-Crop Interactions: A*  
616 *Physiological Approach*. CAB International, Wallingford, UK, pp. 319-364.

617 Van Noordwijk, M., Lusiana, B., 1998. WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems.  
618 *Agrofor Syst* 43, 217-242.

619 Van Oijen, M., 2017. Bayesian methods for quantifying and reducing uncertainty and error in forest models. *Current*  
620 *Forestry Reports* 3: 269-280. <https://doi.org/10.1007/s40725-017-0069-9> .

621 Van Oijen, M., Dausat, J., Harmand, J.-M., Lawson, G., Vaast, P., 2010a. Coffee agroforestry systems in Central America:  
622 I. A review of quantitative information on physiological and ecological processes. *Agrofor Syst* 80, 341-359.

623 Van Oijen, M., Dausat, J., Harmand, J.-M., Lawson, G., Vaast, P., 2010b. Coffee agroforestry systems in Central  
624 America: II. Development of a simple process-based model and preliminary results. *Agrofor Syst* 80, 361-378.

625 Van Oijen, M., Reyer, C., Bohn, F.J., Cameron, D.R., Deckmyn, G., Flechsig, M., Härkönen, S., Hartig, F., Huth, A.,  
626 Kiviste, A., Lasch, P., Mäkelä, A., Mette, T., Minunno F., Rammer, W. 2013. Bayesian calibration, comparison  
627 and averaging of six forest models, using data from Scots pine stands across Europe. *Forest Ecology and*  
628 *Management* 289: 255–68. <https://doi.org/10.1016/j.foreco.2012.09.043> .

- 629 Van Oijen, M., Rougier, J., Smith, R., 2005. Bayesian calibration of process-based forest models: bridging the gap  
630 between models and data. *Tree Physiol* 25, 915-927.
- 631 Vezy, R., le Maire, G., Christina, M., Georgiou, S., Imbach, P., Hidalgo, H.G., Alfaro, E.J., Blitz-Frayret, C., Charbonnier,  
632 F., Lehner, P., Loustau, D., Rouspard, O., 2020. DynACof: A process-based model to study growth, yield and  
633 ecosystem services of coffee agroforestry systems. *Environmental Modelling & Software* 124, 104609.
- 634 Villatoro-Sánchez, M., Le Bissonnais, Y., Moussa, R., Rapidel, B., 2015. Temporal dynamics of runoff and soil loss on  
635 a plot scale under a coffee plantation on steep soil (Ultisol), Costa Rica. *J Hydrol* 523, 409-426.
- 636 Whitbread, A., Robertson, M.J., Carberry, P.S., Dimes, J.P., 2010. Farming systems simulation can aid the development  
637 of more sustainable smallholder farming systems in Southern Africa. *Eur J Agron* 32, 51-58.
- 638 Yelemou, B., Dayamba, S.D., Bambara, D., Yameogo, G., Assimi, S., 2013. Soil carbon and nitrogen dynamics linked to  
639 *Piliostigma* species in ferugino-tropical soils in the Sudano-Sahelian zone of Burkina Faso, West Africa. *Journal*  
640 *of Forestry Research* 24, 99-108.
- 641 Zuidema, P.A., Leffelaar, P.A., Gerritsma, W., Mommer, L., Anten, N.P.R., 2005. A physiological production model for  
642 cocoa (*Theobroma cacao*): model presentation, validation and application. *Agr Syst* 84, 195-225.

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Table 1. Sites used for model calibration: Turrialba (9.8962N; 83.6673W, 610 masl), Aquiares (9.9383N; 83.7279W, 1100 masl) and Llano Bonito (9.6707N; 84.0951W, 1620 masl) in Costa Rica, and Masatepe (11.9008N; 86.1461W, 467 masl) in Nicaragua.

Site	Climatic zone	Shade	Fertilization (kg N ha <sup>-1</sup> y <sup>-1</sup> )	Shade tree pruning	Annual shade tree thinning
Turrialba-1	3	<i>Terminalia amazonia</i>	280	Regulated	80%
Turrialba-2	3	<i>Terminalia amazonia</i>	150	Regulated	80%
Turrialba-3	3	<i>Erythrina poeppigiana</i>	280	Drastic	50%
Turrialba-4	3	<i>Erythrina poeppigiana</i>	150	Regulated	50%
Turrialba-5	3	Full sun	280	-	-
Turrialba-6	3	Full sun	150	-	-
Aquiares	3	<i>Erythrina poeppigiana</i>	260	Unregulated	Without
Llano Bonito	2	Mainly <i>E. poeppigiana</i>	300	Regulated	20%
Masatepe-1	4	Mainly <i>Inga edulis</i>	144	Regulated	61%
Masatepe-2	4	Mainly <i>Inga edulis</i>	73	Regulated	66%
Masatepe-3	4	Full sun	144	-	-
Masatepe-4	4	Full sun	73	-	-

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Table 2. Output variables for calibration of the CAF2014 model. The frequency indicates the percentage of sites where a variable was measured.

Variable	Identifier	Unit	Frequency
Average content of C in the soil	Csoilave	t C ha <sup>-1</sup>	92%
Average leaf area index of coffee trees	LAIave	m <sup>2</sup> m <sup>-2</sup>	17%
Average leaf area index of shade trees	LAIT	m <sup>2</sup> m <sup>-2</sup>	17%
C in the above-ground portion of coffee plants	CT	kg C m <sup>-2</sup>	50%
C in the above-ground portion of shade trees	CTT	kg C m <sup>-2</sup>	50%
C in coffee leaves in full sun	CL(1)	kg C m <sup>-2</sup>	8%
C in coffee leaves in the shade.	CL(2)	kg C m <sup>-2</sup>	8%
C in coffee trunks in full sun	CW(1)	kg C m <sup>-2</sup>	8%
C in coffee trunks in the shade	CW(2)	kg C m <sup>-2</sup>	8%
Coffee productivity *	harvDMav_year	t DM ha <sup>-1</sup> y <sup>-1</sup>	100%
Leaf area index in full sun	LAI(1)	m <sup>2</sup> m <sup>-2</sup>	8%
Leaf area index in the shade	LAI(2)	m <sup>2</sup> m <sup>-2</sup>	8%
N in the soil	Nsoilave	t N ha <sup>-1</sup>	75%
Shade area	SA	m <sup>2</sup> m <sup>-2</sup>	50%
Tree crown area	CAtree	m <sup>2</sup>	17%
Tree height	h	m	33%
Water content in the soil	WC_F	m <sup>3</sup> H <sub>2</sub> O m <sup>-3</sup>	25%

\* split into "under the sun" and "in the shade" at Llano Bonito

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661 Table 3. Coffee-growing farms in three climatic zones in Nicaragua used for validating the CAF2014 model.

Climatic zone	Farm	Coordinates / Altitude (masl)	Main shade sp.	Soil fertilization (kg N ha <sup>-1</sup> )	Shade tree pruning*	Shade tree thinning**
1	Hammonia	12.99N 85.92W / 1237	guaba	80	Once	No
1	La Pinedita	12.92N 85.90W / 917	guaba	116	None	50%
2	Solingalpa	13.03N 85,91W / 1368	guaba	182	10%	60%
4	El Rosal	11.88N 86.20W / 588	Erythrina	136	10%	50%

662 Selective coffee tree pruning \* Fraction for each tree pruning \*\* Fraction of thinning

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670 Table 4. Average production (10-11 years) in t DM ha<sup>-1</sup> y<sup>-1</sup> for calibration sites in Turrialba, Costa Rica, and in Masatepe, Nicaragua.

Site	Measured production	Simulated production (Single-site calibration)	<i>p-value</i>	Simulated production (Cluster calibration )	<i>p-value</i>	Simulated production (Generic calibration)	<i>p-value</i>
Turrialba-1	2.25	2.22	0.94	2.19	0.91	1.68	0.25
Turrialba-2	1.58	1.73	0.73	1.56	0.98	1.53	0.92
Turrialba-3	3.03	2.82	0.81	2.88	0.70	2.53	0.36
Turrialba-4	1.90	2.31	0.33	2.68	0.14	2.33	0.33
Turrialba-5	3.53	3.22	0.65	2.47	0.13	2.60	0.16
Turrialba-6	2.87	3.27	0.53	2.47	0.54	2.57	0.63
Masatepe-1	1.59	1.29	0.4	1.19	0.23	1.40	0.25
Masatepe-2	1.47	1.24	0.49	1.25	0.51	1.26	0.92
Masatepe-3	2.28	1.55	0.14	1.26	<b>0.045</b>	1.31	<b>0.05</b>
Masatepe-4	1.78	1.55	0.51	1.30	0.18	1.31	0.198

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678 Table 5. Effect of shade on coffee production at three different altitudes with fertilization fractionated in three doses of 150 kg N ha<sup>-1</sup>  
 679 y<sup>-1</sup>.

Altitude (m above sea level)	Site	Production average over 11 years (t DM ha <sup>-1</sup> y <sup>-1</sup> )	
		Sun	Shade/ <i>Inga edulis</i>
453	Masatepe	1.61	1.68 (42% shade)
600	Turrialba	3.00	2.70 (53% shade)
1620	Llano Bonito	3.16	2.47 (56% shade)

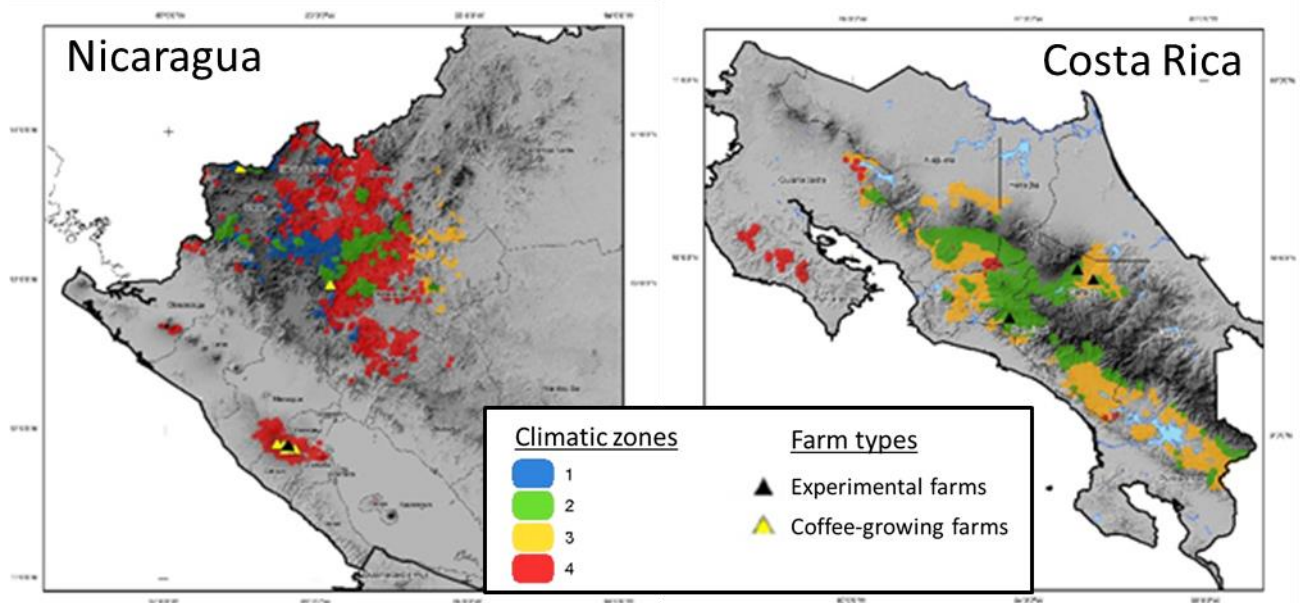
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Table 6. Effect on coffee production of fertilization in different fractions and at different doses for Turrialba and Masatepe.

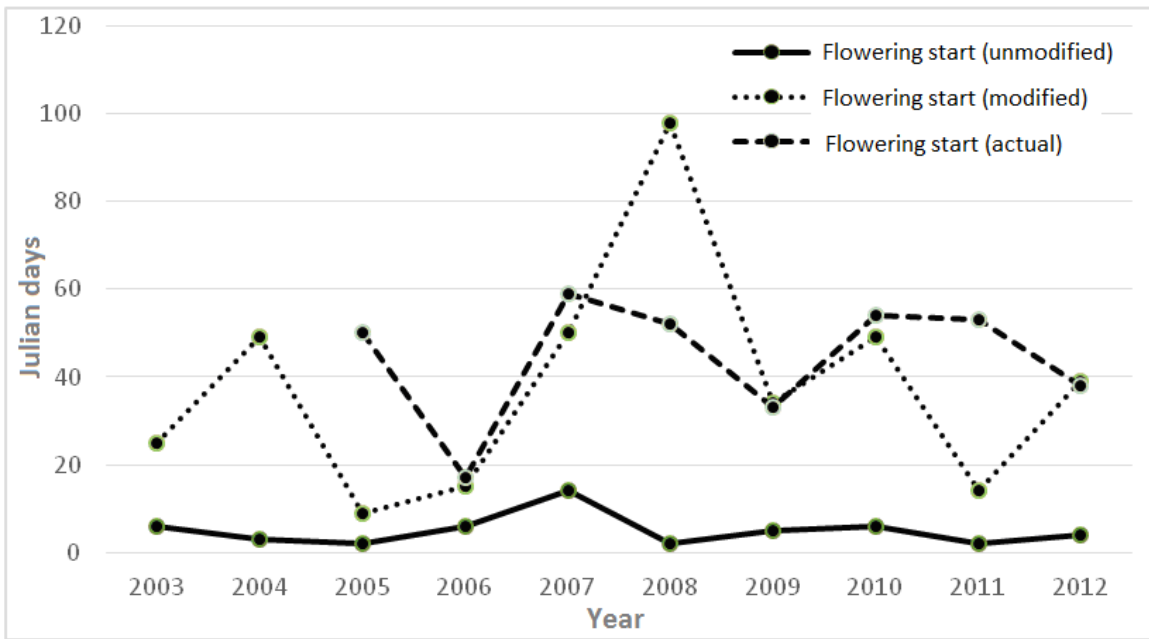
Dose (kg N ha <sup>-1</sup> y <sup>-1</sup> )	Fractionation (day of year)	Production average over 11 years (t DM ha <sup>-1</sup> y <sup>-1</sup> )		
		Turrialba		Masatepe
		Full sun	Erythrina trees	Full sun
50	(135,289,350) Turrialba (185, 256, 276) Masatepe	2.61	2.52	1.46
100		2.85	2.73	1.54
200		3.09	2.90	1.66
300		3.17	2.97	1.73
400		3.20	2.95	1.76
300	(135,289) Turrialba (165,275) Masatepe	3.09	2.92	1.72
	(135,289,350) Turrialba (185,256,276) Masatepe	3.17	2.97	1.73
	(135,210,289,350) Turrialba (165,215,275,300) Masatepe	3.17	2.94	1.73

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Figure 1. The coffee growing regions of Nicaragua and Costa Rica. Four climatic zones: 1 = cold and dry; 2 = cold and humid ; 3 = hot and humid; 4 = hot and dry. Triangles indicate the experimental and coffee-growing farms from which data were used for model simulations.

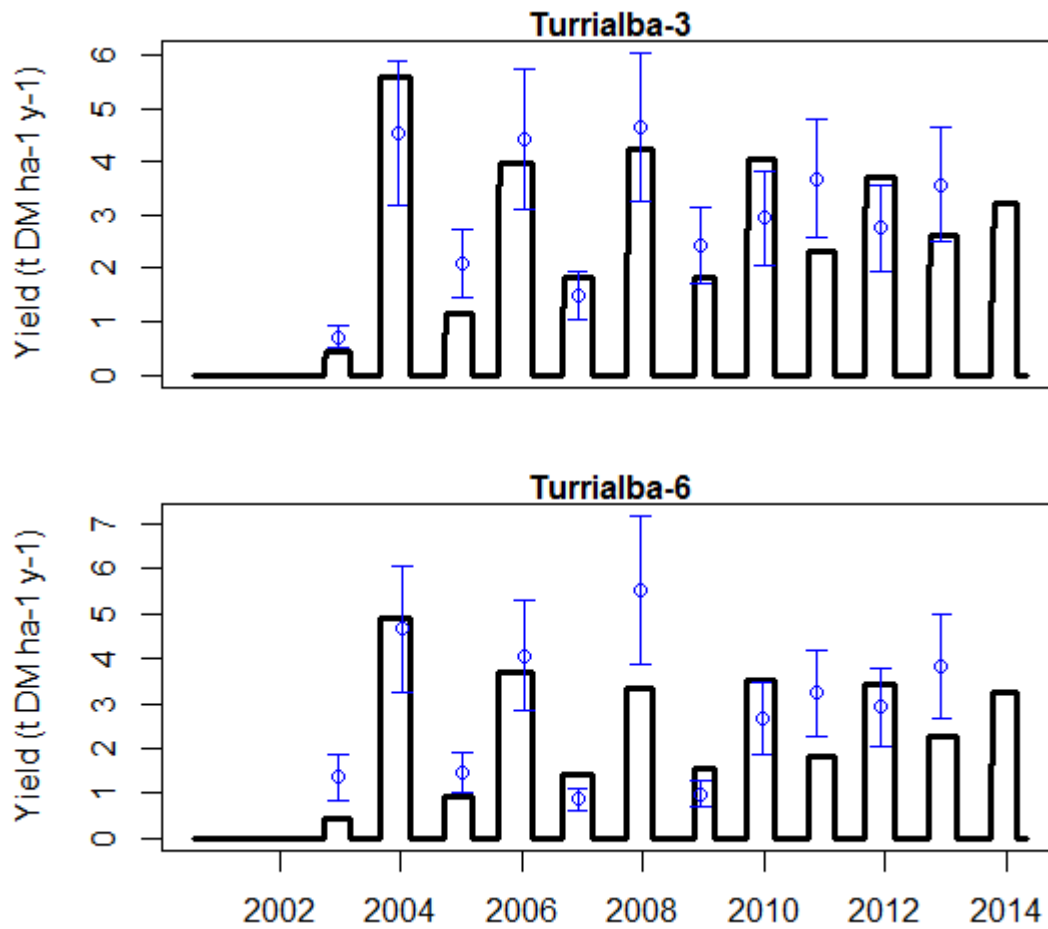


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705 Figure 2. Start date of flowering simulated with the original unmodified model, the modified model (CAF2014)  
 706 and actually observed flowering in Turrialba, Costa Rica.

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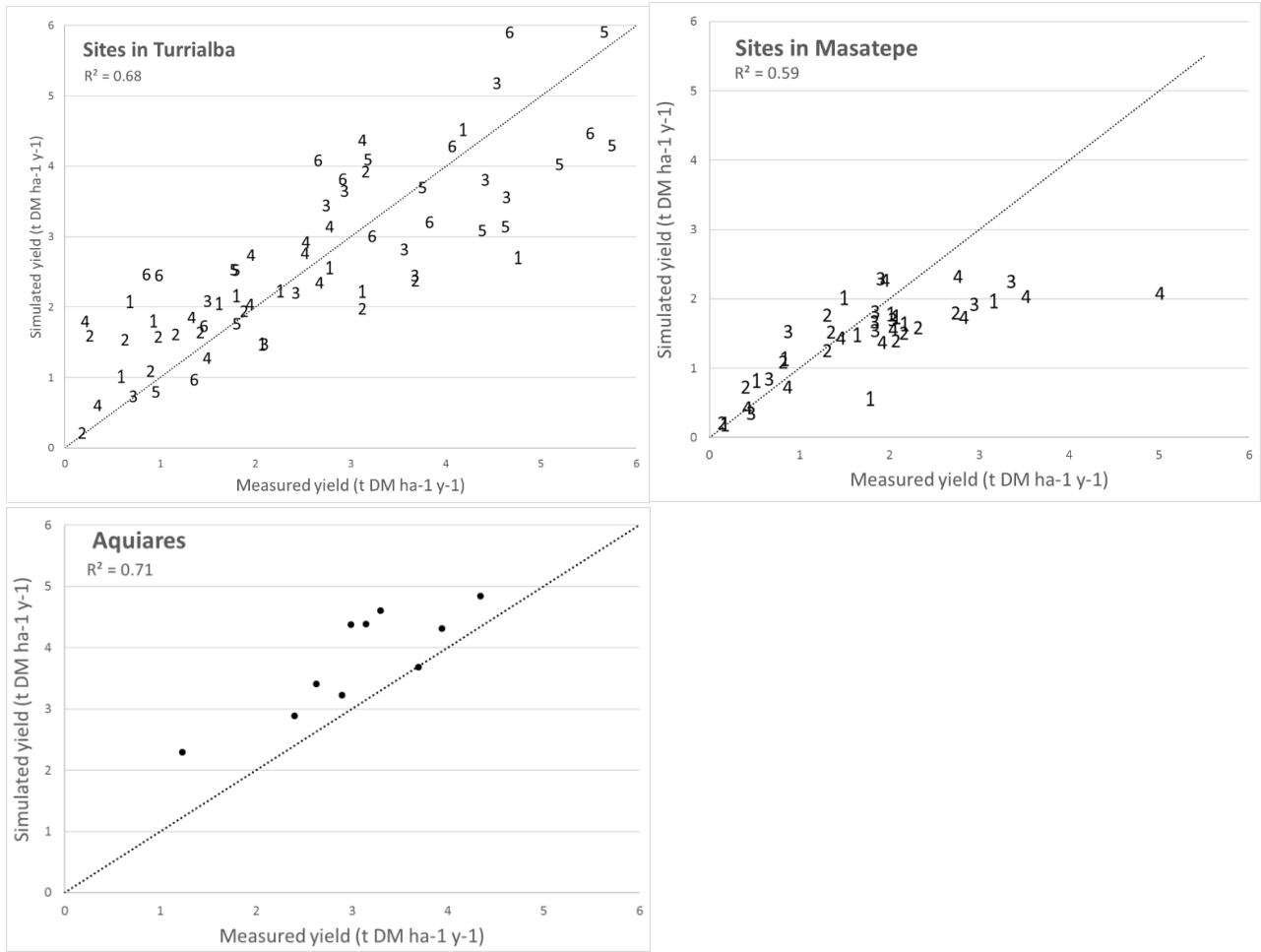


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710 Figure 3. Coffee production at two sites in Costa Rica. Fertilization rate was high in Turrialba-3 (280 kg N  
711 ha<sup>-1</sup> y<sup>-1</sup>) and intermediate in Turrialba-6 (150 kg N ha<sup>-1</sup> y<sup>-1</sup>). Blue circles and error bars: measurements. Black  
712 lines: simulations using the posterior mode from cluster calibration, showing cumulative yield within each  
713 calendar year.

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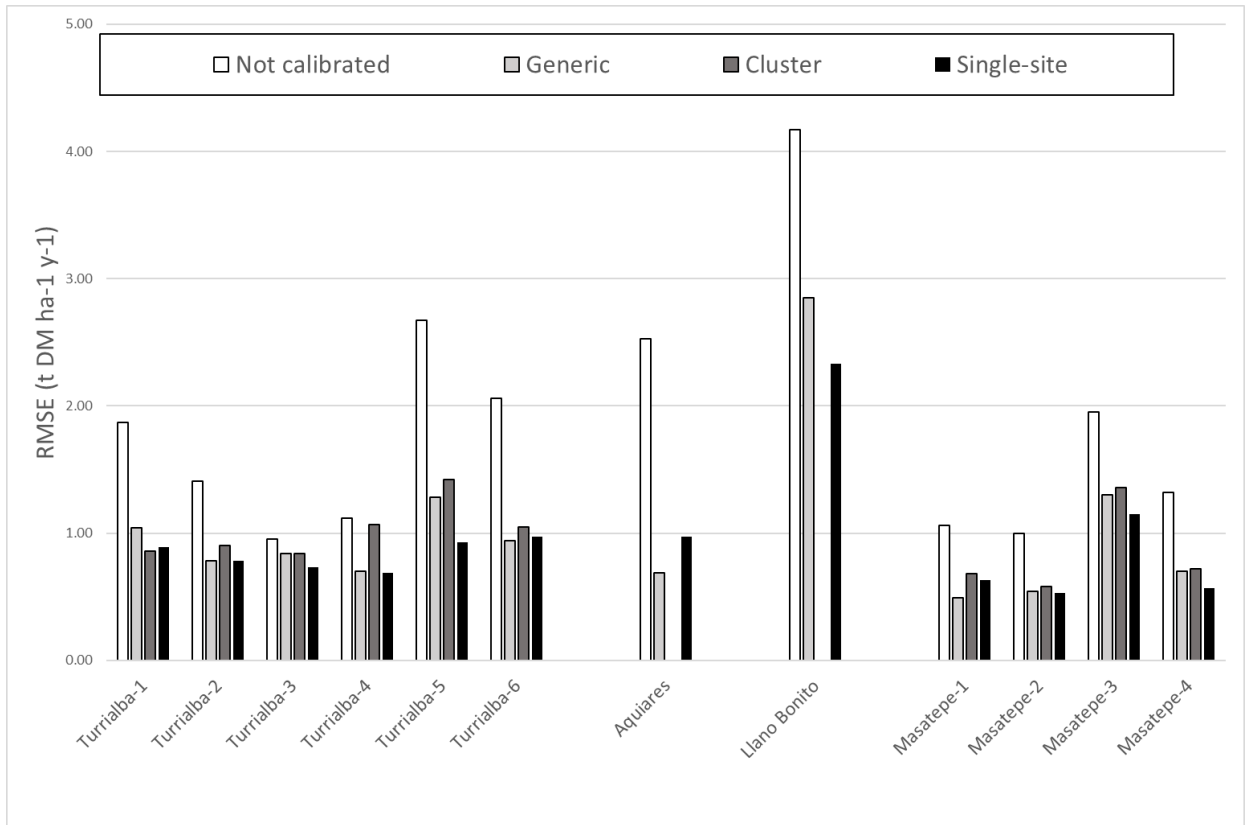


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718 Figure 4. Simulated vs. measured coffee productivity (t DM ha<sup>-1</sup> y<sup>-1</sup>) at each calibrated site. The simulated  
719 yields are from the posterior mode after single-site calibration. The Llano Bonito site is not shown because it  
720 has data for only two years of production. The digits on the top two panels identify the six different sites in  
721 Turrialba and the four sites in Masatepe (see Table 1).

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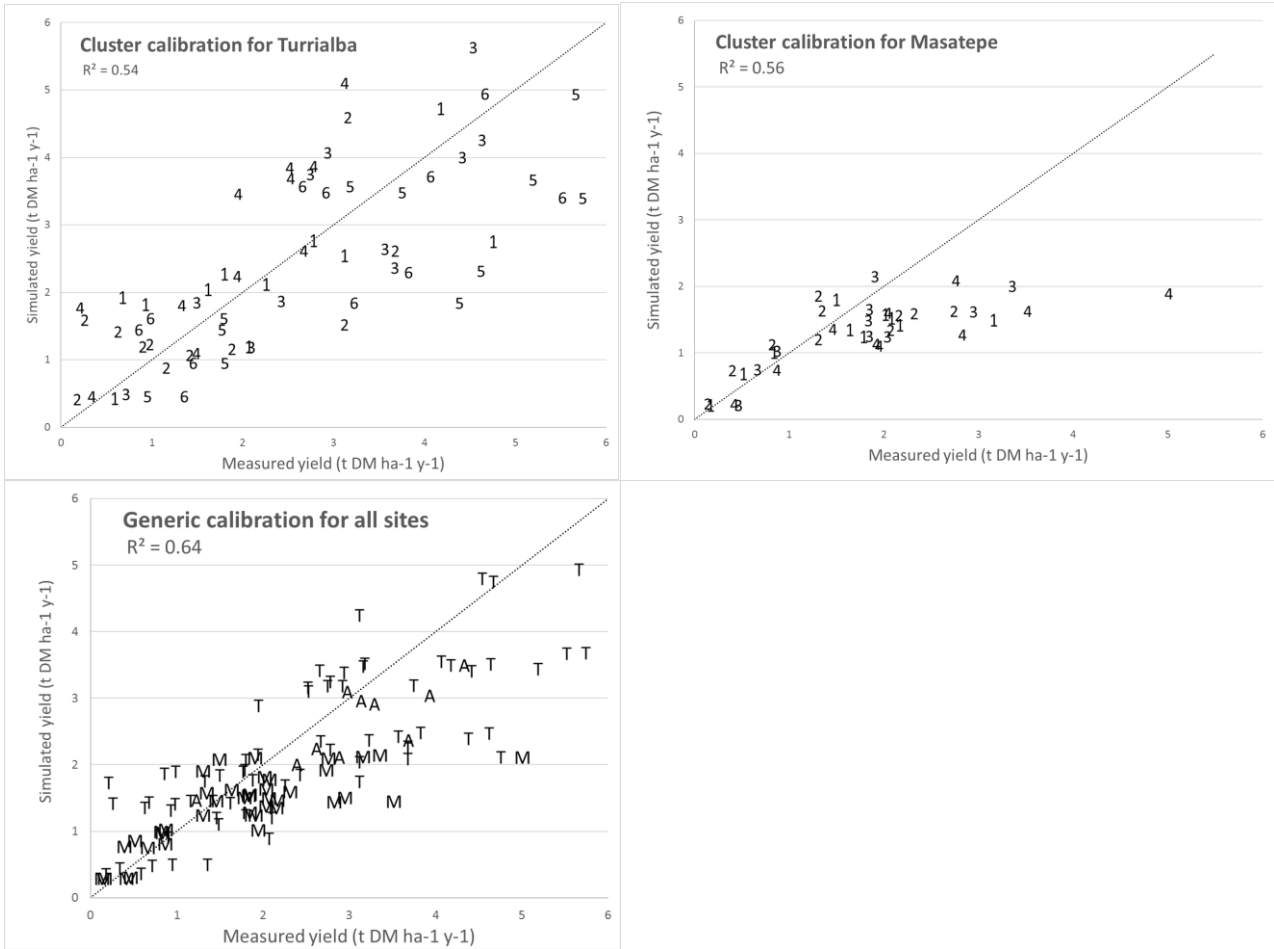


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724 Figure 5. RMSE values for coffee production (t DM ha<sup>-1</sup> y<sup>-1</sup>) from 12 sites after different calibrations in Costa  
 725 Rica and Nicaragua. See Table 1 for details about the sites.

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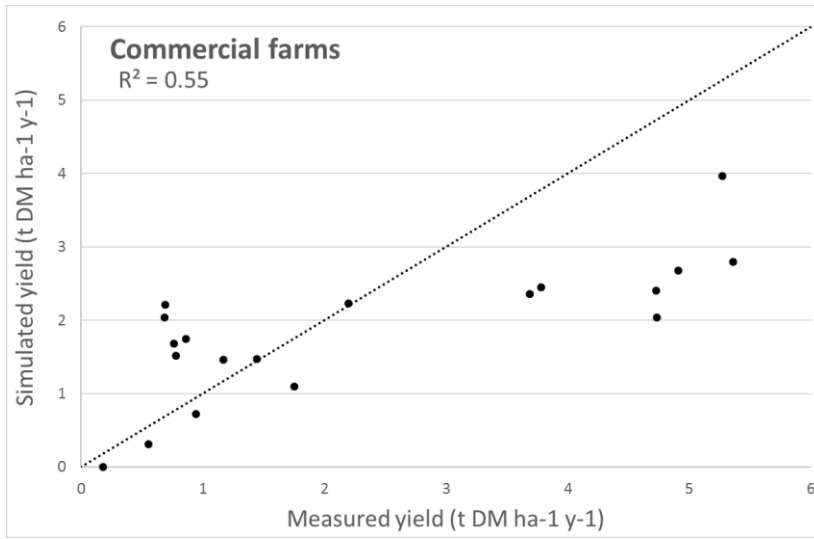


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729 Figure 6. Simulated vs. measured coffee productivity (t DM ha<sup>-1</sup> y<sup>-1</sup>) after two types of multi-site calibration.  
730 Top two panels show results for the posterior mode from cluster calibration, the bottom panel for the posterior  
731 mode from generic calibration. The digits on the top panels identify the six different sites in Turrialba and the  
732 four sites in Masatepe (see Table 1). The letters in the bottom panel identify the Aquiares site and the Turrialba  
733 and Masatepe clusters.

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737 Figure 7. Simulated vs. measured coffee productivity (t DM ha<sup>-1</sup> y<sup>-1</sup>) for commercial farms in Nicaragua.

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