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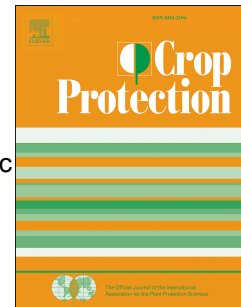
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1 **Coffee agroforestry systems capable of reducing disease-induced yield and economic losses**

2 **while providing multiple ecosystem services**

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24 **Abstract**

25 Crop losses caused by pests and diseases decrease the incomes and threaten the livelihoods of thousands

26 of families worldwide. A good example of the magnitude of these impacts are the massive crop losses

27 experienced by coffee farmers in Central America due to coffee leaf rust. Coffee farmers need

28 agroecosystems that are capable of regulating the negative impacts of pests and diseases while providing

29 other ecosystem services on which their households and society depend. In this study, we aimed to identify

30 the most promising coffee agroforestry systems for regulating diseases and ensuring the provision of other

31 ecosystem services. During two years, in a research network of 61 coffee plots under a wide variety of shade

32 and management conditions in Turrialba, Costa Rica, we quantified primary and secondary coffee losses

33 (yield and economic losses) and indicators of three other ecosystem services: provisioning of agroforestry

34 products (bananas, plantains, other fruits, and timber), maintenance of soil fertility and carbon sequestration.

35 We then performed an analysis of the relationships between losses and ecosystem service indicators. Based

36 on the results of relationships and on three criteria, we identified the coffee agroforestry systems that had the

37 lowest losses due to diseases and that provided desirable levels of agroforestry products, soil fertility and

38 carbon sequestration. We found multiple significant relationships between losses and ecosystem services

39 (including both tradeoffs and synergies) which allowed us to derive recommendations for better management

40 strategies to reduce yield losses. We identified six coffee agroforestry systems (CAFs) as the most promising

41 ones for reducing losses while simultaneously providing other ecosystem services. One of these CAFs was a

42 simple agroforestry system (dominated by service trees), three were medium diversified CAFs and two were

43 highly diversified CAFs (systems including service trees, timber trees, fruit trees and musaceas). The six

44 CAFS differed in their cropping practices and farmer profitability objectives. The six CAFs offer several

45 options for the design of new coffee plantations or for the transformation of existing plantations. Several of

46 this promising CAFs use little fungicides, which is an indicator that the reduction of chemical inputs could be

47 possible. Our results suggest that the regulation of diseases and associated losses in agroforestry systems

48 should be based on, and take advantage of, the positive effects of plant biodiversity, adequate shade cover,

49 good soil fertility, and minimal use of fungicides.

51 **1.   Introduction**

52   Regulation of pests and diseases is an important ecosystem service worldwide. Pests and diseases cause

53   severe crop losses, threatening agricultural production and reducing the food security and incomes of farmers

54   (Oerke et al., 1994; Oerke, 2006). In the countries of Central America in 2011–2012, an outbreak of coffee

55   leaf rust, due to the pathogen *Hemileia vastatrix*, along with suboptimal cropping practices, caused significant

56   yield losses leading to an average yield reduction of 20% in the following years. Since then, coffee production

57   in the region has continued to be low (Cerda et al., 2017b).

58   Injury profiles, i.e. a given combination of injury levels caused by a range of diseases and pests (Savary et

59   al., 2006), can differ dramatically according to crop systems in terms of encountered injuries and the levels

60   they reach. A specific crop system can help regulate some diseases but promote others. In coffee systems,

61   for instance, it is known that full-sun crops are more prone to coffee berry disease (*Colletotrichum kahawae)*;

62   branch dieback, a syndrome exacerbated by *Colletotrichum* fungi; brown eye spot (*Cercospora coffeicola)*,

63   and Phoma leaf blight (*Phoma costarricensis*). In contrast, shaded coffee systems are deemed prone to

64   coffee leaf rust (*Hemileia vastatrix*), American leaf spot disease (*Mycena citricolor*), coffee wilt disease

65   (*Fusarium xylarioides*) and thread blight (*Corticium koleroga*) (Avelino et al., 2011; Avelino et al., 2018).

66   Quantifying the overall pest and disease regulation service within coffee systems is therefore difficult;

67   however, valuing this service can be achieved through crop loss assessments (Avelino et al., 2011; Cerda et

68   al., 2017a; Avelino et al., 2018). Crop systems that help reduce crop losses due to pests and diseases are

69   those that will be of interest to farmers, even if some pests and diseases are present.

70   Crop losses due to pests and diseases include losses in quantity and/or quality of the crop product (Oerke,

71   2006), normally resulting in economic losses (Nutter et al., 1993). Both primary and secondary crop losses

72   should be considered. Primary crop losses are those caused in the specific year when pest and disease

73   injuries occur, while secondary crop losses are those resulting from negative impacts of these pests and

74   diseases in subsequent years (Zadoks and Schein, 1979; Avelino et al., 2015). For instance, foliar diseases

75   in coffee cause defoliation and death of branches that will no longer bear fruits, leading to secondary losses.

76 A recent study on coffee has shown that the secondary yield losses (38%) can be higher and therefore more

77 important than primary yield losses (26%) caused by foliar pests and diseases (Cerda et al., 2017b). Since

78 coffee has a biennial production rhythm characterized by a repetitive cycle of high production one year and

79 low production the following year (DaMatta et al., 2007), the interaction between the biennial behavior of

80 production and pests and diseases impacts on coffee yield can lead to strong economic fluctuation and

81 instability for coffee farmers. The main coffee diseases to consider in Latin America and the Caribbean are

82 coffee leaf rust (*H. vastatrix*), American leaf spot (*Mycena citricolor*), brown eye spot (*Cercospora coffeicola*)

83 and anthracnose (*Colletotrichum gloeosporioides*); ultimately branch dieback must be considered, which is

84 itself aggravated by a complex of opportunistic fungi.

85 Given such a problematic scenario, combating coffee diseases is a priority for governments and private

86 sectors in the Latin American and Caribbean region. There is a need to better understand how different

87 management practices and the agroecosystem structure influence crop losses. Coffee is produced under a

88 wide variety of different conditions with different levels of management intensity. There are coffee plantations

89 in monocultures (full sun) and shaded coffee plantations which range from simple to highly complex

90 agroforestry systems (Toledo and Moguel, 2012).

91 An important and major challenge is to design coffee agroforestry systems capable of regulating pests and

92 diseases and reducing resulting losses while, at the same time, maintaining other ecosystem services

93 necessary for farmers and for society as a whole. For instance, for farmers and their families, the provision of

94 diversified products such as fruits, timber, firewood and others from coffee agroforestry systems is important

95 for household income and food security (Rice, 2008). The maintenance of soil fertility (a regulation service) is

96 of interest to farmers, given that their production depends in great part on soil quality (Müller et al., 2015). For

97 the society in general, carbon sequestration is a key regulation service, as it contributes to the mitigation of

98 climate change (MEA, 2005). All of these services can be provided individually or simultaneously by coffee

99 systems, depending on the type of agroforestry system and its management.

100 It is also important to understand the relationships among different ecosystem services, since management

101 decisions that improve the delivery of a particular service can affect other services (Cheatham et al., 2009;

102 Mora et al., 2016). To increase beneficial or synergetic relationships, trade-offs between ecosystem services

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103 must be minimized and synergies promoted (Iverson et al., 2014; Rapidel et al., 2015). In the case of multiple

104 cropping, such as agroforestry systems, knowledge of the trade-offs and synergies among ecosystem

105 services is important for improving the management of the biodiversity. This knowledge is a necessary step

106 towards the ecological intensification of agriculture, i.e. an agricultural intensification to increase yields with

107 improved ecosystem services and reduced negative externalities (Kremen and Miles, 2012; Geertsema et al.,

108 2016). It is also important to estimate the monetary values of ecosystem services and use this information in

109 the assessment of relationships, because this can shed light on the magnitude of trade-offs or synergies (Peh

110 et al., 2016). Several recent studies have already demonstrated the usefulness of assessing relationships

111 among ecosystem services to guide farm management decisions. For instance, trade-off analysis in

112 agroforestry systems (with coffee and cocoa especially) have yielded strategic recommendations to improve

113 the design and management of different types of such systems (Wade et al., 2010; Meylan et al., 2013;

114 Somarriba et al., 2013; Cerda et al., 2017a).

115 With this research, we aimed to identify the most promising coffee agroforestry systems (CAFs) that can

116 serve as production models for farmers. Here we define 'promising' CAFs as those capable of reducing yield

117 and economic losses due to diseases while also providing other ecosystem services. We studied a wide

118 variety of coffee agroecosystems with different cropping practices, contrasting types of shade canopies and

119 different altitudinal locations. Our specific objectives were to (1) quantify the delivery of provisioning services

120 (coffee yield, agroforestry products, cash flow, value of domestic consumption) in different CAFs; (2) quantify

121 indicators of regulation services (coffee yield losses and economic losses, incidence of diseases) plus

122 indicators of maintenance of soil fertility and carbon sequestration in the aboveground biomass; and (3)

123 analyze the relationships among those ecosystem services in order to identify the most promising CAFs.

124 From these promising CAFs, we also aimed to derive technical recommendations to prevent losses from

125 diseases. The indicators of ecosystem services chosen in this study are relevant for characterizing the basic

126 needs of farmers´ families, the natural resources in agroforestry systems and the environment in general

127 (Rice, 2011; Somarriba et al., 2013; Cerda et al., 2014; Pinoargote et al., 2016).

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130 **2.   Materials and methods**

131 **2.1 Data collection and calculation of indicators of ecosystem services**

132 **2.1.1 Location and coffee plot network**

133 To characterize the delivery of multiple ecosystem services in coffee agroforestry plots, we collected data for

134 two years (2014–2015) in 61 coffee plots in a research network established in Turrialba, Costa Rica.

135 Turrialba is characterized as a premontane wet forest life zone (with mean annual rainfall = 2781 mm and a

136 mean annual temperature = 22.2°C; 10 year averages), where coffee is grown from 600 to 1400 meters

137 above sea level (m.a.s.l.). To sample the diverse set of conditions under which coffee is grown, we selected

138 coffee plots that varied in terms of their management practices (e.g. fertilizers, weeding, pests and disease

139 control, etc.), shade types (ranging from coffee systems in full sun to CAFs with high plant biodiversity) and in

140 different altitudes from 600 to 1200 m.a.s.l. All coffee plots were owned by smallholder farmers and had the

141 coffee variety *Caturra* as the dominant variety on the farm; this variety is also the most common in the region.

142 **2.1.2 Measurements in coffee plants**

143 In each coffee plot, we marked a subplot composed of eight coffee rows with 15 plants each and selected

144 eight coffee plants (one per row). In these plants, we measured the number of fruiting nodes (yield

145 component) and the number of dead productive branches (yield-reducing factor) as predictors of yield and

146 yield losses (Cerda et al., 2017b). In the same plants, we measured the presence of foliar diseases in the

147 leaves of three lateral branches (one branch in the lower part of the coffee plant, another in the middle and a

148 third in the upper part) five times during the year, and then we calculated the standardized area under the

149 disease progress curve (sAUDPC) for each disease. We also took measurements of the dieback level in all

150 plants of the subplot. Dieback was considered as a result of negative effects of both biotic and abiotic factors.

151 Additional details on the coffee plant measurements can be found in Table 1.

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154 **2.1.3 Characterization of shade canopy**

155 In order to characterize the structure of the shade canopy, we marked a circular area of 1000 m^2 in the center

156 of each subplot for the identification and measurements of plants and trees. We measured the species

157 richness, tree abundance and trunk diameters (at breast height = 1.30 m; for trunks with diameter >5 cm) of

158 each tree and classified shade plants into different types: timber trees, fruit trees, service trees and *musacea*

159 plants (bananas and plantains). We defined 'service trees' as leguminous trees that provide leaf litter

160 biomass to the soil and/or fix nitrogen; these trees can also provide fodder to feed livestock. Four times per

161 year we measured the shade cover with a spherical densitometer in the four corners and in the center of the

162 subplot and obtained yearly averages. We used this data to group coffee plots in three main types of coffee

163 agroecosystems: coffee in full sun (CFS), coffee agroforestry systems with low plant diversification (CLD) and

164 coffee agroforestry systems with high plant diversification (CHD).

165 **2.1.4 Farmer surveys**

166 We interviewed the farmers to collect data on management and agroforestry production, which we used to

167 calculate indicators of provisioning services such as cash flow and value of domestic consumption. We

168 applied semi-structured interviews to obtain the necessary data on cropping practices and production costs

169 differentiated by inputs and labor (family labor and hired labor); yields of agroforestry products other than

170 coffee (bananas, plantains, other fruits, timber); quantity of agroforestry products for domestic consumption

171 and quantity of agroforestry products sold; and local cost of hired labor and of agroforestry products.

172 **2.1.5 Calculation of indicators of ecosystem services**

173 We used our field data to calculate indicators of four ecosystem services: regulation of diseases, provisioning

174 of agroforestry products, maintenance of soil fertility and carbon sequestration. Table 1 lists the ecosystem

175 service indicators, along with the main methods used to obtain them. In addition to being relevant for farmers,

176 these indicators meet useful criteria in the study of ecosystem services, such as possible to quantify,

177 sensitive to changes in the system management, respond to change in a predictable manner and reflect the

178 features of the system (Dale and Polasky, 2007). Models and equations to estimate yields and yield losses

179 and economic losses are shown in Table 2; their indicators of prediction quality are presented in

180 supplementary materials.

2.2 Analytical methods

2.2.1 Characterization of the relationships between indicators of losses and indicators of
ecosystem services

184 To analyze the relationships between losses (yield and economic losses) and indicators of ecosystem

185 services, we carried out bivariate linear regressions between losses and indicators of presence of diseases

186 (reflected by the sAUDPC) and between indicators of losses and indicators of the other ecosystem services

187 studied (Table 1). The regressor variables were the indicators of presence of diseases, provisioning of

188 agroforestry products, maintenance of soil fertility and carbon sequestration listed in Table 1. The dependent

189 variables were the indicators of yield losses: primary yield losses (%) and their economic primary losses

190 (USD ha^{-1}) and secondary yield losses (%) and their economic secondary losses (USD ha^{-1}). A total of 48

191 regressions were performed and represented graphically. Since both yield losses and economic losses

192 should be reduced, the relationship is interpreted as a synergy if the relationship between a loss and a given

193 indicator of ecosystem service is negative (Fig. 1B): the increase of this given indicator is related to a

194 reduction of the loss (i.e. greater yield). Conversely, if the relationship is positive, then this relationship is

195 interpreted as a trade-off (Fig. 1C) because the improvement of this given ecosystem service is related to the

196 increase of loss (i.e. lower yield).

2.2.2 Identification and characterization of the most promising coffee agroecosystems

198 In each graphical representation of the 48 regressions, a 'desirable area' was determined as part of the

199 procedure to identify the most promising CAFs. The desirable area was defined as the area containing points,

200 i.e. coffee plots, delimited by 'desirable levels' of the two indicators of ecosystem services analyzed in each

201 regression (Fig. 1). The delimitation of the desirable areas followed three steps: (1) the outlier points of

202 indicators of yield and economic losses were removed from the analysis to avoid bias from uncommon

203 observations; (2) medians for all indicators of ecosystem services were calculated; and (3) each desirable

204 area was delimitated based on the data of the medians, which were considered as boundary values in this

205   study. In the case of regressions between losses and indicators of provisioning services, maintenance of soil

206   fertility and carbon sequestration, the graphical representation was divided into four quadrants according to

207   the medians in each axis and only one quadrant represented the desirable area. In the case of regressions

208   between losses and indicators of diseases, the graphical representation was divided into only two zones

209   according to the median in the axis of losses (because it was considered that low yield loss, even with high

210   levels of a disease, is an acceptable situation). Thus, only one zone represented the desirable area (Fig. 1).

211   This approach of identifying plots that attain desired values of pairs of ecosystem services was proposed as

212   an important part of designing agroecosystems (Rapidel et al., 2015) and has already been applied in a

213   previous study on ecosystem services provided by coffee systems (Cerda et al., 2017a).

214   The most promising CAFs (specific coffee plots) for providing multiple ecosystem services were those that

215   met three criteria. First, the plots had to have lower values of secondary yield losses and secondary

216   economic losses than the median of the dataset, given that secondary losses were the most important

217   (higher than primary losses). This means that promising plots had to be at least within the 50% of the plots

218   with lower secondary losses. Second, the coffee plots could not present negative values of cash flow in either

219   of the two studied years, because cash flow reflects the gain or loss of money in cash taking into account the

220   sales of agroforestry products and the costs of production invested (Table 1). Promising coffee plots,

221   therefore, should never produce a loss of cash for the farmer. Third, and finally, the coffee plots had to be

222   located in at least 32 desirable areas of the 48 regressions (two thirds—67—of the desirable areas). We

223   chose this cutoff in order to identify a reasonable number of most promising coffee plots that can be

224   considered as successful production models from which we can learn. A lower cutoff (e.g. 50%) would have

225   resulted in too many apparently promising plots, and a higher cutoff (e.g. 80%) would have resulted in only

226   one promising plot. We considered that the coffee plots fulfilling all three criteria were the most promising

227   coffee agroecosystems for the regulation of diseases (reduced crop losses), the provisioning of products for

228   farming families and the maintenance of soil fertility and sequestration of carbon. Finally, for each of the most

229   promising CAFs identified, we described its characteristics of structure and composition of the shade canopy,

230   cropping practices, production costs and the indicators of ecosystem services it provides.

231

232

233 **3.   Results**

234   We found 21 significant relationships (p<0.05) between yield losses and economic losses and ecosystem

235   service indicators (out of total 48 regressions). We identified six promising CAFs that hold the greatest

236   potential to provide multiple ecosystem services simultaneously. We first present figures of relationships

237   among different ecosystem service provisions. In each figure, the types of coffee agroecosystems can be

238   differentiated, and the six most promising CAFs are identified. We then describe their characteristics in detail.

239   **3.1 Relationship between diseases and losses**

240   The percentages of coffee leaf rust and dieback were positively related to yield losses and economic losses,

241   which indicates that these phytosanitary problems are the most dangerous for the crop. According to the

242   determination coefficient (R^2), primary yield and economic losses were more related to dieback, and

243   secondary yield and economic losses were more related to coffee leaf rust. The percentage of brown eye

244   spot were low in general and no related losses were highlighted (not significant), which means that this

245   disease was not as important as the other two in our context (Fig. 2).

246   An important finding was that despite several coffee plots having high levels of disease (up to 70% of coffee

247   leaf rust and up to 60% of dieback index), they were still located in the desirable areas with low yield losses

248   and economic losses; most of them were agroforestry systems of CLD and CHD types. This is an important

249   insight that there are systems capable of avoiding high losses despite a high presence of pathogens. The six

250   most promising CAFs were among them (Fig. 2).

251   **3.2 Relationships between indicators of losses and indicators of ecosystem services**

252   We found five significant relationships of yield losses and economic losses with indicators of provisioning

253   services, three with indicators of maintenance of soil fertility and five with indicators of carbon sequestration,

254   yet, the R^2 in most of those relationships were equal or lower than 0.10 (Figs. 2, 3, 4 and 5). Such very low

255   R^2s do not indicate clear relationships. Therefore, in the following paragraphs we focus on interpreting only

256   relationships with R^2s higher than 0.10.

257   Most of the coffee plots in the desirable areas with low losses and indicators of provisioning services were

258   agroforestry systems (CLD and CHD). Among them, the systems with high diversification (CHD) were those

259   capable of contributing the most to domestic consumption of agroforestry products, while the systems with

260   low diversification (CLD) contributed the most to both coffee yields and cash flow in both years of evaluation.

261   Very few systems at full sun (CFS) were identified as capable of maintaining low losses and at the same time

262   providing good cash flows. All six most promising CAFs were in desirable areas between low secondary

263   losses and desirable provisioning indicators, but not all of them were in desirable areas with low primary

264   losses (Fig. 3).

265   We found few significant relationships between losses and indicators of maintenance of soil fertility. Only the

266   relationships between soil K and secondary losses registered $R^2>0.10$ and were positive (Fig. 4), but in such

267   figures we noted that only the high K data of two coffee plots could be leading to the positive relationships;

268   therefore, it is not possible to conclude that high K soil contents (specially in CHD) would lead to the increase

269   of losses in general.

270   We found more CAFs (CLD, CHD) than coffee at full sun (CFS) registering low yield losses, low economic

271   losses and good indicators of soil fertility (desirable areas in Fig. 4). This was more evident in the desirable

272   areas with soil acidity and soil K, which reflects the importance of trees and other plants maintaining healthy

273   soils. The six most promising CAFs were in desirable areas between losses and soil acidity, but not all of

274   them in desirable areas between losses and soil K and soil C (Fig. 4).

275   We found a significantly positive relationship between secondary economic losses and carbon in timber trees,

276   with an $R^2 = 0.16$. We also found a similar tendency with carbon in fruit trees (Fig. 5). Although the R^2s were

277   low, such relationships provide an insight that there can be trade-offs associated with tree densities, because

278   while the service of carbon sequestration is improved, increased tree densities can lead to the increase of

279   yield losses and resulting economic losses.

11

280   We noted that none of the coffee plots with carbon in timber trees higher than 8 Mg ha^{-1}, and none of the

281   coffee plots with carbon in fruit trees higher than 4 Mg ha^{-1} registered low yield and economic losses (out of

282   desirable areas, Fig. 5). It was interesting to find that coffee plots with carbon in service trees up to 27 Mg ha^{-}

283   ^{1} were still located in desirable areas with low secondary losses, which indicates that the presence of that

284   type of tree does not cause trade-offs between services and can contribute to reducing losses (Fig. 5).

285   In general, less than the third part of the coffee agroecosystems (full sun systems and agroforestry systems)

286   evaluated in this study where located in each of the desirable areas between losses and indicators of

287   ecosystem services (Figs. 3, 4 and 5). Among them, two desirable areas were the most difficult to reach: low

288   secondary yield losses in combination with high soil K content, and low secondary yield losses in combination

289   with high carbon content in fruit trees and timber trees. Only less than 16% of coffee agroecosystems

290   reached desirable levels of such combinations.

3.3 The most promising coffee agroforestry systems for providing multiple ecosystem services
291

292   **simultaneously**

293   We identified six CAFs as the most promising ones for the simultaneous regulation of diseases (low yield

294   losses and low economic losses) and provision of other ecosystem services. Although they differed in their

295   agroforestry structure, agronomic management and indicators of ecosystem services, all six CAFS metthe

296   three criteria proposed (in section 2.2.2) to be the most promising systems: 1) low secondary losses, 2)

297   positive cash flow, and 3) located in at least 32 of the 48 possible desirable areas, deduced from the bivariate

298   relationships between indicators of ecosystem services. Our results suggest that the provision of important

299   benefits for farmers is not restricted to a given type of shade of the system but can be achieved by different

300   agroforestry systems depending on their particular management strategies.

301   We numbered the CAFs from 1 to 6 according to the complexity of their shade canopies: from the simplest

302   (CAF1) to the most complex (CAF6). The six CAFs were notably different in the structure and composition of

303   their shade canopies, their agronomic management and the ecosystem services they provide. The densities

304   and basal areas per type of tree (service, fruit, timber trees and bananas), as well as the species richness

305   and shade cover of the plot, also differed among the six CAFs (Table 3).

306   The agronomic management differed mostly in the number of fungicide and herbicide applications and in the

307   cost of hired labor and cost of inputs. In general, more practices and higher costs were applied in 2014 than

308   in 2015 (Table 4), because when farmers realize that a given year (2015) is going to produce low yields, they

309   prefer to reduce expenses. The management of shade trees was considered similar among the six CAFs,

310   because farmers in the study area usually prune service trees twice a year in (once a few weeks before the

311   beginning of the coffee harvest season and the other after the end of the harvest season). Farmers do not

312   apply silvicultural practices to fruit or timber trees; and management of bananas is sporadic (they just cut

313   diseased leaves when they are applying practices to coffee plants).

314   In Tables 3 and 4, we present summary data of the 61 coffee plots evaluated in this study (mean, standard

315   deviation, minimum and maximum of all variables) to show the overall characteristics of coffee

316   agroecosystems in the study area. It is possible to note that the most promising CAFs had lower densities of

317   trees than many of the other coffee plots, which indicates that these promising CAFs avoid excessive

318   densities (Table 3). However, the promising CAFs had similar frequencies of cropping practices as others,

319   but lower production costs (Table 4).

320   Although all six CAFs presented good values of most of the indicators of ecosystem services, they were quite

321   different in each indicator. In Table 5 we show the data of ecosystem services for each promising CAF and

322   the summary data for all the 61 coffee plots. The six CAFs, although different among them, in general, were

323   superior to other systems in terms of ecosystem service provision. For instance, yield losses and economic

324   losses were lower than the means of all systems. Finally, in Table 6, we present a summary of the

325   characteristics of the six CAFs related to their agroforestry structure, yield losses, yields and management

326   strategies.

327   **4.   Discussion**

328   **4.1 Yield losses to identify crop systems tolerant to diseases**

329   Primary and secondary yield losses were positively related to coffee leaf rust and dieback that leads to the

330   death of productive branches, considered as the main yield-reducing factor (Cerda et al., 2017b). However,

331   we highlight as an important finding that the coffee plots with the lower primary and secondary losses were

332   not necessarily associated with lower disease levels. For instance, among the six most promising CAFs, the

13

333   percentage of coffee leaf rust ranged from 24% to 63%, but their primary yield losses did not surpass 6% and

334   their secondary yield losses did not surpass 18%, much lower than the other coffee agroecosystems. In other

335   words, some crop systems tolerate disease incidences better than others. Plant tolerance to pests and

336   diseases, i.e. the plant's ability to produce a good harvest even with high disease or pest intensities (Agrios,

337   2005), can be related to good nutrition and appropriate shade cover in agroforestry systems (Toniutti et al.,

338   2017; Villarreyna et al., 2020).

339   Given that reduced yield losses can be considered as indicators for valuing the regulation of pests and

340   diseases as an ecosystem service (Avelino et al., 2011; Avelino et al., 2018), the six most promising CAFs

341   can be considered as crop systems that provide such a service. However, it is important to clarify that these

342   CAFs did not reduce yield losses only due to their natural capacity to tolerate diseases, thanks to their plant

343   biodiversity levels and good soil fertility, but such capacity was reinforced by the control of diseases. In all of

344   these promising systems, fungicides were applied with certain frequency. In this matter, it is also worth

345   mentioning that strict control of diseases based only on pesticide application or on the removal of trees of the

346   canopy to reduce excessive shade cover (such as in agroforestry systems) can be detrimental to the

347   provision of other ecosystem services (Cheatham et al., 2009). Therefore, for effective regulation of diseases

348   without trade-offs with other services, we believe that the control of phytopathogens must be combined with

349   the regulation that the system itself provides, i.e. through the use of plant diversification, adequate shade

350   cover and maintenance of soil fertility. A moderate shade cover (about 30%), for instance, helps avoid

351   excessive fruit loads that increase the susceptibility of coffee plants to diseases, and good soil fertility

352   enhanced by the organic matter provided by shade trees improves the ability of coffee plants to tolerate

353   pathogen attacks (Cerda et al., 2017a; Villarreyna *et al.*, 2020). Thus, shade trees contribute to improve

354   coffee diseases management, reducing the dependence of farmers on chemical pesticides use for disease

355   control. When there is excessive shade cover, instead of removing shade trees, management of these shade

356   trees by pruning should therefore be encouraged.

357   **4.2 Management and economic strategies to maintain the crop system sustainability**

358   The six most promising CAFs were identified by their ability to provide various ecosystem services

359   simultaneously, which is important to enhancing ecological sustainability while being profitable. Each of the

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360 CAFs has a specific agroforestry structure and different combination of cropping practices, showing that there

361 can be several and varied strategies that farmers can choose for the design of new plantations or for

362 transforming existing plantations. There appear to be two pathways for reducing yield losses to disease: 1)

363 applying fungicides to maintain high yields (as in CAF1 and CAF5), or 2) obtaining lower but acceptable

364 yields with limited use of fungicides (e.g., CAF 2, 3, 4 and 6) (Fig. 6). These latter systems indicate that the

365 reduction in fungicide use can be possible. An alternative to fungicides can be the use of biological products

366 with bacteria or fungi that are antagonists to pathogens. In addition, the use of fungicides for avoiding

367 epidemic growth must be planned based on the monitoring of diseases and the rainfall regime (Belan et al.,

368 2015; Zambolim, 2016). Such actions can help reduce the use of chemical fungicides in quantity and

369 frequency and yet help to protect the system, instead of only applying pesticides as an urgent measure when

370 the epidemic has reached loss-inducing levels. The idea is to structure and manage coffee systems to

371 maximize their preventive strengths against pests and diseases (Lewis *et al*., 1997).

372 It is known that farmers do not apply radical changes to their systems when they want to make improvements

373 in structure or management; instead, they will apply incremental changes step by step according to the

374 availability of resources (Mussak and Laarman, 1989). Therefore, one way to encourage farmers to change

375 their coffee systems to more sustainable systems is to identify what type of coffee plantation they currently

376 have and provide technical advice on how to change this plantation into one of the 6 more promising CAFs,

377 depending on which one they are most interested in and their resources. Figure 6 shows potential

378 transformation pathways for each of the main types of coffee agroecosystems. For instance, monocultures in

379 full sun could be transformed into simple agroforestry systems coffee-service trees (CAF1); depending on the

380 initial level of diversification and on the management strategy, coffee systems with low diversification could

381 be transformed into CAF2, CAF3 or CAF 4; and coffee systems with high diversification could be transformed

382 into CAF5 or CAF6. Then, it is possible to incrementally change the level of shade diversification and so

383 improve ecosystem services while reducing pesticide use to increase sustainability of the crop system, as

384 indicated by the colored arrows in Figure 6. Since our study did not include organic farms, we do not have

385 promising systems without any chemical pesticide use; therefore, the design of a transition pathway toward

386 completely agroecological systems should be a future topic of study.

387   Another important strategy is to replace varieties susceptible to the main diseases with resistant varieties, as

388   is being promoted by development projects in the region. However, it is important to take into account several

389   considerations. The change of varieties implies moderate to high costs to farmers, thus, the process should

390   be gradual and could take several years, especially in the case of smallholder farmers. The resistance of

391   improved coffee varieties is being surpassed after several years due to the evolution of pathogens, so

392   farmers cannot rely on these new varieties to confer long-term resistance; instead, the integral management

393   of agroforestry systems (soil fertility, uniform shade cover, microclimate, plant diversity) will be always

394   necessary to prevent the development of diseases and resulting losses (Avelino and Anzueto, 2020).

395   **4.3 Management recommendations derived from the characteristics of the most promising coffee**

396   **agroforestry systems**

397   From the six most promising CAFs, we can identify specific characteristics of their shade canopies and

398   management and use them as guides for reducing losses and providing ecosystem services. Based on the

399   range of characteristics of the six CAFs (Tables 3 and 4), we derived six important recommendations for

400   farmers who want to grow coffee in a sustainable manner and obtain other benefits, not only coffee yield.

401   **a. Densities and management of service trees:** service trees can be managed with densities up to

402   350 trees ha^{-1} in simple agroforestry systems where the service tree is used as the main shade

403   species. In more diversified agroforestry systems, service trees could reach up to 200 trees ha^{-1} when

404   the service tree species are wanted to be the most represented into the system. In diversified

405   systems where bananas and other fruits or timber trees are more important for the farmer, service

406   trees should not surpass 30 trees ha^{-1}. It is important to note that in this study we are referring to

407   service trees of the family *Fabaceae,* mainly of the species *Erythrina poeppigiana,* which are easily

408   pruned once or twice per year to maintain low shade cover with crowns of low height. If the user is

409   planning to manage different service trees, for instance *Inga spp,* which are not easily nor frequently

410   pruned, then the densities should be much lower because these trees tend to have wider and denser

411   crowns, and high densities can result in excessive shade.

412   **b. Densities of musaceae plants:** the density of museacaea plants can reach up to 300 plants ha^{-1} in

413   medium diversified agroforestry systems where the production of bananas or plantains is a priority for

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414   the farmer apart from coffee. For plantations with high densities of musaceae plants, there should be

415   very low density of shade trees (<40 shade trees ha^{-1}). In highly diversified agroforestry systems

416   where the objective is to cultivate fruit or timber trees, the density of musaceae plants should be

417   much lower (~30 plants ha^{-1}).

418   **c.** **Densities and species of fruit trees:** in diversified agroforestry systems, such as CAF 5 and CAF 6,

419   the density of fruit trees reached up to 80 trees ha^{-1}, but with small trees, most of them *cas (Psidium*

420   *friedrichsthalium)* and *arazá (Eugenia stipitata),* which were young trees (according to their basal

421   areas) and had low shade cover. If the farmer wants to use other types of fruit trees, such as oranges

422   or avocados, which have denser crowns, then we estimate that the density of such trees could be

423   between 20 and 30 trees ha^{-1}, in order to avoid risk of excessive shade and competition with coffee

424   plants for soil nutrients.

425   **d.** **Densities and management of timber trees:** in diversified agroforestry systems, timber trees

426   should not surpass 30 trees ha^{-1} when they are tree species similar to *Cordia alliodora* or *Cedrela*

427   *odorata,* as found in this study. One of the CAFs had 170 trees ha^{-1} but these were young and small

428   trees; the farmer will likely reduce the density of trees in future years. Low densities of timber trees

429   can be managed in agroforestry systems and still sequester important amounts of carbon and

430   produce timber, as long as the silvicultural management favors as much as possible thickness

431   increment of the main trunk (Somarriba et al., 2013).

432   **e.** **Level of shade cover:** the shade cover was variable among the most promising CAFs, but none of

433   them surpassed 35%. This should be the maximum percentage of shade cover to manage in a

434   climate such as that of Turrialba, where it is rainy most part of the year (mean annual rainfall = 2781

435   mm).

436   **f.** **Cropping practices:** weed control (with herbicides and/or machete weeding) should be done as

437   necessary: at least three controls per year would be ideal. The use of herbicides should be limited if

438   possible, which could be achieved by the use of a uniform shade cover in the plantation. At least one

439   application of fertilizers per year is needed: two would be better. Harvests should be every two weeks

440   in an area such as Turrialba, where ripe fruits can be seen frequently during the six-month harvest

441   season. The application of fungicides per year was variable among the most promising CAFs, from

442   one to six applications. In case of small farmers, we believe the ideal to be two applications per year

443   (as in several of the most promising CAFs). As mentioned, the quantity of fungicides used in the

444   system can be reduced based on disease monitoring, by applying fungicides as soon as the disease

445   reaches specific low incidence thresholds that help prevent the epidemic growth and further control

446   needs. This practice has the potential to reduce the frequency of applications and quantity of inputs.

447   More than four applications of fungicides can be justifiable when there is a strong risk of plant

448   defoliation and high yield losses, but this is not always feasible for small farmers due to the

449   investment needed. The use of fungicides should be the last resort.

450   **4.4 Lessons from the analysis of relationships between indicators of ecosystem services**

451   The analysis of the relationships between indicators of losses and indicators of other ecosystems services,

452   and the determination of desirable areas (Figs. 2-5) were useful for identifying crop systems that maintained

453   high yields (i.e. low losses to diseases), were financially profitable and ecologically sustainable. Although the

454   R^2s were low for most relationships, these relationships can still be considered as indicators of possible

455   trade-offs or synergies, as long as they are significant ($p<0.05$). Similar approaches, methods and findings

456   were used in an assessment of ecosystem services by a set of agroforestry systems with coffee, cocoa,

457   basic grains, pastures and home gardens (Cerda et al., 2019). In this study, the trade-offs found between

458   ecosystem services become important warnings to avoid high yield losses and economic losses. For

459   instance, the trade-off of increasing carbon sequestration (in fruit and timber trees) that leads to increased

460   losses of coffee yields suggests that excessive presence of that type of tree should be avoided. In the case of

461   relationships that could reflect synergies, such as the one of increasing soil carbon and reducing losses, the

462   indication is that the increase of organic matter could help reduce losses, i.e. not necessarily by regulating

463   diseases directly but by reducing their negative impact on yield (Avelino et al., 2006).

464   Some relationships, such as the ones between losses and domestic consumption, should be interpreted

465   carefully. The positive relationship between the value of domestic consumption of agroforestry products and

466   secondary losses of coffee could be seen as an undesirable relationship (trade-off); however, this can be

467   seen as the farmers' strategy to face coffee losses by using the biodiversity—they increase the consumption

468   of other products coming from the system when they realize that coffee yield is going to be low. Farmers use

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469 agroforestry products (fruits, timber and others) to increase the self-consumption of on-farm products,

470 increase incomes and therefore reduce financial risk (Ramírez et al., 2001; Rice, 2011).

471 When no significant relationships were found, that means that a given ecosystem service can be increased

472 without increasing yield losses and economic losses. Independent of the significance and type of

473 relationships (trade-offs or synergies), the identification of desirable areas in the regression graphics makes it

474 possible to identify which type of agroecosystems are achieving desirable levels of ecosystem services

475 (Rapidel et al., 2015). In addition, this approach was also useful for identifying which desirable combinations

476 of ecosystem services are the most difficult to achieve. For example, few coffee systems achieved desirable

477 combinations of low secondary losses with more soil K, and more carbon in timber and fruit trees. This

478 indicates that soil fertilization strategies and silvicultural tree design-management should be improved.

479 Suggestions for how to improve the structure of the agroforestry systems and their management must be in

480 line with farmer priorities. In this study, our proposed recommendations are primarily focused on improving

481 disease regulation and increasing coffee yields, given that the coffee in the region is in a severe crisis due to

482 the attack of coffee leaf rust and unfavorable socioeconomic and climate conditions; therefore, actions are

483 needed to reduce crop losses (Avelino et al., 2015). The other goals are to promote plant diversity in

484 agroforestry systems in order to provide other tangible products (fruits, timber), maintain soil fertility and

485 contribute to climate mitigation through carbon sequestration. In other regions, the most promising systems

486 should be identified or designed based on the priorities established according to the particular context and/or

487 the interests of the main stakeholders. However, it is always critical to give an important weight and focus to

488 disease regulation and control, given that the actions needed directly or indirectly affect the biodiversity and

489 provision of ecosystem services of the crop system (Cheatham et al., 2009).

490 The quantification of several indicators of ecosystem services and the identification of trade-offs or synergies

491 between them can also be inputs for decision support systems or multi-criteria decision analysis for

492 agroforestry systems at the farm or landscape scale In that kind of analysis, the key stakeholders (farmers,

493 technicians, scientists, decision makers) can combine the quantitative and qualitative information about

494 ecosystem services to rank them according to their priorities to achieve goals and generate possible

495 scenarios of trade-offs or synergies that can guide decision making processes (Domptail et al., 2013;
496 Saarikoski et al., 2015).

497 A caveat of our study is that the boundaries (medians) to demarcate the desirable areas for identifying the
498 most promising agroforestry systems used in this study are not generalizable for studies on coffee in other
499 areas. In this study, the boundaries are dependent both on the indicators of ecosystem services of the
500 sampled coffee plots and on the number of coffee plots. If similar studies were developed in other areas, their
501 boundaries should be the medians registered in that study. Alternatively, the boundaries could be established
502 according to the specific boundaries desired by the user (according to particular objectives of farmers or
503 researchers), as done in a previous study (Cerda et al., 2017a). To define boundaries for a given region, for
504 instance, the sampled plots should represent a huge variability of production situations and management
505 strategies within the studied region so that the medians obtained could be considered as "threshold
506 boundaries" for the region.

507 **5.   Conclusions**

508 Identifying agroforestry systems that enhance the regulation of diseases while delivering good yields and
509 other ecosystem services can help improve the sustainability of coffee farming by providing farmers and
510 technicians with successful coffee production models. The six most promising CAFs identified in this study
511 belonged to different types of agroforestry systems and management strategies. This is an important finding
512 because such systems represent several options to follow (imitate) for the design of new coffee plantations or
513 the transformation of existing plantations.

514 This study allowed us to identify the most important relationships between indicators of yield losses and
515 economic losses and the indicators of other ecosystem services, which gives insights into better
516 management of coffee agroforestry systems. The regulation of diseases must concentrate on reducing coffee
517 leaf rust and dieback, as they were the main diseases that increased losses. The integrated management of
518 diseases should take advantage of combining the management of plant biodiversity, soil fertility and the use
519 of low quantities of fungicides, applied when inoculum pressure is still low. Increasing carbon in timber and

520 fruit trees implied slight trade-offs with disease regulation, because such increments also increased losses,

521 indicating that densities of these types of trees, for caution, should be low.

522 In this study, the analysis focused mainly on yield losses and economic losses as indicators of the regulation

523 of diseases and on their bivariate relationships with indicators of other ecosystem services. This means that

524 for the identification of the most promising agroforestry systems, more weight was put on the service of

525 regulation of diseases, a highly relevant service for farmers currently due to the coffee crises in the region.

526 Despite this specificity, our study provides a useful methodological approach for other contexts (regions,

527 crops), particularly in situations where other ecosystem services not assessed here, as hydric regulation, soil

528 erosion regulation, or habitat for bird biodiversity, could be considered as relevant.

529 **6. Acknowledgements**

537 **7. Literature**

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Table 1. Indicators of ecosystem services measured for two years (2014-2015) in 61 coffee plots in Turrialba, Costa Rica

Indicators of ES	Methods/Formulas	Data sources/times of measurement
Regulation of pests and diseases		
sAUDPC of Coffee leaf rust (%) sAUDPC of Brown eye spot (%)	$$AUDPC = \sum_{i=1}^{n-1} \frac{I_i + I_{i+1}}{2} \times (t_{i+1} - t_i) \qquad sAUDPC = \frac{AUDPC}{Nd}$$ where *AUDPC*: area under the disease progress curve; I_i: incidence of a given disease at the *i*th measurement; t_i: time (in days) of the *i*th measurement; n: total number of measurements; *sAUDPC*: standardized AUDPC; *Nd*: total number of days in which the plants were measured Source: (Simko and Piepho, 2012)	Incidences were measured five times: 1st, fruit formation (slightly dry period); 2nd, beginning of fruit ripening (beginning of rainy period); 3rd, just before the harvest (rainy period); 4th, during the peak of harvest (slightly dry period); 5th, end of coffee harvest period (highest rainy period).
Maximum dieback index (%)	Each plant of the subplot was classified in a scale (1-4): 1: plant with few defoliated branches; 2: plants with several defoliated and dead branches; 3: plants with a lot of defoliated and dead branches, and with withered dry fruits; 4: plants with almost all dead branches, almost dead plants. Dieback index was calculated with the formula below (where N: number of plants registered in each scale of dieback); and the maximum dieback index during the year was identified. $$Dieback\ index = \frac{1xN_1 + 2xN_2 + 3xN_3 + 4xN_4}{4xNtotal} \times 100$$	The same as above
Primary and secondary yield losses (%) Primary and secondary economic losses (USD ha^{-1})	These indicators were estimated through several models and equations. See the explanations in Table 2	
Provisioning of agroforestry products		
Coffee yield (USD ha^{-1})	These indicators were estimated through models and equations of actual yields. See the explanations in Table 2	
Cash flow (USD ha^{-1}) Value DC (USD ha^{-1})	*GI = AS x MP* *CF = GI – CC* *Value DC = ADC x MP*	where: *GI*: gross income from sale of coffee and other agroforestry products; *AS*: amount of agroforestry products for sales; *MP*: local market price; *CF*: cash flow; *CC*: cash costs; *Value DC*: value of domestic consumption of agroforestry products; *ADC*: amount of agroforestry products for domestic consumption Sources: (Ambrose-Oji, 2003; Cerda et al., 2014)	Data on management practices of coffee plots, costs of labor and inputs, and agroforestry production (fruits, bananas, plantains, etc.) were obtained through interviews with the owners of the coffee plots.
Maintenance of soil fertility*		
Acidity (mg kg^{-1}) K (mg kg^{-1}) Carbon (%)	Eight subsamples of soil at a depth of 0-40 cm were taken near the trunk of eight coffee plants (at 50cm approximately) in each experimental subplot. The subsamples were mixed to obtain a composite sample, and sent to a soil laboratory for the chemical and texture analyses. Source: (Briceño and Pacheco, 1984).	The subsamples and composite samples were obtained during the peak of harvest in 2014.
Carbon sequestration*		
Carbon (Mg ha^{-1}) in: Fruit trees Timber trees Service trees	Biomasses of plants and trees in the shade canopy were estimated through allometric equations, which use the trunk diameters at breast height (1.3 m from soil) as predictors. Detailed equations can be found in Cerda et al., 2017a. Then, biomasses were multiplied by a 0.47 fraction to obtain the carbon content.	The trunk diameters were measured the coffee fruit formation (slightly dry period).

Coffee leaf rust (*Hemileia vastarix* Berkeley and Broome); Brown eye spot (*Cercospora coffeicola* Berk and Curtis)
*: these indicators were measured only in the year 2014, the year of high production according to the biennial cycle of coffee production.
Source: adapted from (Cerda et al., 2017a)

Table 2. Models and equations used to estimate attainable yields, actual yields, and primary and secondary yield losses of coffee

Explanations	Models and equations	Eq.
For the estimation of primary yield losses in 2014		
Model 1	$Y_{(14)} \sim NFN_{(14)} + DeadB_{(14)} + ShadeC_{(14)} + (1 \mid Plot)$	
Based on the results of the Model 1, we obtained an equation to estimate the actual yield of 2014 ($Y_{(14)}$)	$Y_{(14)} = I + a \times NFN_{(14)} + b \times DeadB_{(14)} + c \times ShadeC_{(14)}$	1
By setting the dead branches to "zero", we estimated the specific attainable yield of 2014 ($Ya_{(14)}$)	$Ya_{(14)} = I + a \times NFN_{(14)} + c \times ShadeC_{(14)}$	2
We estimated the primary yield loss in weight as the difference between $Ya_{(14)}$ and $Y_{(14)}$	$PYL_{(14)} = Ya_{(14)} - Y_{(14)}$	3
We estimated the primary yield loss as a percentage of the specific attainable yield of 2014	$\%PYL_{(14)} = \dfrac{PYL_{(14)}}{Ya_{(14)}} \times 100$	4
For the estimation of secondary yield losses in 2015		
Model 2	$Y_{(15)} \sim NFN_{(15)} + DeadB_{(15)} + ShadeC_{(15)} + (1 \mid Plot)$	
Based on the results of the Model 2, we obtained an equation to estimate the actual yield of 2015 ($Y_{(15)}$)	$Y_{(15)} = I + a \times NFN_{(15)} + b \times DeadB_{(15)} + c \times ShadeC_{(15)}$	5
Model 3	$NFN_{(15)} \sim DeadB_{(14)} + ShadeC_{(14)} + (1 \mid Plot)$	
Based on the results of the Model 3, we obtained an equation to estimate the actual fruiting nodes of 2015 ($NFN_{(15)}$)	$NFN_{(15)} = I + a \times DeadB_{(14)} + b \times ShadeC_{(14)}$	6
By setting the dead branches to "zero", we estimated the fruiting nodes that would have been attainable ($NFNa_{(15)}$) without reducing factors of 2014	$NFNa_{(15)} = I + b \times ShadeC_{(14)}$	7
Then, we estimated the loss of fruiting nodes for 2015 ($NFNl_{(15)}$)	$NFNl_{(15)} = NFNa_{(15)} - NFN_{(15)}$	8
Thereby, we considered that estimating a yield with this $NFNl_{(15)}$ using the equation (5), and setting dead branches to "zero" represented the secondary yield losses	$SYL_{(15)} = I + a \times NFNl_{(15)} + c \times ShadeC_{(15)}$	9
To estimate an attainable yield without negative impacts of 2014 and 2015 ($Ya_{(14-15)}$), we replaced equation 7 in equation (5) and then set as zero the dead branches of both years to assume that there were no reducing factors	$Ya_{(14-15)} = I + a \times NFNa_{(15)} + c \times ShadeC_{(15)}$	10
We calculated the secondary yield loss of 2015 $\%SYL_{(15)}$ as a percentage of the $Ya_{(14-15)}$	$\%SYL_{(15)} = \dfrac{SYL_{(15)}}{Ya_{(14-15)}} \times 100$	11

For the estimation of primary economic losses in 2014 and secondary economic losses in 2015

Coffee actual yields and primary and secondary yield losses were estimated in grams of fresh coffee cherries per plant with the equations above, and then were calculated as kilograms per hectare using the data of coffee plant densities. With these latter, economic losses were calculated as following:

Primary Economic loss (PEL) in 2014 was calculated with the price of coffee in that year (USD ha^{-1})	$PEL = PYL_{(14)} \times Price\ of\ coffee_{(14)}$	12
Secondary Economic loss (SEL) in 2015 was calculated with the price of coffee in that year (USD ha^{-1})	$SEL = SYL_{(15)} \times Price\ of\ coffee_{(15)}$	13

Y: actual coffee yield per plant; Ya: attainable yield per plant; NFN: number of fruiting nodes per plant; DeadB: number of dead productive branches per plant; ShadeC: mean annual shade cover; $_{(14)}$: represents the variables in the year 2014; $_{(15)}$: represents the variables in the year 2015; I: represents the intercepts in the equations; a, b and c represent the coefficients in the equations
Yields were estimated in kg of fresh coffee cherries per hectare (using a factor 1/5.6, they can be transformed to green coffee)
The price of coffee in 2014 was 0.48 USD per kg of ripe fresh coffee cherries; in 2015 it was 0.39 USD per kg of ripe fresh coffee cherries. These prices were the same for all coffee plots, given that the farmers sell the coffee to the same company "Compañía Santa Rosa de Turrialba". Indicators of prediction quality in supplementary materials.

Table 3. Characteristics of the structure, diversity and shade cover of the six most promising coffee agroforestry systems (CAF) for providing multiple ecosystem services

Characteristics	CAF1	CAF2	CAF3	CAF4	CAF5	CAF6	Mean ± SD*	Range* (min – max)
Color in Figs. 1-4	red	green	orange	blue	brown	purple		
Size of coffee plantation								
Plot area (ha)	0.22	0.40	0.37	0.22	1.40	1.40	0.9 ± 0.8	0.1 - 4
Densities of coffee plants								
Density of coffee plants (individuals ha^{-1})	5079	3358	3864	4341	4480	4652	4990 ± 1137	3328 - 8943
Distances between coffee rows (cm)	175	204	200	199	196	193	173 ± 25	100 - 234
Distances between coffee plants (cm)	113	146	129	116	114	111	121 ± 18	77 - 169
Densities in the shade canopy								
Density of fruit trees (individuals ha^{-1})	0	0	0	0	80	70	24 ± 44	0 - 270
Density of timber trees (individuals ha^{-1})	0	30	10	20	30	170	33 ± 55	0 - 280
Density of Musaceae plants (individuals ha^{-1})	10	60	260	300	20	20	216 ± 299	0 - 1410
Density of service trees (individuals ha^{-1})	340	280	20	30	180	120	188 ± 156	0 - 550
Total density in shade canopy (individuals ha^{-1})	350	370	290	350	310	380	461 ± 377	0 - 1650
Basal (BA) areas in the shade canopy								
BA of fruit trees (m^2 ha^{-1})	0.00	0.00	0.00	0.00	0.87	0.60	0.4 ± 0.8	0 - 4-0
BA of timber trees (m^2 ha^{-1})	0.00	5.53	0.29	0.71	1.11	2.67	1.5 ± 2.6	0 - 10.4
BA of Musaceae plants (m^2 ha^{-1})	0.05	0.66	3.32	8.83	0.17	0.22	3.5 ± 5.0	0 - 17.3
BA of area of service trees (m^2 ha^{-1})	6.52	6.43	0.12	5.16	1.27	0.61	5.6 ± 5.2	0 - 23.4
Total BA in shade canopy (m^2 ha^{-1})	6.58	12.62	3.72	14.70	3.42	4.10	11.1 ± 8.1	0 - 28.3
Species richness in the shade canopy								
Species richness	2	4	6	5	8	7	4 ± 3	0 - 13
Shannon diversity index	0.13	0.81	0.97	0.61	1.43	1.40	0.8 ± 0.6	0 - 1.9
Shade cover								
Shade cover in 2014 (%)	6	34	7	20	30	20	17 ± 15	0 - 54
Shade cover in 2015 (%)	7	29	8	10	23	16	17 ± 13	0 - 54

*Mean, Standard deviation (SD) and Range (minimum – maximum) of the data of the 61 coffee plots

Musaceae plants: include mainly bananas but also plantains; Service trees: include mainly poro trees *(Erythrina poeppigiana)*; Fruit trees: include mainly oranges *(Citrus sinensis)* and mandarin lemons *(Citrus aurantifolia)*, but also avocados *(Persea americana)*, cas *(Psidium friedrichsthalium)*, arazá *(Eugenia stipitata)* and peach palm *(Bactris gasipaes)*; Timber trees: include mainly *Cordia alliodora* and *Cedrela odorata*

Table 4. Characteristics of cropping practices and management costs of the six most promising coffee agroforestry systems (CAF) for providing multiple ecosystem services

Characteristics	CAF1	CAF2	CAF3	CAF4	CAF5	CAF6	Mean ± SD*	Range* (min – max)
Color for being identified in Figs. 1-4	red	green	orange	blue	brown	purple		
Cropping practices in 2014								
Machete weeding (number yr^{-1})	2	0	3	1	1	1	1.3 ± 1.3	0 - 5
Harvests of coffee (number yr^{-1})	12	10	8	12	13	13	10.6 ± 2.1	5 - 14
Applications of fertilizers (number yr^{-1})	2	1	1	2	0	0	1.4 ± 0.8	0 - 3
Applications of fungicides (number yr^{-1})	6	4	1	1	5	1	2.2 ± 1.9	0 - 7
Applications of herbicides (number yr^{-1})	2	3	1	1	2	2	1.6 ± 1.2	0 - 4
Pruning of coffee plants (number yr^{-1})	1	1	0	0	1	1	0.8 ± 0.4	0 - 1
Cash costs in 2014								
Cost of hired labor (USD ha^{-1})	0	465	907	2512	226	226	646 ± 860	0 - 2919
Cost of inputs (USD ha^{-1})	624	391	245	682	253	42	449 ± 245	0 - 1414
Total cash cost (USD ha^{-1})	624	856	1152	3194	479	268	1094 ± 931	111 - 3645
Cropping practices in 2015								
Machete weeding (number yr^{-1})	1	0	1	3	1	1	1.4 ± 1.4	0 - 5
Harvests of coffee (number yr^{-1})	12	9	12	10	12	12	8.5 ± 3.4	0 - 13
Applications of fertilizers (number yr^{-1})	1	1	2	1	0	0	1.1 ± 0.8	0 - 3
Applications of fungicides (number yr^{-1})	6	4	1	1	6	2	2.2 ± 1.9	0 - 7
Applications of herbicides (number yr^{-1})	2	2	1	0	2	2	1.5 ± 1.1	0 - 5
Pruning of coffee plants (number yr^{-1})	1	1	1	1	1	1	0.9 ± 0.3	0 - 1
Cash costs in 2015								
Cost of hired labor (USD ha^{-1})	0	418	0	0	121	121	190 ± 398	0 - 2182
Cost of inputs (USD ha^{-1})	626	526	353	283	277	62	365 ± 251	0 - 1449
Total cash cost (USD ha^{-1})	626	943	353	283	399	184	555 ± 536	0 - 2824

Mean, Standard deviation (SD) and Range (minimum – maximum) of the data of the 61 coffee plots.

Table 5. Indicators of ecosystem services of the most promising coffee agroforestry systems (CAF) to provide multiple ecosystem services

Indicators of ecosystem services	Boundary value* (median)	CAF1	CAF2	CAF3	CAF4	CAF5	CAF6	Mean ± SD**	Range** (min – max)
Color for being identified in Figs. 1-4		red	green	orange	blue	brown	purple		
Regulation of diseases in 2014									
Primary yield loss (%)	9	2	6	4	5	2	3	14 ± 13	0.5 - 66
Primary economic loss (USD ha^{-1})	291	90	66	76	120	79	55	460 ± 486	14 - 2326
sAUDPC Coffee leaf rust (%)	-	36	45	55	63	24	20	58 ± 15	11 - 81
sAUDPC Brown eye spot (%)	-	7	5	3	1	6	13	8 ± 4	0.8 - 27
Maximum index of dieback (%)	-	34	23	40	34	41	32	39 ± 11	3 - 63
Provisioning of agroforestry products in 2014									
Coffee yield (kg ha^{-1})	6174	11185	2257	3742	5137	7189	4241	6389 ± 3680	1223 - 18818
Cash Flow (USD ha^{-1})	1645	4673	213	620	2400	2926	1740	2081 ± 1853	-1435 - 8574
Value of domestic consumption (USD ha^{-1})	47	85	70	419	256	70	70	158 ± 272	0 - 1222
Regulation of diseases in 2015									
Secondary yield loss (%)	36	11	18	4	17	18	0	38 ± 26	0 - 100
Secondary economic loss (USD ha^{-1})	807	284	564	70	357	504	0	1082 ± 956	0 - 4499
sAUDPC Coffee leaf rust (%)	-	21	41	45	48	19	23	44 ± 13	19 - 75
sAUDPC Brow eye spot (%)	-	15	14	5	9	14	16	15 ± 6	3 - 32
Maximum index of dieback (%)	-	40	43	49	50	31	46	43 ± 11	25 - 80
Provisioning of agroforestry products in 2015									
Coffee yield (kg ha^{-1})	712	6481	8892	4056	1926	6347	917	2262 ± 3354	0 - 15765
Cash Flow (USD ha^{-1})	-21	1657	2190	1076	396	1838	139	323 ± 1315	-2579 - 5040
Value of domestic consumption (USD ha^{-1})	8	413	68	37	331	68	68	157 ± 283	0 - 1342
Maintenance of soil fertility									
Potassium (mg ha^{-1})	42	25	43	90	82	20	21	68 ± 61	20 - 314
Carbon (%)	3	5	4	2	2	8	9	4 ± 3	2 - 13
Acidity (mg ha^{-1})	139	53	139	65	122	36	47	173 ± 128	9 - 555
Carbon sequestration									
Carbon in fruit trees (Mg ha^{-1})	0	0	0	0	0	2.0	1.3	1 ± 3	0 - 16
Carbon in timber trees (Mg ha^{-1})	0.3	0	7.8	0.4	0.9	1.5	3.4	2 ± 4	0 - 15
Carbon in service trees (Mg ha^{-1})	2.4	3.0	2.5	0.2	5.1	1.4	0.3	5 ± 6	0 - 32
Number of desirable areas (out of 48) in which the CAF were located		36	32	32	38	40	38		

*The boundary values used to determine desirable areas in this study (See Figs. 1-4) were the medians of ecosystem service indicators, which meant that the desirable levels of ecosystem services indicators were those located at least within the 50% of the best levels.

**Mean, Standard deviation (SD) and Range (minimum – maximum) of the data of the 61 coffee plots.

sAUDPC: standardized area under the disease progress curve

Table 6. Summary of the agroforestry structure, coffee yield losses due to diseases, yields, and strategies of management of the six most promising coffee agroforestry systems (CAF)

CAF	Agroforestry structure	PYL (%)	SYL (%)	Coffee yields*	Disease management	Other cropping practices
CAF1	Simple coffee agroforestry system, basically a combination of coffee and service trees. Highest density of coffee plants	2	11	High yields with bienality	High chemical input	High chemical input and family labor
CAF2	Medium diversified coffee agroforestry system, coffee-service trees-musaceaes-timber trees, where service trees dominate the shade canopy and timber trees are big	6	18	High yields with bienality	High chemical input	High chemical input and hired labor
CAF3	Medium diversified coffee agroforestry systems, coffee-musaceaes-service trees-timber trees, where musaceas dominate in the shade canopy	4	4	Acceptable and stable yields	Low chemical input	Rational use of chemical input and family labor
CAF4	Medium diversified coffee agroforestry systems, coffee-musaceaes-service trees-timber trees, where musaceas dominate	5	17	Acceptable yields with bienality	Low chemical input	Rational use of chemical input and family labor
CAF5	Highly diversified coffee agroforestry systems, coffee-service trees-timber trees-fruit trees-musaceas, where service trees dominate	2	18	High and relatively stable yields	High chemical input	High chemical input and hired labor
CAF6	Highly diversified coffee agroforestry systems, coffee-service trees-timber trees-fruit trees-musaceas, where timber trees dominate	3	0	Acceptable yields with bienality	Low chemical input	Rational use of chemical input and hired labor

PYL: primary yield loss; SYL: secondary yield loss
*We considered acceptable yields those around 4000 kg of fresh coffee cherries per hectare, and high or low yields those above or below that number, respectively
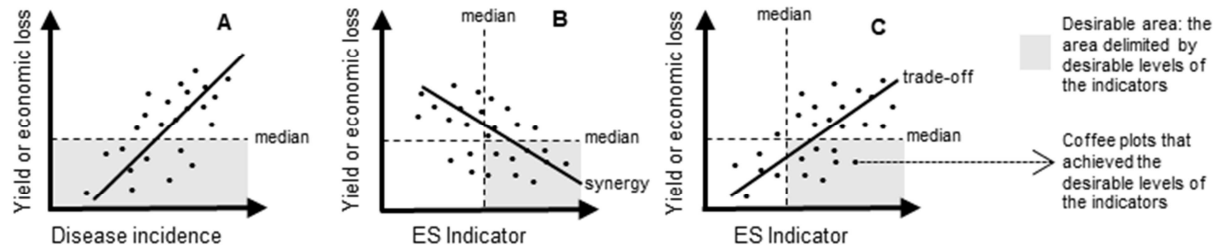
ES Indicator: represents ecosystem service indicators of provisioning of agroforestry products, maintenance of soil fertility or carbon sequestration

Fig. 1. Interpretation of the relationships between yield or economic losses and disease incidence, and indicators of ecosystem services (A: represents the loss due to diseases; B: represents synergy; C: represents trade-off) and the identification of 'desirable areas' in which coffee plots achieved desirable levels of ecosystem service provisions.
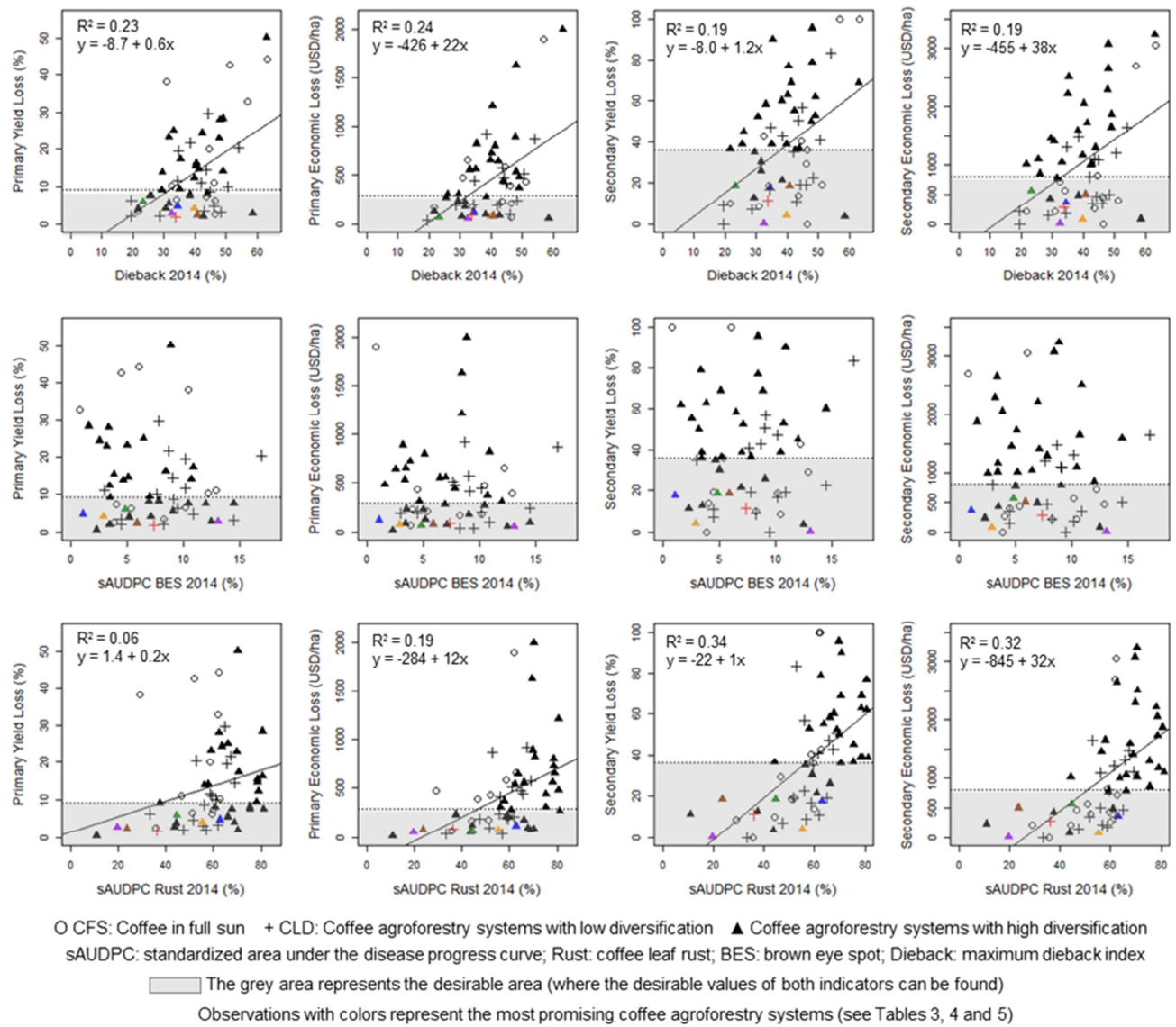
1

Fig. 2. Relationships between indicators of losses and indicators of presence of diseases and different types of coffee plots achieving the most desirable low levels of losses.
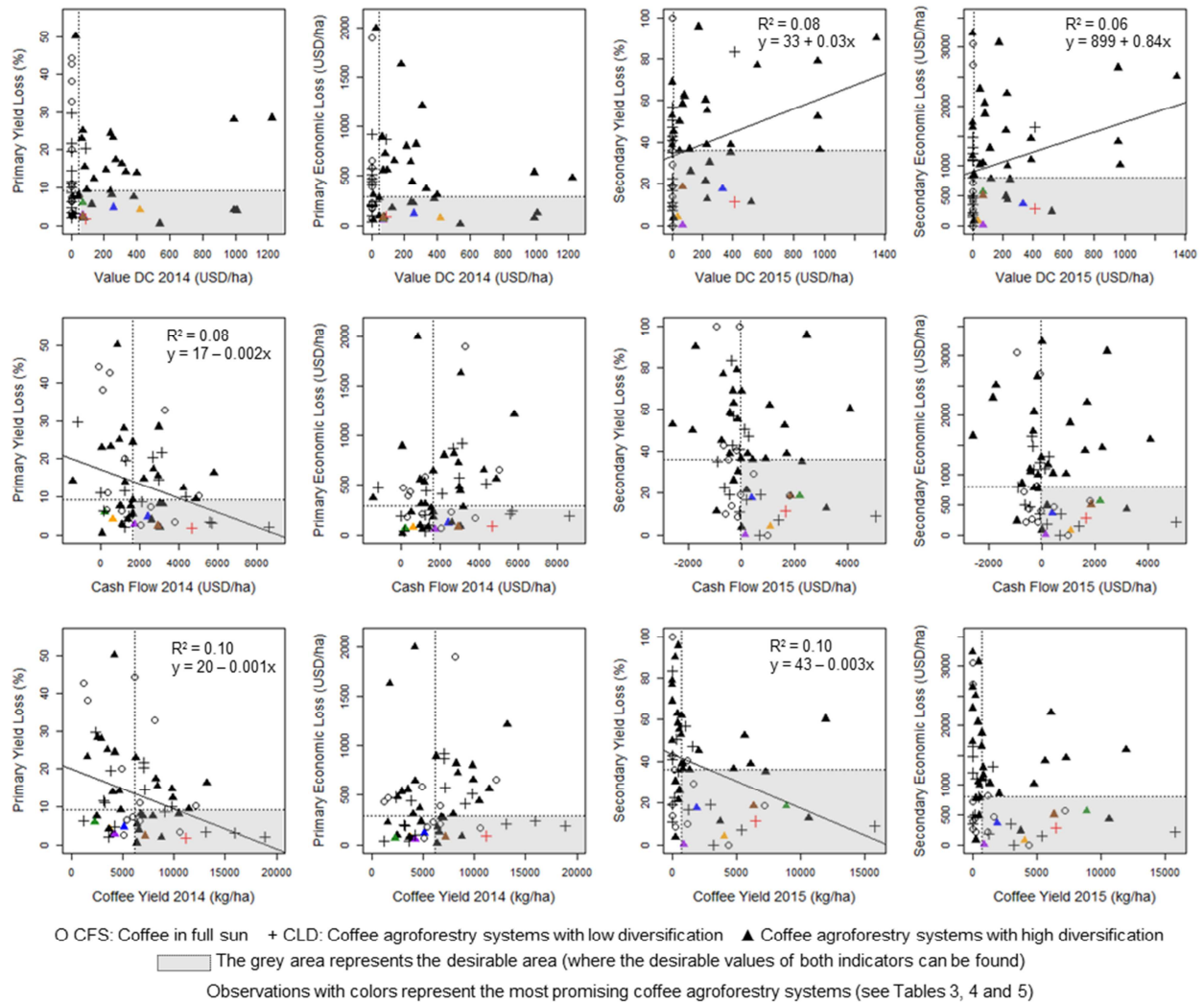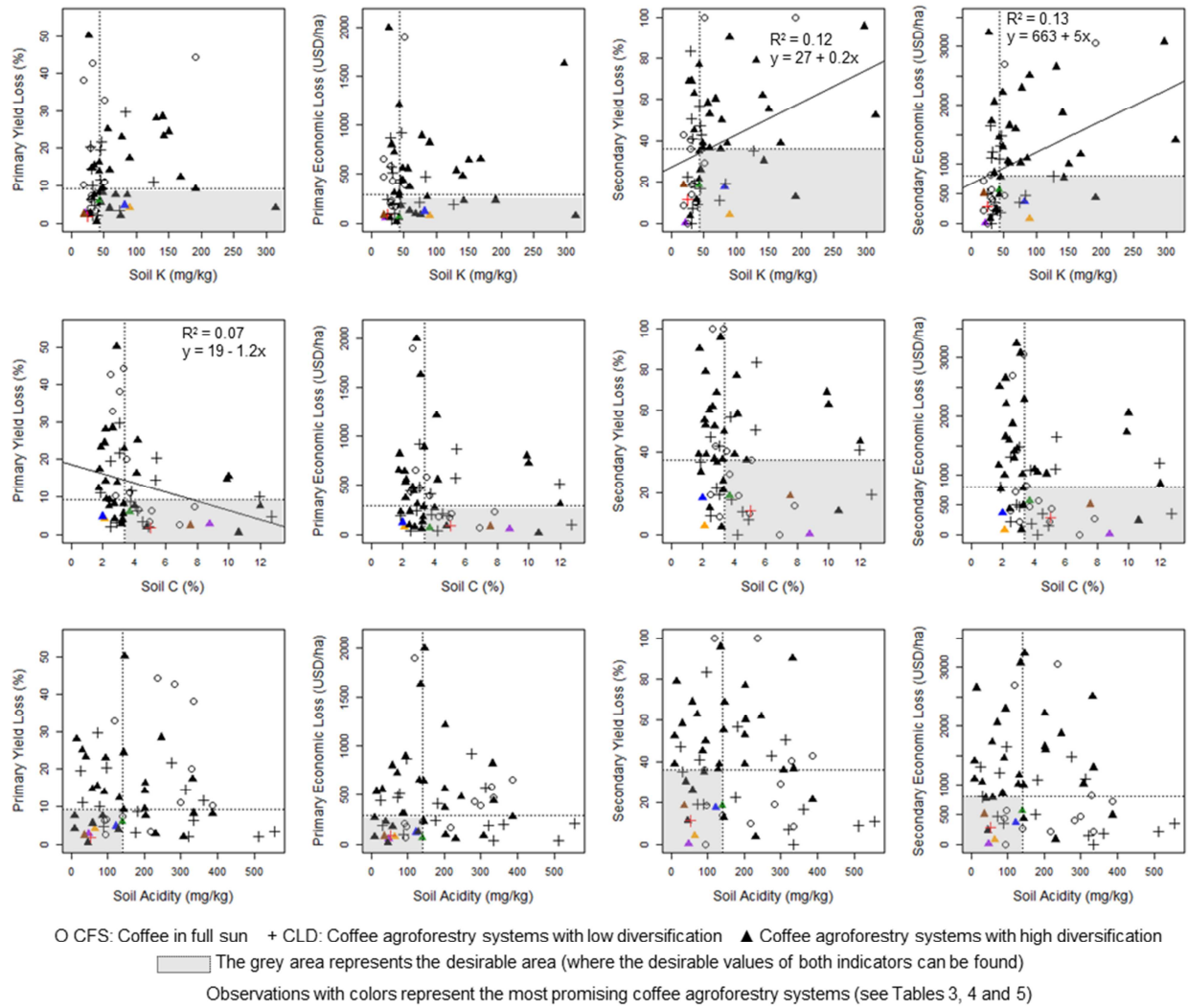
Fig. 3. Relationships between indicators of losses and indicators of provisioning of agroforestry products and different types of coffee plots achieving the most desirable levels of ecosystem services.

Fig. 4. Relationships between indicators of losses and indicators of maintenance of soil fertility and different types of coffee plots achieving the most desirable levels of ecosystem services.
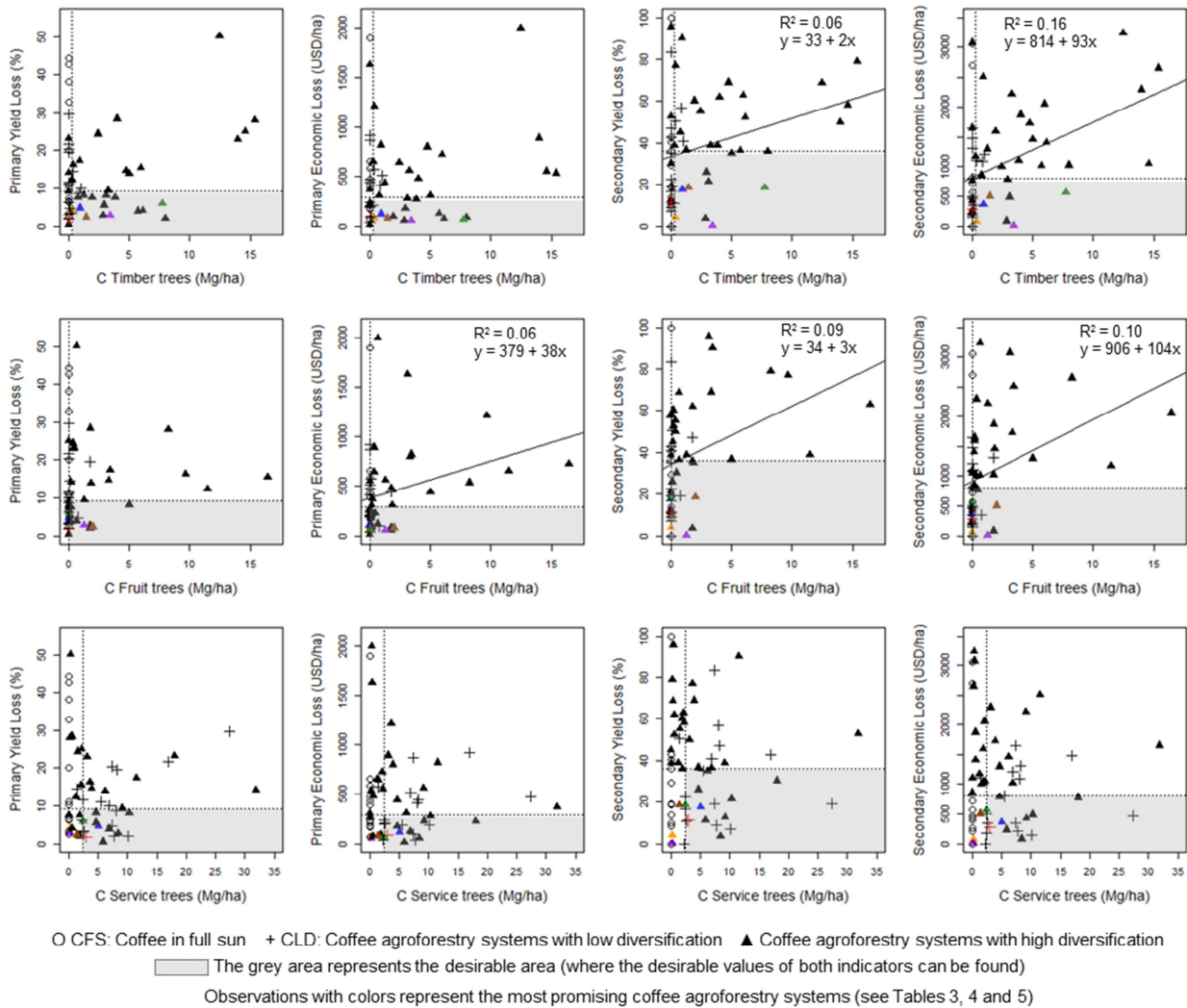
Fig. 5. Relationships between indicators of losses and indicators of carbon sequestration and different types of coffee plots achieving the most desirable levels of ecosystem services.
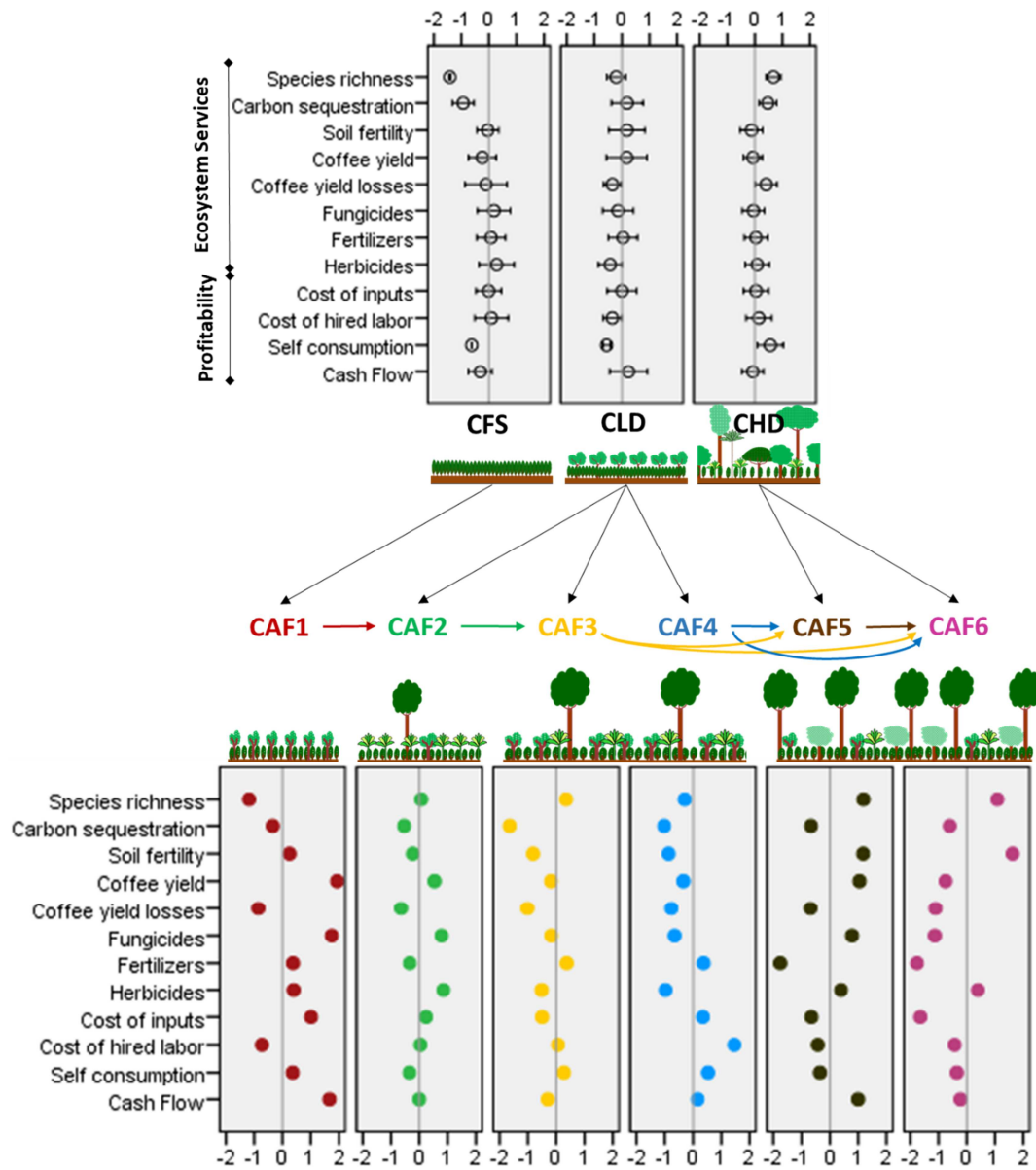
Fig. 6. Summary of ecosystem services and economic profitability provided by coffee in full sun (CFS), agroforestry systems with low diversification (CLD) and high diversification (CHD) and the proposed pathway toward the six most promising coffee agroforestry systems (CAF1 to CAF6). The possible transition pathway to go from actual coffee systems types (CFS, CLD, CHD) to the most promising CAFs are indicated by black arrows. Pathway to go from the low sustainable to the more sustainable cropping system (in terms of pesticide use) are indicated by colored arrows. The illustrative variables of ecosystem services provision: species richness, carbon sequestration, soil fertility, coffee yield, coffee yield losses, fungicides, fertilizers, herbicides; the illustrative variables of economic profitability: cost of inputs, cost of hired labor, self-consumption and cash flow, were calculated from the original variables. Respectively: species richness, carbon sequestration ($Mg\ ha^{-1}$), maintenance of soil fertility (%C), coffee yield ($kg\ ha^{-1}$), coffee yield losses ($kg\ ha^{-1}$), applications of fungicides (number yr^{-1}), applications of fertilizers (number yr^{-1}), applications of herbicides (number yr^{-1}), value of domestic consumption ($USD\ ha^{-1}$), cost of inputs ($USD\ ha^{-1}$), cost of hired labor ($USD\ ha^{-1}$), cash Flow ($USD\ ha^{-1}$). These variables were cumulated over two years, then centered to the average and standard deviation of the 61 plots. Error bar represents 95% of the confidence interval.

6

Highlights

We quantified primary and secondary yield losses due to diseases in coffee agroecosystems

We also quantified indicators of ecosystem services: provisioning of agroforestry products, soil fertility and carbon sequestration

We identified six most promising coffee agroforestry systems (CAFs) for reducing losses while providing other ecosystem services

The six CAFs are promising production models for the design or re-design of coffee agroecosystems

Disease regulation in CAFs can be enhanced by the appropriate combination of plant biodiversity, shade cover, soil fertility and cropping practices

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: