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1 **Towards integrated pest and pollinator management in tropical crops**

2

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14

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16

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22

23

24 **Abstract**

25 Biotic pollination and pest control are two critical insect-mediated ecosystem services
26 that support crop production. Although management of both services is usually
27 treated separately, the new paradigm of *Integrated Pest and Pollinator Management*
28 (IPPM) suggests synergetic benefits by considering them together. We reviewed the
29 management practices in two major tropical perennial crops: cocoa and coffee, to
30 assess IPPM applications under the tropics. We found potential synergies and
31 antagonisms among crop pest and pollination management, however, very few
32 studies considered these interactions. Interestingly, we also found management
33 practices focusing mainly on a single service mediated by insects although species
34 can show multiple ecological functions as pests, natural enemies, or pollinators. The
35 tropics represent a promising area for the implementation of IPPM and future
36 research should address this concept to move towards a more sustainable
37 agriculture.

38

39 **Keywords:** Biodiversity; Pest control; Cocoa; Coffee; Ecosystem services; IPPM;
40 Landscape management; Pollination

41 **Introduction**

42 Insect-mediated ecosystem services are critical in agriculture [1**]. Beyond interac-
43 tions between crops and their abiotic environment, crop yield is driven by ecosystem
44 services including pollination and pest control and pollination, which are governed by
45 antagonistic and mutualistic biotic interactions [2]. Animal pollination is critical for
46 yield improvement of three-quarters of the world's major crops [3]. Overall, 5 to 8% of
47 global crop production would be lost without animal pollination [4]. A wide diversity of
48 insects are often assessed as efficient pollinators [5,6*] but pollination limitation is
49 frequently driven by a lack of insect pollinators [7]. Crop pests herbivory is another
50 well-known driver of important crop yield losses due to a decrease in plant survival,
51 growth, and reproduction [8]. Worldwide yield losses are estimated from 7.9% to
52 15.1% [8]. Biological pest control is defined as a process by which predators, parasi-
53 toids or pathogens reduce pest abundance. Apart from alleviating the negative im-
54 pact from crop pest, managing the diversity of natural pest enemies to support crop
55 yield could help reduce both the use of synthetic pesticides in agriculture [9*] and the
56 associated detrimental effects on biodiversity and human well-being [10]. Given the
57 evidence of benefits from pest control and pollination on crop production, manage-
58 ment practices should be developed to foster the ecosystem services and mitigate
59 the ecosystem disservices provided by insects [1**,11].

60 Crop pest control is commonly performed by means of species management
61 approaches such as pesticide use [12–14]. However, many concerns are associated
62 with over-reliance on pesticide applications including not only pest resistance, out-
63 breaks of secondary pests, but also loss of natural enemies [9*]. Alternatively, there
64 is evidence that landscape management can promote the presence of natural ene-
65 mies, and thus enhance biological control which could reduce pesticide application
66 [18**–21**]. Pest control practices are distinguished between human input-based
67 practices and biodiversity based, respectively [18**,19**], along with the concept of
68 Integrated Pest Management (IPM). On the other hand, the management of crop pol-
69 lination was also divided among different strategies from human input-based practic-
70 es (e.g. the implementation of managed beehives [11]) to habitat and resource pro-
71 motion to maintain or attract wild pollinators [20,21]. Nevertheless, the management
72 practices of pest control and pollination services are usually treated independently
73 [18**]. IPM has been used as a response to mitigate pollinator decline, yet IPM itself
74 is not necessarily "pollinator friendly" [18**]. The impact on yield is affected by the

75 success of both pollination and insect pest control services, thus a more holistic ap-
76 proach is essential.

77

78 **New paradigm of *Integrated Pest and Pollinator Management (IPPM)***

79 The concept of Integrated Pest and Pollinators Management (IPPM) emerged in
80 2015 with the main goal of considering adverse effects and synergies of pest control
81 management on pollinators and *vice versa* [18**,19**,22,23]. IPPM has been further
82 defined by categorizing and prioritizing co-management practices to limit adverse
83 environmental impacts. A pyramid has thus been proposed as a decision support tool
84 for choosing preventive and biodiversity-based management practices rather than
85 curative and human-based ones [18**,19**] (**Figure 1**). At the top of the pyramid are
86 the human-based practices, such as pesticide application, which are widely used for
87 their effectiveness on target species but are also highly criticized for their effects on
88 beneficial insects [24]. These practices involve a direct management of targeted spe-
89 cies (e.g. controlling pests or fostering pollinators) and are differentiated in two man-
90 agement strategies according to the use of biotic or abiotic inputs (**Figure 1**). The
91 biodiversity based-practices stand at the base of the pyramid and are differentiated
92 among field and landscape management strategies [19**] (**Figure 1**). Landscape
93 components, namely habitat quantity and density, have a primary role in maintaining
94 insect communities [25**]. Landscape simplification affects pollination and pest con-
95 trol services through negative effects on the abundance, richness and diversity of
96 pollinators and predators [26**]. Consequently, the objective in such practices is no
97 longer to directly manage the arthropod population but to manage their dynamics
98 through the provision of nesting sites and food resources. However, while recent
99 studies applied the concept of IPPM in field-based trials [25**], IPPM remains essen-
100 tially conceptual since its establishment in 2015 [23]. Here, we carried out a system-
101 atic review of the management practices of pest control and pollination services in
102 two major tropical crops: cocoa and coffee, in order to assess for the first time IPPM
103 applications on those crops.

104

105 **IPPM application in tropical crops**

106 Coffee (*Coffea canephora* and *Coffea arabica*) and cocoa (*Theobroma cacao*) are
107 two tropical crops with different levels of animal-mediated pollination required for
108 yield improvement. The species *T. cacao* and *C. canephora* have a high dependence

109 on pollinators for fruit set, *C. arabica* has a moderate dependence [3]. Coffee and
110 cocoa suffer important pressures from crop pests [27,28]. We performed our system-
111 atic review on these two crops by selecting the scientific publications published since
112 the emergence of the IPPM concept in 2015 (**Box 1**). Despite the importance of in-
113 sects to coffee and cocoa –as pollinators, pests and natural enemies– very few stud-
114 ies have applied the IPPM concept. We found no study addressing both pollination
115 and pest control services in cocoa and only three in coffee. Some studies assessed
116 the effects of shade cover in agroforestry systems, ground cover, and distance to
117 forest [29*,30]–or the use of vector-disseminated biopesticides [31]–on both services
118 (**Table 1**). Otherwise, most studies focused on a single service or a single insect
119 species mediating that service. Nevertheless, some studies considered a more holis-
120 tic framework by assessing arthropods’ community without considering their ecologi-
121 cal function [32,33*]. Other studies focused only on pest and predator communities
122 [17,34–47] or pollinators and predators [48*–51*].

123 Overall, we found fewer experiments conducted on the pollination service
124 compared to the pest control service (**Figure 1**). Moreover, in cocoa and coffee
125 crops, pollination management seems to depend to a greater extent on the concept
126 of IPM. Conversely to pest management, the promotion of pollination relies more on
127 biodiversity-based practices at the landscape scale than on human practices. Con-
128 sidering both crops, the impact of abiotic and biotic inputs is studied on the pollination
129 service in only 10% of cases (6 experiments) compared to 90% on the pest control
130 service (53 experiments). Conversely, 69% of the experimental units (35 experi-
131 ments) investigated the effect of landscape-level practices on pollination, compared
132 to 31% (16 experiments) on pest control (**Figure 1**). While IPPM encourages the use
133 of landscape-level practices as a priority, plot-level practices are the most common
134 since they represent 57% of the practices studied on cocoa (11 pollination experi-
135 ments vs. 19 pest control experiments) and 49% on coffee (36 pollination experi-
136 ments vs. 49 pest control experiments). This particularity could be explained by the
137 fact that coffee and cocoa plantations are complex systems where the implementa-
138 tion of agroecological practices within the plot, such as agroforestry [52], is easier
139 than in annual crop plantations. Importantly, we found that landscape level manage-
140 ment strategies are rarely studied in cocoa compared to coffee for the pollination ser-
141 vice. It is likely that this difference is explained by the short distance foraging behav-

142 ior of the main cocoa pollinators (e.g. small flies) [53] compared to those of coffee
143 crop (e.g. bees) [54*].

144

145 **Synergies and antagonisms among crop pest and pollination managements**

146 Complementary and synergistic effects can occur in crop management practices with
147 potential positive interactions between pollinators and natural enemies on crop yield
148 [55]. We examined such synergies but also potential antagonisms among the prac-
149 tices performed for crop pest and pollination management in cocoa and coffee. Sev-
150 eral practices were studied specifically on one of the two services (i.e. pollination or
151 pest control) in both cocoa and coffee, although there were fewer studies on cocoa
152 (**Table 1**). The large majority of the practices involving abiotic and biotic inputs (i.e.
153 pesticides, traps, biopesticides and biocontrol agents) were evaluated for their effec-
154 tiveness on pest control but rarely on pollination service (**Table 1**). However, these
155 practices can have antagonistic effects by negatively affecting the pollination service
156 [24] or the community of beneficial arthropods [56]. Surprisingly, we found an exper-
157 iment showing an increase of pollination service linked with pesticide use. This result
158 can be explained by the family of the pesticide used, a fungicide, and by its effect on
159 the plant physiology by increasing flower retention capability that could attract more
160 insect pollinators [57]. Similarly, several biodiversity-based practices applied at the
161 plot level and landscape level (e.g. mechanical management such as sanitary har-
162 vesting, pruning and exclusion netting, and the practices of biodiversity conservation
163 such as bird-mediated predation) were only considered affecting pest control (**Table**
164 **1**). Nevertheless, these practices may also lead to antagonistic adverse effects on
165 pollination or pest control services if, for example, birds also predate on pollinators
166 and predators [22].

167 On the other hand, practices such as promoting floral resources in the plot and
168 enhancing abundance of semi-natural habitats at the landscape scale are almost ex-
169 clusively studied on the pollination service. However, studies carried out in temperate
170 regions, i.e. where farmers can receive financial incentive to set flower strip, show
171 benefits of such practices on pest control [58], suggesting that floral resources and
172 semi-natural habitats could represent an interesting approach that offers a synergetic
173 practice on both services. For instance, breeding substrates, vegetal ground cover
174 and agroforestry are practices that could validate the IPPM concept through syner-
175 getic effects among pest control and pollination. However, the impact of agroforestry

176 on insect-mediated services is mixed (**Table 1**). This result is likely due to the large
177 diversity of agroforestry systems with variability in tree size and the species of shade
178 trees [59] and the differences in the survey scales chosen by the different studies.
179 Shade tree species may affect their attractiveness and repellency to arthropod spe-
180 cies. The size of the trees influences the microclimate, which in turn affects the de-
181 velopment cycle of arthropods in various ways, depending on the species considered
182 [52,53]. Surprisingly, most of the practices studied at the landscape scale aim to
183 promote forest areas as arthropod-friendly habitats. Indeed, little attention has been
184 paid to the landscape composition in terms of crops [60]. However, these crops can
185 share the same pest or pollinator species assemblage, or can host arthropods per-
186 forming multiple functions in the cropping system.

187

188 **Multiple services mediated by insects**

189 Our systematic review confirms that pest control and pollination management are
190 mainly treated separately in cocoa and coffee (**Figure 1**). Interestingly, we also found
191 that most management practices focus on targeted insect species for a single service
192 (i.e. pollination or pest control) although numerous species have multiple ecological
193 functions as crop pests, natural enemies or pollinators. In other words, very few
194 works consider the multiple ecological functions of insects while the species are usu-
195 ally classified by their major ecological function for example pollinators, pests, or nat-
196 ural enemies. Nevertheless, many insects can provide multiples services improving
197 crop production due to their double ecological functions over their development stag-
198 es (e.g. larvae as herbivore vs. adult as pollinator) or over different crops. For in-
199 stance, *Forcipomyia* spp (Diptera) are pollinators in cocoa [53] and also natural ene-
200 mies of *Dione juno* (Lepidoptera: Nymphalidae) [61] that damages many tropical
201 crops (e.g. passion fruit, tomato, sugarcane, among others) [62,63]. In coffee, *Syr-*
202 *phus* sp. (Diptera: Syrphidae), *Allobaccha brevis* (Diptera: Syrphidae) and *Hemipyrel-*
203 *lia* sp. (Diptera: Calliphoridae) are recorded as pollinators but these species are also
204 reported as insect natural enemies in passion fruit and avocado [62,64].

205 On the other hand, other insects can have adverse effects (e.g. providing a
206 service and a disservice) such as Sciaridae that are pollinators in cocoa [65] but are
207 also considered as pests in watermelon [66]. *Trigona spinipes* Fabr. (Hymenoptera:
208 Apidae) is a pollinator in coffee that can be detrimental to coffee fruit set [67] and is
209 also considered as a pest due to its damages of open galleries on fruits reducing fruit

210 quality [68]. The *Azteca sericeasur* ant is known to be an effective predator of the
211 coffee berry borer [69], a major coffee pest, but its aggressiveness towards pollina-
212 tors visiting the coffee flowers has been studied little [56]. Overall, it is accepted that
213 improving insect diversity in croplands benefits crop yield [70]. However, despite di-
214 versity being important, studies that evaluate whether an insect is an efficient and or
215 effective pollinator, predator or has multiple ecological functions are valuable [54*].
216 For instance, *Trigona jaty* (Hymenoptera: Apidae, meliponinae) is a flower visitor in
217 cocoa but is considered as an inefficient pollinator given its pollen robbing action that
218 weakens flower fitness [71]. Pollination efficiency of many flower visitors in coffee
219 and cocoa crops are not yet tested and although studies suggest their ecological
220 function as pollinators, they can also act as pests or natural enemies in other crops.
221 Neglecting the multiple ecological functions of insects and their efficiency carrying out
222 these ecosystem services and disservices would considerably limit crop yield im-
223 provement.

224

225 **Perspectives**

226 The tropics are home to the highest diversity and abundance of arthropods [72], and
227 as such, represent an excellent area for considering IPPM approaches in agricultural
228 systems. Through the study of two tropical crops, we found that few experiments
229 have investigated the effect of agricultural practices simultaneously on pests, natural
230 enemies and pollinator communities despite IPPM recommendations. Although it is
231 rather recognized that analyzing the influence of a single ecosystem service on crop
232 yield can be complex due to context-dependency, studying combined effects of
233 pollinator and pest managements implies interacting relationships that are current
234 challenges in applied ecology [55]. Integrating pest and pollinator management
235 strategies in agriculture is therefore pioneering and represents future a direction
236 towards sustainable food production. Consideration of the landscape scale also
237 invokes the possibility of multiple ecological functions that insects may have [22] as
238 pests of one crop and pollinators of a neighboring crop. This consideration should be
239 even more important when species richness and abundance are high. In the future,
240 the growing awareness of the landscape scale effect and the multiple ecological
241 functions of arthropods in relation to crops should lead to further consideration of the
242 neighboring agricultural landscape, i.e. the nature of the established crops and their
243 pollinator, pests and predator assemblages.

244

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250

251 **Declarations of interest:** none.

252

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899 **Box 1. Cocoa and coffee tropical crops**

900 The genus *Coffea* (Rubiaceae) originates from tropical and subtropical Africa. Coffee
901 is a crop of global importance cultivated in approximately 80 tropical countries with
902 Brazil being the greatest producer and exporter [73]. The two main varieties cultivat-
903 ed in the tropics have different pollination requirements since in *Coffea arabica* (self-
904 compatible), animal pollination represents only 10 to 40% of total pollination while
905 animal pollination represents more than 40% in *Coffea canephora* (self-incompatible)
906 (Figure S2 in [3]). Interestingly, the absence of pollinators could decrease coffee
907 yields from 20 to 30% [20] and pest attacks harm up to 26 to 38% of productions [28].
908 The species *Theobroma cacao* is the main fruit cultivated from the genus *Theobroma*
909 (Malvaceae). Native to the rainforest regions of the northern part of South America, it
910 is currently cultivated mainly in Africa, and the Ivory Coast is the leading producer
911 country providing more than a third of global production [73]. Most of the cocoa culti-
912 vated varieties are self-incompatible and the sticky pollen is not dispersed by the
913 wind. Cocoa pollination is therefore highly dependent on animal-mediated pollination
914 [3]. We performed a systematic review on the management practices of pest control
915 and pollination services in cocoa and coffee crops, from 2015 (i.e. the establishment
916 of the IPPM concept, [23]) to May 2021 and based on two search string equations in
917 Web of Science (using the "topics" field search, [74]). Each of the equations identified
918 the scientific articles dealing with one of the two services on both crops: (*Equation 1*)
919 pest* and (damage* or control* or monitor* or manag* or suppress* or regulat*) and
920 (cocoa or cacao or coffee or coffea); (*Equation 2*) pollin* and (manag* or enhance* or
921 benefi* or success or increase* or promot* or monitor* or facilita* or support* or im-
922 prov* or favo*) and (cocoa or cacao or coffee or coffea). Out of 1224 reviewed stud-
923 ies, only 32 studies on cocoa [14,21**,37,39,48*,53,65,75–99] and 70 studies on cof-
924 fee [13,15–17,20,29*,44,45*,51*,56,57,67,69,100–156] were considered by reading
925 the abstracts and full texts and selecting that (i) address coffee and cocoa in field
926 experiments, (ii) include arthropods and (iii) did not consider the effect of a practice
927 on the ecosystem service (e.g. pest or pollinator biology, climate effect, monitoring
928 and detection). The combination of the article, the ecosystem service studied, the
929 management practice and the response metric (ex: the abundance, the diversity, the
930 richness or the infestation) was named an 'experimental unit' and used to perform an
931 analysis of the management strategies conducted on cocoa and coffee crops.

932

933 **Figure legends**

934

935 **Figure 1.** Integrated Pest and Pollinator Management (IPPM) application in coffee
936 and cocoa illustrated with a systematic review of the management strategies for
937 pollination and pest control services from 102 scientific articles. The pyramid and the
938 four categories of management from human input-based strategies (in gray) to
939 biodiversity-based strategies (in dark green) are inspired from Lundin et al. 2021
940 [19**]. The category "sampling, monitoring and threshold" was not considered in the
941 pyramid because these practices aim to monitor the level of arthropods communities
942 without trying to regulate or promote them. Icons: www.flaticon.com and
943 www.vecteezy.com

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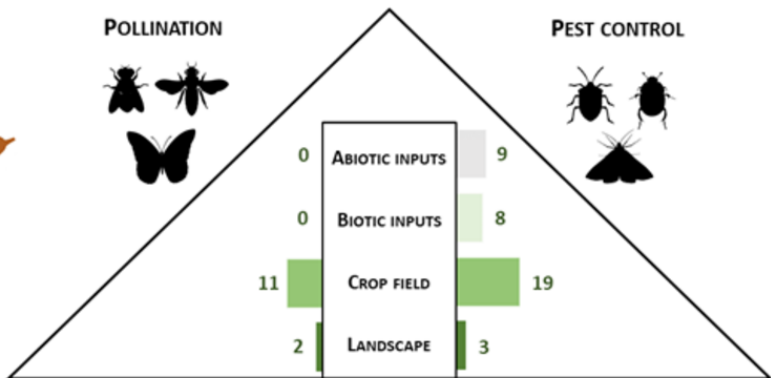
(A) COCOA



POLLINATION



PEST CONTROL



(B) COFFEE



POLLINATION



PEST CONTROL

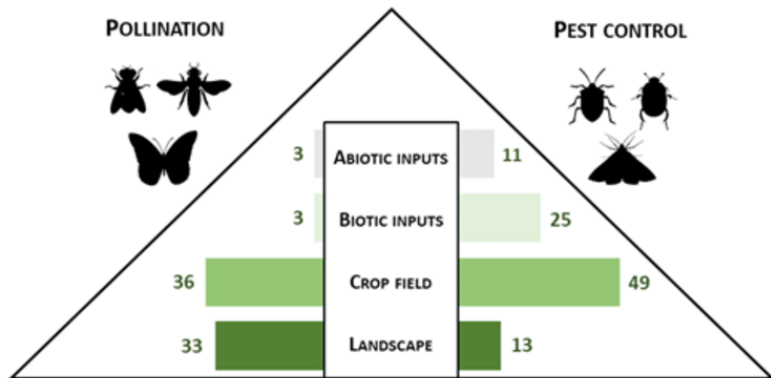


Table 1: Effects of IPPM management strategies and practices on pest control and pollination services in cocoa and coffee. Studies are synthesized from January 2015 to May 2021 through a systematic review, as explained in **Box 1**. The effects presented are the result obtained on the expected ecosystem service, i.e. a practice that increases the abundance, richness and visitation rate of pollinators, or decreases their mortality, is considered to have a positive effect on the pollination service. For the pest control service, a practice that reduces the abundance or diversity of pests, or decreases their observed damage level is assumed to have a positive effect. Among the selected studies, we chose to consider only the ones that provided a conclusion on the overall effect of the practice. So, we did not include studies that aimed to compare the modalities of implementation, such as color traps or biopesticides' date of application on practice effectiveness, and studies that compared agroecosystems with many differences in term of management. N = total number of action effects; n = action effect not considered for the synthesis because they were comparisons of action modalities (ex: trap's color, biopesticide's dose) instead of showing a negative, positive or null effect. Icons: www.flaticon.com and www.vecteezy.com

Crop	Management strategy	Practice	Pollination				Pest control				References
			Negative	Null	Positive	N(n)	Negative	Null	Positive	N(n)	
Cocoa	Abiotic inputs	Pesticides	0	0	0	0	0	1	1	2(0)	[75]
		Traps	0	0	0	0	0	3	2	10(5)	[14,76–81]
	Biotic inputs	Biocontrol agent	0	0	0	0	3	4	5	12(0)	[37,82–86]
		Biopesticides	0	0	0	0	0	0	1	2(1)	[75,87]
	Crop field management	Agroforestry	1	3	1	6(1)	1	4	4	9(0)	[21**,37,39,53,65,88–91]
		Fertilization	0	0	0	0	0	2	2	4(0)	[89,92,93]
		Intensification	0	0	0	1(1)	0	0	0	2(2)	[94,95]
		Mechanical management	0	0	0	0	0	0	2	2(0)	[91,96*]
		Plot floral abundance	0	1	1	2(0)	0	0	0	0	[21**]
		Nesting habitat diversity	0	2	2	7(3)	2	1	1	5(1)	[21**,48*,75,83,96*–99]
Landscape management	Biodiversity conservation	0	0	0	0	2	2	2	6(0)	[37,88]	
	Semi-natural habitats	0	1	1	2(0)	0	0	0	0	[21**]	
Coffee	Abiotic inputs	Pesticides	0	1	1	2(0)	0	3	3	6(0)	[13,57,100–103]
		Traps	0	0	0	2(2)	0	1	0	6(5)	[104–110]
	Biotic inputs	Biocontrol agent	3	0	0	3(0)	3	11	12	26(0)	[15–17,56,69,101,111–117]
		Biopesticides	0	0	0	0	0	1	7	10(2)	[100,106,118–123]

Crop field management	Agroforestry	7	8	3	18(0)	6	15	8	30(1)	[16,29*,44,45*,101,124–140]
	Fertilization	2	2	2	6(0)	0	2	1	3(0)	[45*,136,140,141]
	Intensification	3	3	1	7(0)	1	3	2	7(0)	[20,45*,125*,128,142–144]
	Mechanical management	0	0	0	0	2	3	5	10(0)	[13,103,106,145–148]
	Plot floral abundance	2	3	8	13(0)	0	0	0	0	[20,129,130,140]
	Nesting habitat diversity	1	3	1	5(0)	2	4	4	10(0)	[29*,101,130,136,137,149,150]
Landscape management	Biodiversity conservation	0	0	0	0	1	2	3	6(0)	[29*,151,152]
	Semi-natural habitats	4	19	13	38(2)	4	5	7	16(0)	[15,17,20,29*,44,51*,67,125*,130,133,140,152–156]

Pollination



Pest control



IPPM

Application to tropical crops?



Cocoa



Coffee