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Climate-friendliness of cocoa agroforests is compatible with productivity increase

Abstract

There is increasing demand for agricultural commodities that are produced in a climate-friendly manner. At the same time, in many or most tropical countries there is need for intensification of agricultural production to increase yields and incomes, and this usually requires higher external inputs that may cause additional greenhouse gas emissions. Here we investigate if production methods that have a beneficial effect on the climate (are climate-friendly) are compatible with increased inputs and yields for traditional, shaded cocoa (*Theobroma cacao*) production systems (locally known as cabruças) in southern Bahia, Brazil. We use two easily measurable and manageable dimensions of climate-friendliness, namely the carbon (C) stocks in the large trees and the C footprint as related to on-farm agrochemical and fuel use. Through interviews and field inventories in 26 cabruça farms representing a range of production practices and intensities, we identify the combinations of management practices, yields, C stocks and C footprints typically found in the region. We find that yield levels up to the highest encountered yield of 585 kg ha⁻¹, or twice the current regional average of 285 kg ha⁻¹, are compatible with an aboveground C stock in the large shade trees (>30 cm diameter at breast height) of up to 65 Mg ha⁻¹ and up to 55% shade. Higher C stocks and shade levels are generally associated with yields below the regional average. Input-related C emissions increased non-linearly with increasing yield, but even the highest encountered yields were compatible with low (<0.25 kg CO₂e kg⁻¹ of cocoa) to medium (<0.5 kg CO₂e kg⁻¹ of cocoa) input-related emission levels. Cocoa yields responded positively to increased fertilizer applications, provided that other factors, including shade levels, were not limiting. Consequently, the highest input-related emissions (>1 kg CO₂e kg⁻¹ of cocoa) were related to large fertilizer applications that did not proportionately increase yields. We conclude that doubling the cocoa output from southern Bahia, where cabruças are the predominant form of growing cocoa, is compatible with climate-friendly production practices, measured by local standards. We suggest that the presented methodology can be used to identify opportunities for climate-friendly intensification of tree crops more generally, thereby increasing the contribution of commodity production to global climate change mitigation.

Key words: Carbon stock; Climate-smart agriculture; Cocoa agroforest; Green intensification; Product Carbon Footprint; *Theobroma cacao*

37 **1 Introduction**

38 There is increasing demand for sustainably produced commodities (Tscharrntke et al.
39 2011; Millard 2011; Waldron et al. 2012). In an era of climate change, criteria of
40 sustainability should also consider the impact of commodity production on greenhouse
41 gas emissions (Rahn et al. 2014; van Rikxoort et al. 2014). Here we define practices
42 that have a more positive or less negative effect on the climate than local standard
43 practices as climate-friendly. Climate-friendliness in combination with practices that
44 reduce the vulnerability of production systems to climate change result in climate-
45 smart practices.

46 Two measures for the impact of agricultural commodities on the climate are
47 commonly discussed, in most cases independently of each other. Popular among
48 supply chain actors is the carbon (C) footprint, which reflects the amount of
49 greenhouse gases (in CO₂ equivalents, CO₂e) emitted for the production of a unit of the
50 respective commodity (Hillier et al. 2011; van Rikxoort et al. 2014). Variables
51 influencing the C footprint at farm level include the use of mineral and organic
52 fertilizers and pesticides, fossil fuel use for agricultural operations and transport, and
53 any on-farm processing (van Rikxoort et al. 2014). A key variable is also the per-hectare
54 yield of product (or products in diversified systems), because the emissions generated
55 on a hectare of farm area are divided by the production from that area to obtain the C
56 footprint.

57 The other measure of climate impact that is more popular among agro-ecologists is the
58 standing C stock of a land use system, often compared to the local natural forest
59 vegetation (Somarriba et al. 2013; Schroth et al. 2014). There is a substantial literature
60 on the C storage potential of agroforestry systems (e.g., Kumar and Nair 2011). For
61 agricultural commodities such as coffee (*Coffea* spp.) and cocoa (*Theobroma cacao*)
62 that can be produced in shaded agroforests with high standing C stocks or in full-sun
63 systems with much lower C stocks, measuring C stocks is particularly important and
64 the fact that they are not considered in the calculation of a product C footprint is a
65 significant caveat of that metric. Therefore, it has been proposed to consider C
66 footprint and C stock in combination as two dimensions of climate-friendliness when
67 classifying land use systems and products according to their climate impact (van
68 Rikxoort et al. 2014).

69 Here we apply both metrics of climate-friendliness to traditional cocoa production
70 systems (cabruças) in southern Bahia, located in the northeast of Brazil and the
71 country's main cocoa production region. In cabruças, the cocoa is grown under the
72 canopy of predominantly native forest trees that were either retained when cocoa was
73 first planted into thinned forest or regenerated later. Some trees are also planted
74 (Johns 1999; Schroth et al. 2011; Sambuichi et al. 2012). The native or planted trees
75 forming a canopy above shade-tolerant tree crops such as cocoa or coffee (*Coffea* sp.)

76 are often referred to as shade trees (Tscharntke et al. 2011). The diversified tree
77 canopy of the cabruças, which are the predominant land use and the main form of
78 producing cocoa in southern Bahia, is partly credited with maintaining the biodiversity
79 of this part of the Atlantic forest biome despite its highly fragmented and much
80 reduced natural forest cover (Faria et al. 2007; Cassano et al. 2009). A recent study
81 also estimated that cabruças contribute 59% to the total C stocks in the region's tree
82 vegetation, while natural forest remnants are only responsible for 32% and fallows for
83 9%, illustrating the critical importance of these traditional land use systems for
84 conserving regional C stocks (Schroth et al. 2014).

85 However, owing to a combination of extensive management practices and high disease
86 pressure, average cocoa yield levels for southern Bahia in 2010 were only around 285
87 kg ha⁻¹ (Midlej and Santos 2012), lower than in major African cocoa producing
88 countries (Gockowski and Sonwa 2011). The average value given by Midlej & Santos
89 (2012) also includes more intensively managed areas, suggesting that typical yield
90 levels of cabruças are even lower. Following a period of low cocoa prices and the
91 introduction of the witches' broom fungus (*Monilophthora perniciosa*) into Bahia in the
92 late 1980s, Brazil switched from a major cocoa exporter to a cocoa importer as the
93 national cocoa output collapsed from 380,000 tons in 1990/91 to 138,000 tons in
94 1998/99 (International Trade Centre 2001). Moreover, a recent study shows that at
95 typical prices of the last years and average levels of productivity, the income from
96 cocoa under the common share-cropping system of the region remains below the
97 legally stipulated minimum salary (Gomes et al. 2013). Therefore, there is a strong
98 pressure to intensify cocoa production systems to increase the incomes of the rural
99 population and meet the needs of the national cocoa industry. However, in Bahia as
100 elsewhere, the intensification of traditional cocoa farms is often associated with a
101 technological package of replanting or grafting, pruning and fertilization that also often
102 involves the reduction of the shade canopies. Schroth et al. (2014) showed that low-
103 shade, intensified cocoa production systems in southern Bahia had on average only
104 53% of the C stocks of traditional cabruças, indicating a considerable risk to regional C
105 stocks if intensification measures involving shade reduction are implemented on a
106 large scale. The question whether the intensification of cocoa farms to increase their
107 yields and profitability can be conducted in such a way that their climate-friendliness is
108 maintained is therefore of particular relevance to the region.

109 Through interviews with farm owners or managers and field inventories, we
110 determined levels of C footprints and C stocks in cabruça systems representing the
111 wide range of management intensities, yield levels and vegetation characteristics
112 found in the core of the cocoa production region of southern Bahia. We identify
113 practices associated with the more climate-friendly cocoa production systems and
114 propose target values for climate-friendly cocoa for the region. We show that there is
115 no inherent contradiction between a substantial productivity increase over the current

116 regional baseline and climate-friendliness. We also discuss how public and private
117 actors could provide incentives for productive yet climate-friendly tree crop
118 production systems. We suggest that a similar methodology could be used in other
119 regions to identify opportunities for jointly increasing climate-friendliness and
120 productivity of tree crop production systems, thereby increasing the contribution of
121 tree crop agriculture to global climate change mitigation.

122

123 **2 Methods**

124 2.1 Field data collection

125 In southern Bahia, Brazil's main cocoa production region, cocoa is mostly grown in
126 traditional shaded systems locally known as cabruças (Schroth et al. 2011). Cabruças
127 were originally established by thinning primary or secondary forest and underplanting
128 the remaining canopy trees with cocoa trees. These systems were often enriched with
129 local or exotic fruit trees, and many tree species regenerated later especially during
130 phases of extensive management. Farms that were originally established after clear-
131 felling of the forest and planting of cocoa with leguminous shade trees, but later
132 invaded by native tree species are also common. The structure, management and
133 diversity of cabruças has been reviewed previously (Faria et al. 2007; Schroth et al.
134 2011; Sambuichi et al. 2012). Traditional cocoa production systems that are similar to
135 cabruças are also common in other humid tropical countries, notably in Cameroon and
136 parts of West Africa (Duguma et al. 2001).

137 Twenty-six traditional shaded cocoa farms (cabruças) were randomly selected in the
138 Ilhéus-Itabuna-Uruçuca triangle in the heart of the cocoa region of southern Bahia
139 during the year 2013, usually by driving up feeder roads and visiting farms located
140 along the road. In some of the farms, contacts with the owners or administrators had
141 been established through prior, unrelated research projects, and some owners were
142 personally known to members of the research team and were included to cover a wide
143 range of management types. An interview based on a questionnaire was conducted
144 with the owner or manager to collect information about the farm, its history,
145 management practices, yields, problems, and future plans. The interview typically took
146 about 1.5 hours. Following the interview, the researcher and respondent identified
147 jointly an area of the farm where yield levels and management practices were typical
148 for the farm as a whole. The area was visited, which usually involved a foot-walk
149 through a considerable part of the farm during which the composition of the cabruças
150 and management practices were observed and discussed.

151 At the selected part of the farm, a field inventory was carried out in a randomly
152 located plot of 100 m by 25 m. After delimiting the plot, the diameter at breast height
153 (DBH), measured at 130 cm above the ground, of all trees with a DBH of more than 30

154 cm was measured. This threshold value was chosen because a previous analysis of
155 inventories in 51 traditional cabruças including all trees with a DBH >10 cm had shown
156 that the trees with DBH between 10 cm and 30 cm only contributed about 10% to the
157 C stocks, while their measurement adds considerably to the time needed for an
158 inventory (Schroth et al. 2014). Moreover, smaller trees are also most affected by
159 management measures such as thinning for shade adjustment and therefore
160 constitute a less durable C pool than trees with a DBH >30 cm. The same applies to the
161 cocoa trees themselves whose C stocks are subject to routine operations such as
162 pruning and replanting. In this paper, we refer to trees with a DBH >30 cm as large
163 trees and propose this stratum as a good proxy of total C stocks in the tree vegetation
164 that is relatively quick to measure and insensitive to day-to-day management
165 practices. Tree species were identified only if special allometric equations were
166 available for the respective species, especially *Cecropia* spp. and palms, although the
167 latter only rarely had the required minimum diameter.

168 Cocoa tree density was determined by drawing circles with a radius of 10 m around the
169 25 m and the 75 m points on the 100 m baseline of the inventory plot and counting all
170 cocoa trees within these circles. To obtain an average diameter of the cocoa trees, the
171 stem diameter at 30 cm height of 10 randomly selected cocoa trees in the proximity of
172 each circle was measured. The shade level above the cocoa canopy was measured with
173 a densitometer by walking a line on or parallel to the baseline through the inventory
174 plot and taking a reading every 10 steps for a total of 10 readings which were
175 averaged. A densitometer is a periscope-like device that allows to observe a defined
176 circular area vertically above the operator. For each reading, the possible levels were
177 predominantly open (0), half open (0.5), and predominantly shaded (1). Only the tree
178 canopy, but not the cocoa canopy, was considered in the readings. If the sight of the
179 densitometer was obstructed by cocoa leaves, the operator moved forward on the
180 same line until an unobstructed reading of the tree canopy could be taken.

181

182 2.2 Data analysis

183 Aboveground biomass was estimated with allometric equations. We used equations
184 developed by Tiepolo et al. (2002) for native trees of the Atlantic forest region, by
185 Pearson et al. (2005) for *Cecropia* spp. and palms, and by Andrade et al. (2008) for
186 cocoa trees. C stocks were then estimated by assuming a C content of the biomass of
187 50%. The input-related C footprint was calculated with the Cool Farm Tool Version 2.0
188 beta 1 (Hillier et al. 2011). This software estimates greenhouse gas (GHG) emissions
189 related to agrochemical inputs and management practices and converts them into
190 carbon dioxide equivalents (CO₂e) per unit product (cocoa). As inputs we considered
191 mineral and organic fertilizer, pesticides and fossil fuel for farm operations, on-farm
192 transport and on-farm processing (e.g. drying). We did not include background

193 emissions of N₂O from soil and litter, because we considered that these emissions
194 would be about similar in an agroforest composed mostly of native trees as in native
195 forest and therefore not truly a result of cocoa production. Moreover, since
196 background emissions are, by definition, unrelated to management practices, they
197 tend to obscure the influence of management decisions on GHG emissions. The C
198 footprint was calculated at farm level, including only emissions that were directly
199 connected to the cocoa system, but not emissions related to cattle (*Bos indicus*) or
200 other crops that were grown in separate areas on the farm.

201

202 **3 Results and discussion**

203 3.1 Characteristics of the cocoa farms

204 The 26 cocoa farms visited for this study covered a wide range of sizes (smallholder to
205 estate size), cocoa tree densities (from about half to 1.3 times the recommended 1100
206 trees per hectare), the use of grafting on either old trees or newly planted seedlings to
207 introduce more productive and disease resistant cocoa germplasm (none to 100% of
208 the trees), and mineral fertilizer use (none to 360 kg ha⁻¹ of nitrogen, phosphorus,
209 potassium and dolomitic lime (see footnote 2 in Table 1 for details), with some farms
210 also applying some cattle manure). Yield levels ranged from a very low 66 kg ha⁻¹ to a
211 reasonable (by regional standards) 585 kg ha⁻¹, about twice the regional average of 285
212 kg ha⁻¹ (Table 1). Average yield of the sample was 275 kg ha⁻¹, very close to the
213 regional average. Pesticide use also varied among farms, with 35% of the farms using
214 none and the others using mostly Roundup (glyphosate, N-(phosphonomethyl)glycine)
215 for chemical weed control, which tends to be cheaper than manual weeding. Less
216 common pesticide uses included products to control leaf-cutter ants as well as lime
217 (calcium carbonate) applied to the cocoa tree trunks and branches as a preventive
218 measure of disputed effectiveness against the witches' broom fungus. One farm used
219 neem (*Azadirachta indica*) extracts to control insects. The cocoa trees were in most
220 cases several decades old. The respondents had generally more than a decade, and
221 mostly several decades, of experience with cocoa growing in the region, and 35% had
222 some formal agricultural training.

223 *[Table 1 here]*

224 Among the different inputs used on the cocoa farms, mineral fertilizer had the
225 strongest positive impact on yield ($r^2=0.47$, $p<0.001$; Fig. 1). Most farms that applied
226 no mineral fertilizer had yields below the regional average, while almost all farms
227 applying more than 150 kg ha⁻¹ of fertilizer had above-average yields. While some
228 farms applied organic fertilizer (mostly cattle manure), the quantities were generally
229 small and the distribution probably very unequal and their inclusion did not improve
230 the relationship with yield ($r^2=0.34$, $p<0.01$). In some farms applying fertilizer, yields

231 were much lower than expected from the overall relationship. This suggests that other
232 factors, such as light or the overall condition of the cocoa plants, were yield limiting
233 and the added fertilizer was largely wasted (Fig. 1). This will be discussed further
234 below. While yields also tended to increase with increased application of pesticides
235 and increased percentage of grafted cocoa trees, these relationships were not
236 significant (data not shown). This was in line with the farmers' opinions about
237 possibilities to increase cocoa production on their farms. The most frequent responses
238 were to apply mineral or organic fertilizer (40% of respondents), to improve the
239 general management of the plantation through weeding and pruning (40%), and to
240 plant or replant more cocoa trees (36%). Reducing the shade (16%) and grafting (12%)
241 were mentioned less frequently. Multiple responses were permitted.

242 *[Figure 1 here]*

243

244 3.2 Carbon stocks

245 While all farms were shaded, as is the norm in the region with very few recent
246 exceptions, numbers of large trees (>30 cm diameter) ranged from 8 to 112 per
247 hectare and shade levels ranged from lightly shaded (20%) to very heavily shaded
248 (90%, suggesting a history of semi-abandonment; Table 1). Recommended shade levels
249 in the region are 40-50% (Gramacho et al. 1992), while Johns (1999) measured shade
250 levels of 50-60%. Average aboveground C stocks in the large shade trees were 59 Mg
251 ha⁻¹, plus 10 Mg ha⁻¹ in the cocoa trees (Table 1). One farm with a notable stock of very
252 large trees had an estimated C stock of 148 Mg ha⁻¹ in the large trees. On average, the
253 C stocks were higher than the 49 Mg ha⁻¹ reported for shaded cocoa systems in Central
254 America (Somarriba et al. 2013), but lower than the 87 (range 14-182) Mg ha⁻¹ on
255 average, of which 82 Mg ha⁻¹ on average were in the shade trees, in 51 traditional
256 cabruças in southern Bahia reported by Schroth et al. (2014). Unlike the present study,
257 this previous study had included all trees with a DBH >10 cm, with trees with DBH
258 between 10 and 30 cm contributing about 10% to the total C stocks. In addition, the
259 previous study had covered the whole cocoa zone of southern Bahia including some
260 remote sites where cabruça management may have been even more extensive than in
261 the present sample that focused on the heart of the cocoa zone.

262 Considering the high C stocks and low yields of cabruças, one objective of this study
263 was to establish what level of C stocks, as one dimension of climate-friendliness, would
264 still be compatible with management intensification and higher yield levels. Overall,
265 yields tended to be negatively related to C stocks, as would be expected (Fig. 2).
266 However, this relationship was only apparent for yields below the regional average of
267 285 kg ha⁻¹, but not for above-average yields. Yield levels up to the maximum observed
268 in this farm sample (585 kg ha⁻¹) and about twice the regional average could be

269 achieved with a C stock in the large shade trees of up to 65 Mg ha⁻¹. Higher C stocks in
270 the large trees than 65 Mg ha⁻¹ were in all cases associated with yields below the
271 regional average (Fig. 2).

272 *[Figure 2 here]*

273 Aboveground C stocks in the large trees of up to 65 Mg ha⁻¹ were associated with
274 shade levels of up to 55% (Fig. 3). Farms with C stocks in the large trees above 65 Mg
275 ha⁻¹ had shade levels above 55% and cocoa yields below the regional average. This
276 suggests that a "65/55 rule" for C stocks and shade, respectively, characterized the
277 boundary conditions of a shade canopy that still permitted cocoa yields above the
278 regional average. As mentioned, current recommendations for cocoa shading in the
279 region are 40-50% and the average shade level found in our study was within this
280 range (Table 1), but recommendations are not always followed (Johns 1999). It should
281 be noted that within this adequate range of C stock-shade combinations, the
282 relationship between those two variables was extremely loose, so that the same level of
283 shading could be associated with widely differing amounts of C storage in the trees.
284 Schroth et al. (2014) have proposed that the concentration of C stocks in few, large
285 shade trees with a high canopy would result in less shading per unit C storage than if C
286 was stored in many small trees with a lower canopy. They therefore suggested that
287 cabruca management should emphasize the conservation of large trees which are also
288 likely to have the greatest value for associated fauna and flora (Schroth et al. 2011;
289 Cassano et al. 2009).

290 *[Figure 3 here]*

291

292 3.3 Carbon emissions

293 Of the input-related GHG emissions, two thirds were caused by fertilizer application
294 and the remainder by pesticide and fossil fuel use (Table 1). All three emissions types
295 were highly variable, ranging from zero for the most extensively managed farms that
296 used no inputs at all to several times the average. On most farms, transport was on
297 mule-back and did not affect the C emissions. On all farms, cocoa was sun-dried or, if
298 necessary, artificially dried using wood from the farm, mostly from the shade trees in
299 the cabruca. Gas drying had in the past been promoted by the extension service and
300 used on some farms but was now generally considered too expensive. Therefore, post-
301 harvest operations did not affect the C footprint. This is an important difference to
302 coffee where the wet-processing and drying can make a major contribution to the total
303 C footprint at farm level (van Rikxoort et al. 2014).

304 On average, the input-related C emissions increased with increasing yields for low yield
305 levels but then reached a plateau upward of around 400 kg ha⁻¹ (Fig. 4). The highest

306 yields were related to below-average emissions. On the other hand, the highest
307 emissions were observed at low to medium yields when excessive levels of fertilizer
308 were applied under conditions where the cocoa trees were not able to respond with
309 proportional yield increases. This was either because they were too heavily shaded or
310 because of other yield-limiting factors, such as poor maintenance of the cocoa trees.
311 High C footprint levels have also been reported for some low-yielding, traditional
312 coffee agroforests in Mesoamerica (van Rikxoort et al. 2014). Our data suggest that
313 under the conditions of southern Bahia, yield increases above the regional average are
314 not in contradiction to low input-related C emissions per unit product. Using the
315 classification of input-related emissions levels proposed in Fig. 4, the highest yield
316 levels observed in this study could be achieved with low to medium emissions levels. It
317 is possible that much higher yields would result in higher emissions per unit product
318 because of the higher agrochemical inputs needed to sustain such yields. However,
319 this could not be tested with our sample of farms which covered the typical range of
320 inputs and yields found in shaded cocoa farms in southern Bahia.

321 *[Figure 4 here]*

322

323 3.4 Towards climate-friendly cocoa intensification

324 Figure 5 is a graphic attempt to quantitatively define climate-friendly cabruca cocoa for
325 the study region, using the two afore-mentioned dimensions of climate-friendliness, C
326 stocks and C emissions, as proposed by van Rikxoort et al. (2014). However, while
327 those authors defined the four quadrants of climate-friendliness in relative terms for a
328 given sample of farms, Fig. 5 proposes absolute thresholds of climate-friendliness for
329 cabruca of southern Bahia. For the input-related C emissions, we propose a threshold
330 of climate-friendliness of $0.25 \text{ kg CO}_2\text{e kg}^{-1}$ which is close to the lowest emissions value
331 that was still compatible with the highest cocoa yields observed in this study. For the C
332 stocks in the large shade trees, we propose a threshold of climate-friendliness of 50
333 Mg ha^{-1} to allow farms to stay below the maximum value of 65 Mg ha^{-1} that was still
334 compatible with the highest cocoa yields observed in this study. The most climate-
335 friendly farms (quadrant A) would thus have input-related C emissions below 0.25 kg
336 $\text{CO}_2\text{e kg}^{-1}$ and C stocks in the large trees above 50 Mg ha^{-1} , the least climate-friendly
337 farms (quadrant D) would have the opposite combination of C emissions and stocks,
338 and the two intermediate quadrants B and C would pass one but not the other
339 criterion of climate-friendliness. There were relatively high-yielding farms (by the
340 standards of the region) in quadrant A but also in quadrant D, while very low-yielding
341 farms were present in all quadrants, confirming again that climate-friendliness is not a
342 direct function of the level of intensification.

343 *[Figure 5 here]*

344 As we have shown before, it is possible to at least double the current average yields of
345 cabruças in southern Bahia through the judicious use of mineral (and organic) fertilizer
346 (Fig. 1), while maintaining a low input-related C footprint (Fig. 3). This level of
347 intensification would be compatible with C stocks in the large trees of up to 65 Mg ha⁻¹
348 (Fig. 2), and it is clear from Table 1 and data presented in Schroth et al. (2014) that
349 many cabruças have lower C stocks than that and may offer potential for increased C
350 storage in the tree stratum even while intensifying cocoa production. On such farms,
351 financial incentives for increasing C sequestration could even help offset the cost of
352 intensification. Providing such financial incentives for C sequestration up to the
353 mentioned threshold may be attractive both for government and private sector,
354 knowing that by doing so they are not jeopardizing the potential of the region to
355 double its current cocoa output.

356 On the other hand, the data presented here and by Schroth et al. (2014) suggest that
357 some cabruças have higher C stocks than is compatible with intensification and
358 increased yield levels (Fig. 2). It is for those cabruças with C stocks in the large trees
359 >65 Mg ha⁻¹ that there is a clear trade-off between C storage and yield. More research
360 on the yield potential of cabruças with high C stocks should be carried out before
361 reaching final conclusions on this threshold of maximum C storage that is still
362 compatible with yield increases. It is, however, not surprising that cabruças with C
363 stocks that are too high to permit above-average cocoa yields exist given their history
364 of two decades of crisis characterized by extensive management and frequent
365 abandonment. It has been shown that during the crisis years the tree species richness
366 of the cabruças has increased (Sambuichi et al. 2012), and it is likely that the same is
367 true for their C stocks. Special policies may be needed to compensate the owners of
368 these cabruças for storing C levels above the threshold permitting intensification.
369 Incentives for retaining these excess C stocks would have to be higher than those for
370 encouraging C storage up to the threshold to be effective, because at these higher
371 levels of C storage they would also have to compensate farm owners for foregone
372 cocoa yields.

373 Where, in the absence of such incentives, reducing levels of shade and C storage below
374 the threshold is necessary in order to enable intensification and increased cocoa yields,
375 the thinning of exotic species is preferable to the removal of native tree species from a
376 conservation point of view (Schroth et al. 2011; Sambuichi et al. 2012). These include
377 the common *Erythrina* spp. that has no direct use value and the prolific seed producers
378 jackfruit (*Artocarpus heterophyllus*) and cajá (*Spondias mombin*) - all very common
379 shade trees in cabruças. Although ecologically not without value (Oliveira et al. 2011),
380 these exotic species have often reached high densities during phases of extensive
381 management (Sambuichi et al. 2012). Their partial removal is also administratively
382 easier than that of native trees since the latter are protected by law in the Brazilian
383 Atlantic forest biome. It should also be mentioned that during the boom years of cocoa

384 planting in the region, many cabruças have been established on soils that are
385 unsuitable for cocoa production and certain low-producing but ecologically valuable
386 plantations might better be retired than intensified, helping farms to attain their
387 legally required forest set-asides. The government of Brazil has also encouraged the
388 creation of private reserves through tax incentives and this is another option for
389 retiring ecologically valuable but unproductive sectors of cocoa farms (Schroth et al.
390 2011). Smaller trees than 30 cm DBH were not included in our C inventories since they
391 contribute relatively little to system C stocks but add considerably to survey effort, and
392 are also often the target of management interventions. Where smaller trees are
393 thinned to increase the space and light environment for the cocoa, it is however
394 important from a conservation point of view to retain enough individuals per species
395 to ensure the eventual replacement of the large trees as these die (Rolim and Chiarello
396 2004), as well as to protect rare and endangered species (Sambuichi et al., 2012).

397

398 **4 Conclusions**

399 The cocoa sector of southern Bahia, Brazil's main cocoa production region, where most
400 cocoa is produced in traditional shaded cocoa agroforests, is in need of intensification
401 to improve the livelihoods of cocoa farmers and attend the supply needs of the
402 national cocoa industry. The same is true for many or most cocoa regions in other
403 countries. We set out to test if this intensification is compatible with climate-
404 friendliness, that is, a positive contribution to climate change mitigation that could add
405 to the well-documented conservation value of Bahian cabruças (Faria et al. 2007;
406 Cassano et al. 2009; Schroth et al. 2011). If this were the case, it could help distinguish
407 the region's cocoa on the global market. We identify two dimensions of climate-
408 friendliness: a low level of input-related greenhouse gas emissions, and high C stocks in
409 the vegetation. We show that at least a doubling of yields compared to the current
410 regional average of 285 kg ha⁻¹ is compatible with maintaining a low input-related C
411 footprint close to 0.25 kg CO₂e kg⁻¹ of cocoa, an aboveground C stock in the large trees
412 of up to 65 Mg ha⁻¹, and a shade level of up to 55%. Higher C stock-shade combinations
413 are associated with below-average yields. We demonstrate that the traditional cocoa
414 production systems of the region have the ability to respond positively to
415 intensification especially through mineral fertilization, provided that the farms are not
416 overstocked with large trees after years of extensive management and abandonment.
417 On the other hand, intensification to reach twice the regional average yield may still
418 allow to increase the system C stocks on many farms where current C stocks are well
419 below 65 Mg ha⁻¹. For farms that allow increased C stocks, special incentives and
420 technical support programs for tree planting and management could be created by
421 government and private sector. This may include companies interested in reducing
422 their corporate C footprint and perhaps in marketing a special kind of biodiversity and

423 climate-friendly cocoa and chocolate from a traditional cocoa origin. The exact
424 thresholds of climate-friendliness require further study and for unproductive parts of
425 farms, the option of retirement of areas to comply with legal requirements for forest
426 set-asides and opportunities to take advantage of tax incentives for the creation of
427 private reserves should be considered (Schroth et al. 2011). Our results provide a
428 practical framework for the climate-friendly intensification of traditional cocoa farms
429 of southern Bahia and its time- and cost-efficient measurement. Our method should be
430 applicable to other tree crops and regions, although the thresholds of climate-
431 friendliness will most likely be site and crop specific.

432

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522 **Tables**

523 **Table 1** Farm characteristics, production practices, yield, carbon stocks and input-
 524 related greenhouse gas (GHG) emissions of cocoa produced in 26 shaded cocoa farms
 525 (cabruças) in southern Bahia, Brazil. Data were collected in 2013. Yields and inputs are
 526 averaged over the previous three years (2010-12). Large trees were defined as trees
 527 with a diameter at breast height (DBH) >30 cm. CO₂e refers to CO₂-equivalents.

Farm characteristic	Mean	Standard Deviation	Range
Area under cocoa (ha)	101	116	4-450
Cocoa tree density (ha ⁻¹)	872	187	557-1401
Grafted trees (%) ¹	35	35	0-100
Mineral fertilizer use (kg ha ⁻¹) ²	89	118	0-360
Cocoa yield (kg ha ⁻¹)	275	137	66-585
Shade (%)	49	20	20-90
Density of large trees (ha ⁻¹)	57	33	8-112
Carbon stock in large trees (Mg ha ⁻¹)	59	30	12-148
Carbon stock in cocoa (Mg ha ⁻¹)	10.0	4.7	2.5-22.3
GHG emissions related to fertilizer use (kg CO ₂ e kg ⁻¹)	0.24	0.45	0-1.64
GHG emissions related to pesticide use (kg CO ₂ e kg ⁻¹)	0.08	0.08	0-0.27
GHG emissions related to transport and energy use (kg CO ₂ e kg ⁻¹)	0.04	0.10	0-0.43
Total input-related GHG emissions (kg CO ₂ e kg ⁻¹)	0.36	0.46	0-1.76

528 ¹ Various improved clones grafted on local rootstock

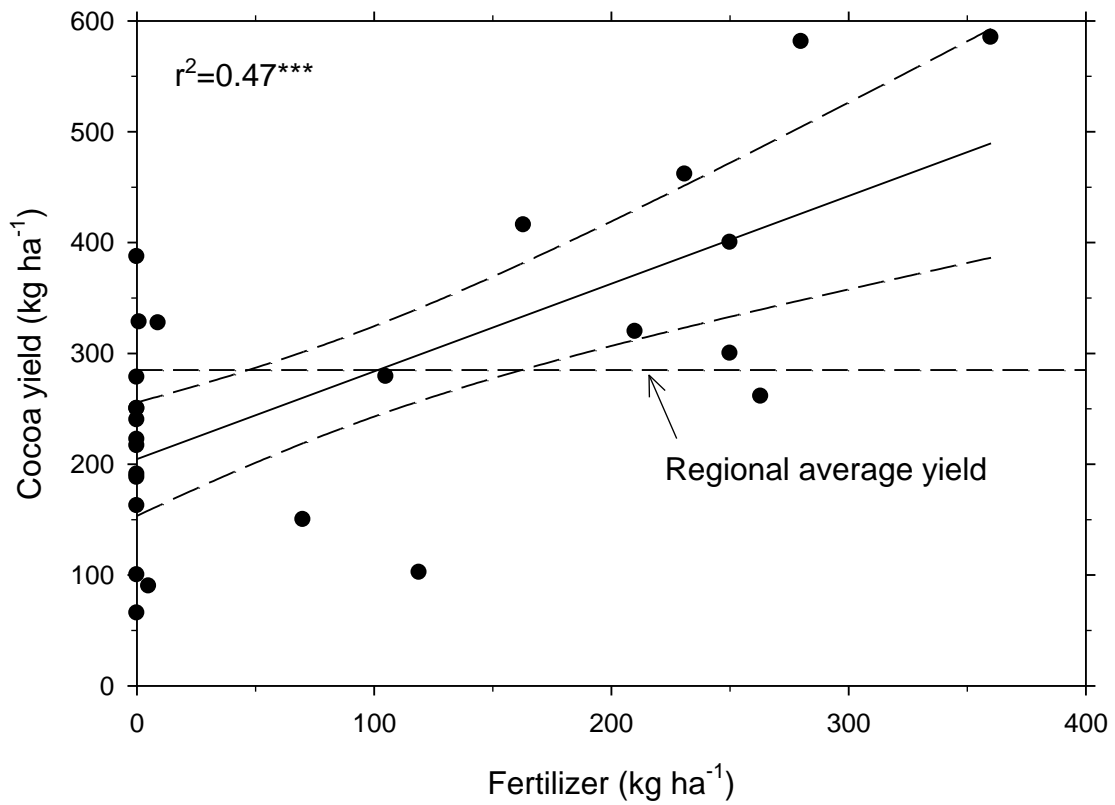
529 ² The mineral fertilizers used for cocoa were combinations of urea (CO(NH₂)₂), mono-
 530 ammonium-phosphate (NH₄H₂PO₄) and potassium chloride (KCl), commonly with a
 531 nutrient content of 11% N, 30% P₂O₅ and 17% K₂O, or alternatively 15% N, 35% P₂O₅
 532 and 10% K₂O. Some farms only applied phosphorus as super-phosphate (Ca(H₂PO₄)₂).
 533 Lime was commonly applied as dolomitic lime (CaCO₃ · MgCO₃) (Chepote et al. 2005).

534

535 **Figures**

536

537 **Fig. 1** Relationship between the quantity of mineral fertilizer applied and the cocoa
538 yield (average, standard deviation and 95% confidence intervals) in 26 traditional
539 cocoa agroforests (cabruças) in southern Bahia, Brazil. Yield data are averages of the
540 previous three years (2010-12). The dashed line indicates the regional average cocoa
541 yield of 285 kg ha⁻¹. The linear correlation was significant at P<0.001.

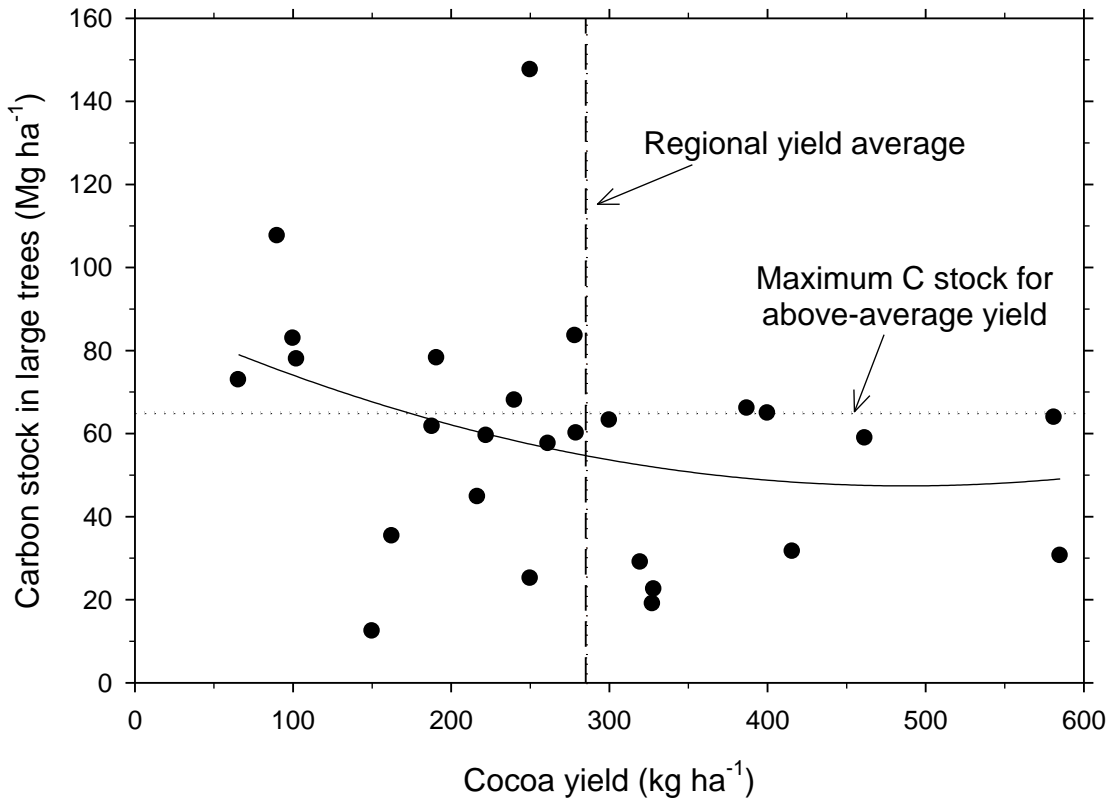


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545 **Fig. 2** Relationship between cocoa yields and aboveground carbon stocks in the large
546 trees (>30 cm DBH) of 26 cocoa agroforests (cabruças) in southern Bahia, Brazil. Yield
547 data are averages of the previous three years (2010-12).

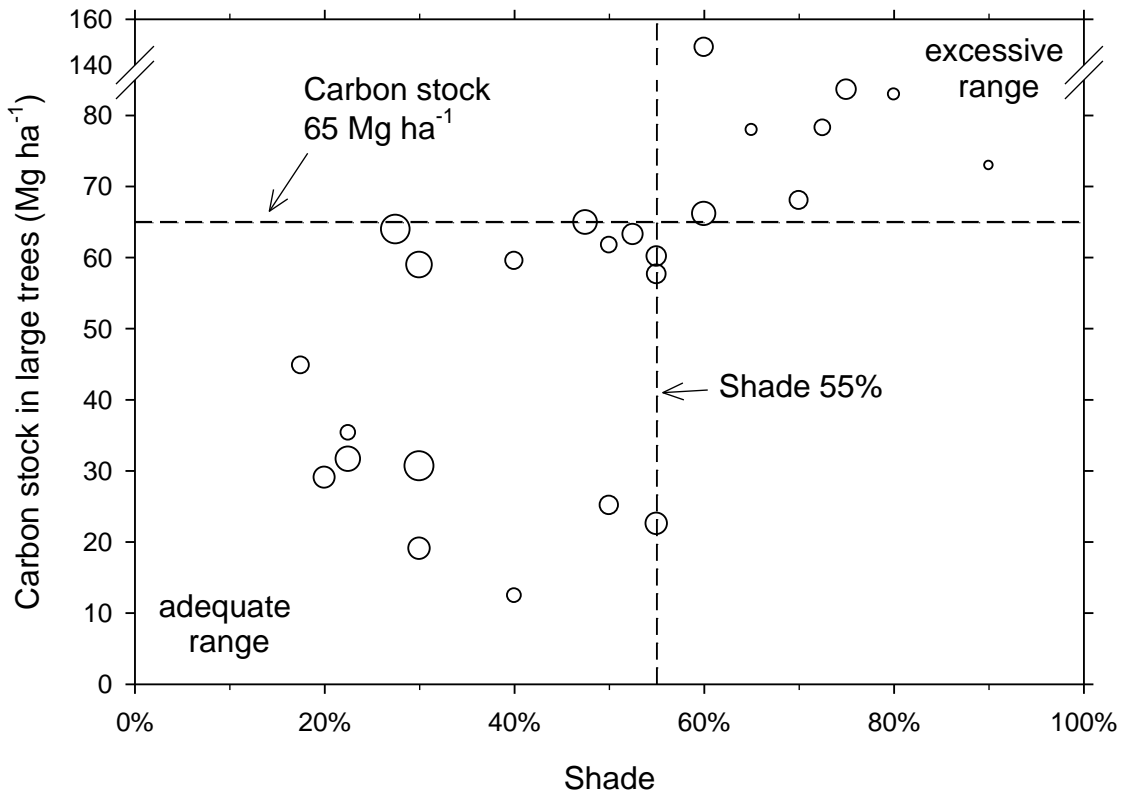


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551 **Fig. 3** Relationship between the level of shade and aboveground carbon stocks in large
552 trees (>30 cm DBH) of 26 cocoa agroforests (cabruças) in southern Bahia, Brazil. The
553 area of the symbols representing the individual farms is proportional to the per-
554 hectare cocoa yield of the previous three years (2010-12).

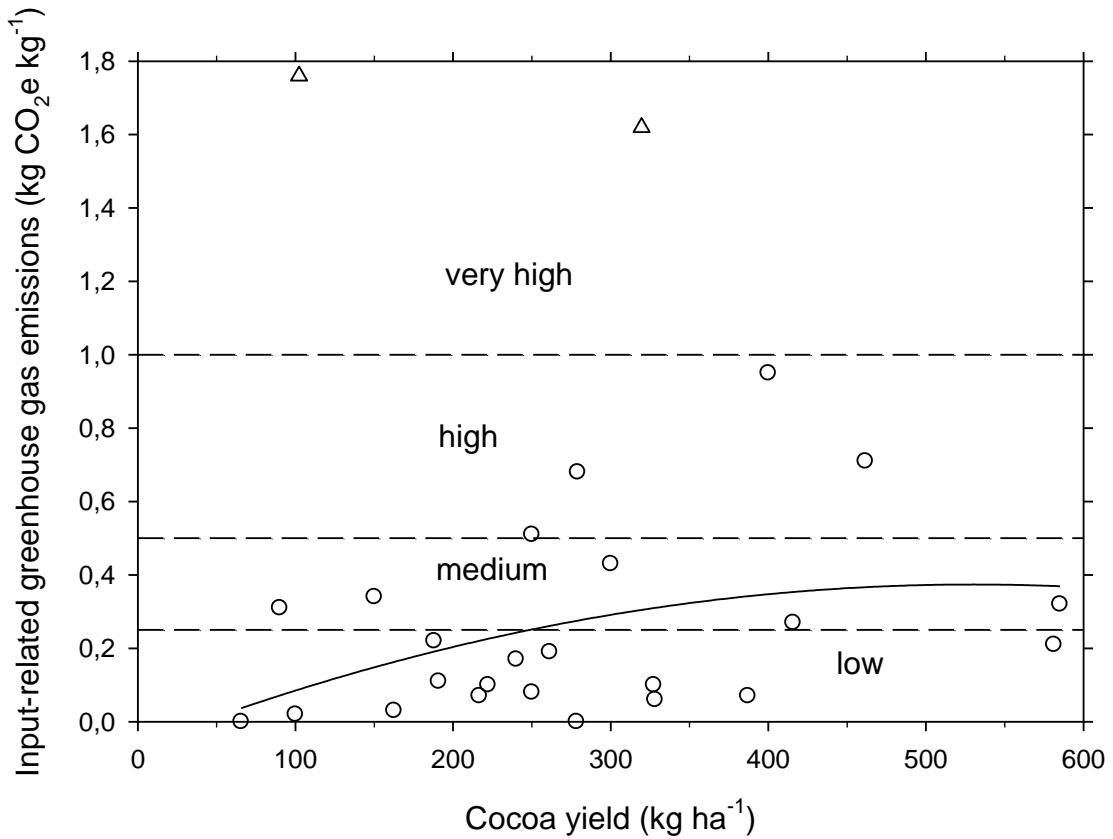


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558 **Fig. 4** Input-related greenhouse gas emissions (from fertilizer, pesticides and fossil
 559 fuels) of cocoa production in traditional cocoa agroforests (cabruças) at different yield
 560 levels in southern Bahia, Brazil, and proposed classification into low, medium, high and
 561 very high input-related emissions levels. The two farms with very high emissions owing
 562 to relatively high fertilizer rates that failed to proportionately increase yields (triangles)
 563 were not included in the second-order regression. Yield data are averages of the
 564 previous three years (2010-12).

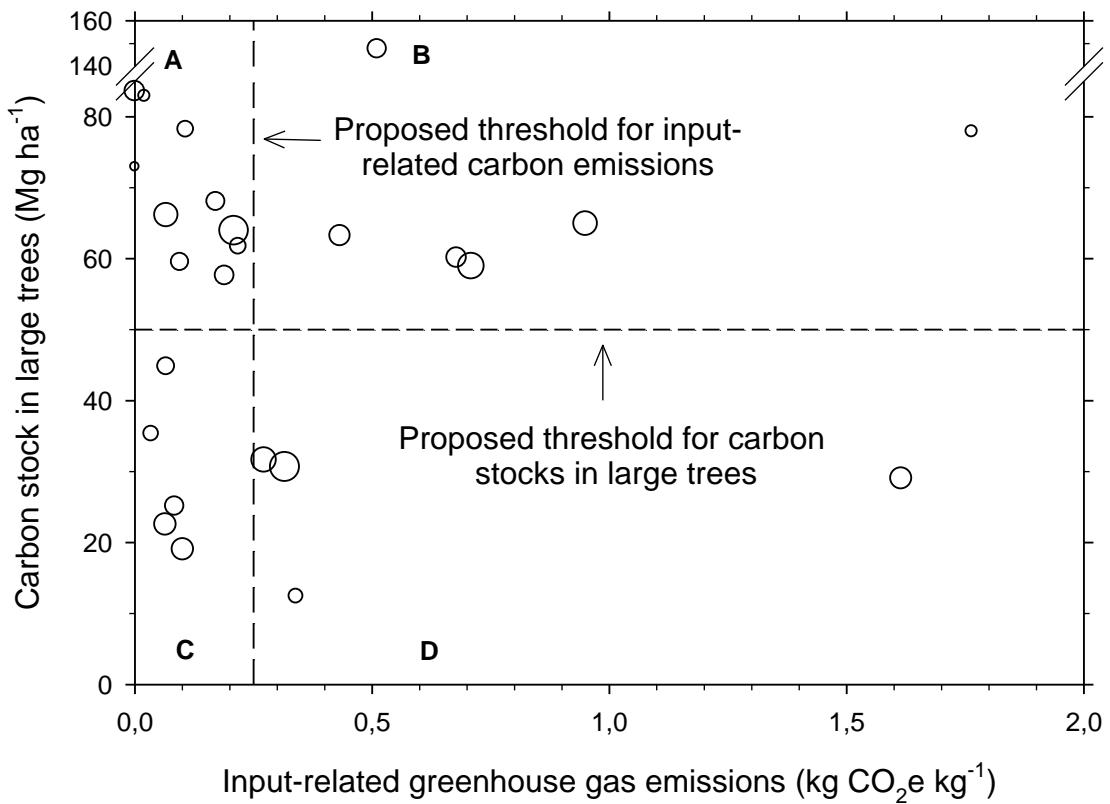


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568 **Fig. 5** Relationship between input-related greenhouse gas emissions and carbon stocks
 569 in the large trees (>30 cm DBH) of 26 cocoa agroforests (cabruças) in southern Bahia,
 570 Brazil. The area of the symbols representing the individual farms is proportional to the
 571 per-hectare cocoa yield of the previous three years (2010-12). The four quadrants
 572 separated by the proposed thresholds of climate-friendliness of 0.25 kg CO₂e kg⁻¹ and
 573 50 Mg ha⁻¹ are (A) most climate-friendly; (D) least climate-friendly; (B) and (C) of
 574 intermediate climate-friendliness.



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