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Chapter 4

Challenges in Cocoa Pollination: The Case of Côte d'Ivoire

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http://dx.doi.org/10.5772/intechopen.75361

Abstract

Cocoa (*Theobroma cacao* L.) is mainly pollinated by ceratopogonid midges (*Forcipomyia* spp.). However, other insect species will also pollinate cocoa flowers when these midges are scarce. In Côte d'Ivoire, inadequate pest control practices (insecticide spraying, mostly against the mirids *Distantiella theobromae* and *Sahlbergella singularis*) and landscape degradation as a result of deforestation and cocoa monoculture, have decreased overall pollinator population levels and, as a result, pollination services to cocoa trees. The current low average Ivorian cocoa yield of 538 kg per ha (in 2016) is the result of global agricultural mismanagement (deteriorated soils, lack of fertilizers, inadequate or absent pest control, absence of shade trees and intercrops). However, there is also an evidence of a pollination gap that could cause low cocoa yield. More research is needed to understand: (i) which agro-ecological efforts to enhance cocoa pollination can improve yield, and (ii) which strategies are effective in enhancing cocoa pollination. In this chapter, we briefly describe the cocoa sector. Next, the cocoa flower and pollinator biology and phenology are presented, followed by an overview of current environmental and management constraints to cocoa pollination in the context of Côte d'Ivoire, the largest cocoa producer in the world. We conclude with exploring possibilities to enhance pollination in the Ivorian small-scale cocoa sector.

Keywords: cocoa, pollination, *Theobroma cacao*, fructification, cherelle wilt, *Forcipomyia*, phenology, pesticides, IPM, Côte d'Ivoire

1. Introduction

Non-bee insect pollinators play a significant role in global crop production [1]. Cocoa (*Theobroma cacao* L.) is one of the 13 most important commercial crops in the world. It entirely

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depends on insects for pollination and successful production [2]. In cocoa, pollination is almost exclusively performed by ceratopogonid midges (Order Diptera) from genus *Forcipomyia* [3, 4]. In 2016, global cocoa production was 4.472 million tons of dry beans, of which 2.655 million tons (59%) were produced in West Africa and 1.472 million tons (33%) in Côte d'Ivoire [5]. In 2016, global average cocoa yield was 438 kg dry beans per ha and per year (480 kg per ha in West Africa), whereas it was shown in research stations that cocoa bean yield could attain up to 2000 kg per ha and per year [6].

Cocoa yield remains under the latter potential level due to: (i) an inadequate cropping system mainly consisting of full-sun monocultures without shade, leading to soil erosion, nutrient depletion, water shortages, weed growth, and increased pest and disease outbreaks [7–11]; and (ii) inadequate pest and disease management [12, 13]; both leading to (iii) below-optimum pollinator population levels. Earlier research showed that increasing pollination, either manually [14] or indirectly by improving breeding opportunities for pollinating midges [14–16], had a significant impact on cocoa yield compared with normal agricultural practices control plots.

Over the past 50 years, cocoa demand has consistently increased annually by some 2.5% [17]. Demand continues to rise, particularly as a result of newly emerging chocolate markets such as China and India [18]. However, cocoa production levels have decreased by 3–5% over the past five years (compared to 2012 levels), leading to unstable prices because of market shortages. Cocoa production could expand through increasing global cocoa acreage (as it has always been done in the past). However, this is not a sustainable solution as it is mostly achieved at the cost of deforestation in tropical areas [19]. The other, more sustainable, approach is increasing productivity per ha. The latter strategy not only increases overall cocoa production without further deforestation, but can also increase income of cocoa farmers who nowadays often leave the cocoa production sector because of its low profitability [9].

In this chapter, we explore how cocoa farmers—besides by improving soil conditions, adequate pruning and integrated pest and disease management—can increase cocoa yield by increasing pollination intensity of their cocoa trees. We will first present the global cocoa sector and then focus on Côte d'Ivoire, the leading cocoa-producing country in the world. Next, we give background information on the biology and phenology of both cocoa flowers and pollinating midges (*Forcipomyia* spp.), followed by a discussion of pollinator-reducing factors (environmental and managerial) in Côte d'Ivoire. We conclude by discussing some options for relieving the constraints on cocoa pollination.

2. The cocoa crop sector

2.1. Global production and economic value

Although global yearly cocoa production quantities are below those of other tropical commodity crops such as sugar cane, rice, soybean, oil palm, cassava or banana, it is a unique crop because more than 90% of its production comes from small-scale farmers (each with a

cultivation area not larger than 3 ha) [5, 17]. As such, cocoa provides a livelihood to around 4.5 million farming families. Globally, 14 million people work in cocoa production [17]. In 2013, the total chocolate confectionary retail consumption had a value of 109,992 million USD [20]. Cocoa is produced on around 10 million ha, which is just 0.7% of the total global arable land, but 7% of the global permanent crop area. As a result, cocoa cultivation, and particularly cocoa agroforestry systems, play an important role in carbon sequestration and consequently have important climate mitigation potential [21].

2.2. The cocoa sector in Côte d'Ivoire

Côte d'Ivoire comprises the main cocoa-producing region in the world. In 2016, the country provided one third (1.472 million tons) of global cocoa supplies on 2.851 million ha of land. Average cocoa yield in Côte d'Ivoire was thus 516 kg/ha of dry cocoa beans, which is slightly below the global average yield of 538 kg/ha for that year [5]. In Côte d'Ivoire, cocoa is exclusively produced by around 1,000,000 small-scale farmers, each cultivating on around 2–3 ha [22]. These smallholders operate in a difficult context. Between 2000 and 2011, Côte d'Ivoire was generally considered a failed state with frequent occurrences of violent conflicts, where cocoa tax revenues were often used to fuel the conflicts [23, 24]. Moreover, the cocoa production in Côte d'Ivoire has often been linked to child slavery on plantations [23]. As in most cocoa-producing regions, fluctuating prices (between 1500 and 3500 USD per ton in the period 2011–2018, see http://www.nasdaq.com/markets/cocoa.aspx) affect Ivorian cocoa smallholders because in a situation with volatile prices, it is difficult to make informed choices on the "right" crop investments [25].

3. Cocoa pollination

Pollination intensity and fruit set largely determine cocoa yield [26]. If natural pollination is limiting cocoa yield, then enhancing pollinator population levels should result in increased fruit set and consequently yield.

3.1. Biology and phenology of cocoa flowers and fruit set

3.1.1. Biology

Cocoa flowers are hermaphrodite. They are produced on the trees' trunks and branches (cauliflory). After 2–3 years, so-called flower cushions, i.e., thickened flower-producing leaf axils, are formed. Every cushion bears up to 50 flowers per flowering season. There are two flowering seasons per year, which thus yields 100 flowers per year. The pentamerous flower is about 15 mm in diameter. A petal consists of a pouch—which conceals the anthers—and a wide tip. The function of the latter tip is unknown, but it does not specifically attract pollinators [27]. A particular aspect of cocoa flowers is the outer whorl of purple staminodes around the style. Right after anthesis, these staminodes align parallel to the style (**Figure 1**). Pollinators move around on the inner side of the staminodes, thereby rubbing their pollen grain-carrying bodies against the style. On older flowers, staminodes are somewhat withered and flexed away



Figure 1. Closed and open flowers as well as fruits (pods) on the trunk of *Theobroma cacao*. Flowers are produced in clusters directly on the trunk and older branches (this is known as cauliflory) and are small, 1–2 cm in diameter, with pink calyx. The floral formula is ✶ K5 C5 A(5° + 5) G(5) [31]. While many of the world's flowers are pollinated by bees (hymenoptera) or butterflies/moths (Lepidoptera), cocoa flowers are pollinated by tiny flies, *Forcipomyia* midges in the family Ceratopogonidae [16, 94]. The tree flowers profusely, but few flowers set particularly in the dry season. When the tree is under water stress, all flowers are dropped within about 5 days. Successful pollination requires the deposition of at least 35 suitable pollen grains on the receptive parts of the flower, and is dependent on the season [95]. (Photos by Guy Smagghe in cocoa plantation at Tiassalé, Côte d'Ivoire, 15/01/2018).

from the style, which obstructs pollen deposition on the style [28]. The ovary consists of 40–70 ovules with axile placentation [29]. At least 20 ovules need to be successfully fertilized for a pod to develop and mature. Maximum pollination is achieved when pollination intensity, i.e., the number of pollen grains deposited on the style, exceeds 115 [30]. Usually, a mature pod contains between 30 and 40 beans [31, 32]. Flower morphological characteristics (size, color, and shape) can differ greatly among varieties. However, even the most noticeable differences (e.g., white vs. red sepals) have no effect on pollination [33].

3.1.2. Bud development and maturation

Flower bud development from meristem to receptive flower takes at least 20 days and can take up to 30 days [31, 32, 34]. In India, it was shown [32] that flower bud development is faster in months with higher mean temperatures (e.g. June with a mean air temperature of 28°C) compared to colder months (e.g. November with mean air temperature of 25°C). Prolonged dry (<125 mm per month) or cold (mean monthly air temperature < 23°C) periods inhibit flowering [35]. Flowering is optimal during rainy days with high relative humidity and moderate temperatures (100 mm per month, 70% RH, and 27°C). High solar radiation incidence is linked with increased flower abscission [32]. Pollen grains are only able to germinate on a receptive stigma [36, 37]. The receptive period is at about 2–3 days after anthesis. Unsuccessful pollination leads to flower abscission. Reported flower abscission rates vary from 63% on the main trunk and 81% on the fan branches to over 90% for all flowers [27, 32, 35].

Anthesis starts at around 2–4 pm. The latter becomes evident through splitting of the five sepals [27]. The process of sepal splitting continues overnight and finishes at around 4–6 am. Complete anthesis (flower fully open) is quickly followed by pollen release from the anthers (also between 4 and 6 am). Higher air temperature, as well as low air humidity, facilitates

anther dehiscence [32]. However, pollen release is maximum between 8 am and 2 pm [10]. Styles and stigmas mature later than anthers, and have maximum receptivity around 12 am–2 pm. Maximum stigma and style receptivity does not concur with maximum anther dehiscence, thus limiting the possibility of self-pollination. The period during which the stigma is receptive to pollen and consequently during which successful pollination is possible, only lasts one day. Non-fertilized flowers will abscise the next day. About 1–5% of all flowers develop into a pod [31, 32].

3.1.3. Cherelle wilt

Even after cocoa flowers are successfully pollinated and led to fruit set, not all young fruits (cherelles) will grow to mature cocoa fruits. Up to 80% of cherelles will shrivel, turn black, and become rapidly colonized by pathogens, while the pod remains on the tree. This so-called cherelle wilt is a physiological mechanism whereby the fruits are naturally thinned to balance nutrient allocation in the tree. Cherelles can wilt up to day 100 after fruit set [38]. Poor soils and impeded photosynthesis result in increased cherelle wilting [39, 40]. Leguminous shade trees, which supply nitrogen to the soil, can therefore lower cherelle wilt [7]. Wilting in an early stage saves energy that can be invested in the development of the remaining fruits [30, 31]. Apart from resource limitation, inadequate pollination (insufficient pollen grains deposited on the stigma surface) and incompatible pollen may also cause cherelle wilting [41].

3.1.4. Pod maturation

There are 130–160 days between fertilization and pod harvest [32]. The cocoa fruit is an indehiscent drupe. During the first 40 days after fertilization, pod growth is slow. Afterward, growth accelerates. The first division of the zygote only takes place between day 40 and 50. Pod and ovule growth decrease from day 85 onwards, when embryos start to develop. On day 140, the embryo has completed its development and pod ripening starts [38].

3.1.5. Self-incompatibility

Most cocoa trees are self-incompatible. Self-pollination on a self-incompatible variety will not result in successful fertilization; as such, cross-pollination is then the only way for successful fertilization [42]. Self-incompatible trees are mostly cross-compatible; i.e., they are able to successfully fertilize flowers on other trees, including trees of the same variety. Incompatibility takes place at the stage of gamete fusion: incompatible gametes are unable to fuse. The underlying mechanism is of a genetic nature [32, 43]. Following unsuccessful fertilization due to incompatibility, the flower drops off after 2–3 days. Even within a single variety, not all trees are necessarily either self-incompatible or self-compatible. However, the proportion of self-incompatible trees of a certain variety is determined by the specific variety. Self-compatible varieties that are cross-incompatible can restrict bean yield. In commercial plantations, it is therefore recommended to always plant different varieties [31]. Self-compatible hybrids produce larger fruits with a higher dry bean yield [44].

Viable pollen is able to germinate (producing a pollen tube) when it reaches the stigma. Pollen viability lies between 80 and 90%, hence does not limit fertilization [32, 45].

3.1.6. Flower phenology

The number of flowers per tree varies throughout the season and is a function of climatic factors, such as photoperiod and temperature regime [46], whereas it is also cultivar dependent [31]. Furthermore, it seems that fruit production in the previous year determines flower production in the following year. Years of high pod production alternate with years with a low level of flowering [47, 48]. In most tropical countries, flowering occurs year-round. Flowering peaks are often preceded by increased temperature and rainfall, and occur at the onset of the rainy season, after which flower numbers gradually decline [45]. In West Africa, the major rainy season commences in April and climaxes in June, a period that is characterized by intense flowering (flowers on branches and trunks) [6]. In the minor rainy season (September–November), flowering intensity is lower (flowers on branches only). Few flowers are observed during the dry season (December–March) [47]. When pods are developing and this sink for assimilates is increasing, new flower production diminishes [40].

3.2. Biology and phenology of cocoa pollinators

3.2.1. Overview of cocoa pollinating species

Early studies have ruled out wind as a pollinating agent—pollen grains form chunks, due to their viscosity and become too heavy to travel on their own [49]. However, in South America, experiments have been conducted to increase pollination by artificially increasing air currents in the field with motorized knapsack sprayers, thus stimulating wind pollination. This technique, however, only proved to be effective (doubling of cocoa bean yield) on self-compatible varieties [50].

Cocoa is almost exclusively pollinated by insects. The most important pollinators are midges from the family Ceratopogonidae. In reference [26], the author claims based on a review of five papers that female specimens are the main pollinators, although in reference [28], four times more males than females were collected in cocoa flowers. Ceratopogonids are biting midges of 1–4 mm length [51]. Males also pollinate, but to a lesser extent. It is not clear why females visit cocoa flowers more frequently than males [28, 52, 53]. Females presumably visit cocoa flowers to feed on the protein-rich pollen grains, necessary for egg maturation.

Besides ceratopogonids, other small dipteran insects such as Cecidomyiidae (gall midges), Chironomidae (non-biting midges), Drosophilidae (fruit flies), Psychodidae (moth flies), and Sphaeroceridae (small dung flies) have been documented to visit cocoa flowers. Other insects, such as aphids, coccids and cicadellids (Hemiptera), thrips (Thysanoptera), and ants (Hymenoptera), also occasionally visit cocoa flowers. However, their contribution to pollination is most probably very low. Up to date, pollen grains have not been detected by microscopic observation on insects other than *Forcipomyia* spp. In some cases, observations suggest that cecidomyiids (in Cameroon) and drosophilids (in Ghana) may contribute to some extent to pollination [26].

Only Diptera, and particularly genus *Forcipomyia* (Fam. Ceratopogonidae), are morphologically able to pollinate cocoa. *Forcipomyia* holds the largest number of cocoa pollinators. Within

that genus, the most frequently reported pollinators belong to the subgenera *Euprojoannisia* (before: *Proforcipomyia* and *Euforcipomyia*), *Thyridomyia,* and *Forcipomyia* [26].

It is well-documented that ceratopogonids breed in humid, decaying organic material such as cocoa leaf litter, decomposing cocoa pod husks, banana pseudostems, and bromeliads [4, 54]. Besides being moist, these breeding substrates are cooler than the ambient environment and provide dark conditions which all benefit ceratopogonid breeding [31].

In the 1970s, cage experiments [28, 52, 53] were performed to characterize the pollination capacity of different ceratopogonid species. However, results of these experiments have little value as they were performed under unrealistic conditions (exposure of a high number of flowers to a single midge and use of small cages, both causing pollination levels that the same midges would not achieve in nature). The only valid method to determine whether a species is a pollinator is through field observation [26]. It has been shown that artificial circumstances bias lab experiment results considerably; for example, successful pollination by *Tyora tessmanni* was shown under lab conditions, but could not be confirmed under field conditions, where the putative pollinator was abundantly present [55].

There is weak evidence for the indirect influence of the ant *Azteca chartifex spiriti* Forel (in Brazil) on cocoa pollination, as it has been shown to attract ceratopogonid midges [56]. There is some evidence of the pollination potential of stingless bees *Tetragona jaty* (Smith), *T. testaceicornis* Lep., *T. coryina* Ckll., *T. pallida* Latr.; *Nannotrigona testaceicornis punctata* (Smith); *Paratrigona lineata subnuda* Moure, and *Plebeia mosquita* (Smith). However, cocoa pollination by the latter species is merely coincidental. Sweat bees (*Lasioglossum* spp.) have also been suggested as possible cocoa pollinators [57, 58].

3.2.2. Biology and phenology of Forcipomyia spp.

Forcipomyia eggs hatch 3 days after deposition. Twelve days later, larvae transform into pupae. Pupation lasts 3 days. Adults live 1–12 days (under laboratory conditions) [59, 60]. A complete life cycle thus covers about 28 days [31].

Female ceratopogonids, in search for sugary nectar, start pollinating cocoa flowers early in the morning (5–8 am) and also actively visit flowers in the afternoon (4–6 pm) [3, 52]. Ceratopogonids carry cocoa pollen grains on their thoracic hairs. Weather conditions affect their flower visiting activities: rain and clouds decrease their activity whereas sunny weather increases it [3]. Some trees receive more attention from pollinators than others, resulting in a greater fruit set in some trees as compared to others. The interest for particular trees shifts with time. Why this happens, is not clear. Female ceratopogonids commonly visit cocoa and other flowers everywhere in the world [4, 61].

Ceratopogonid midge flights might cover long distances, but it is not known how far exactly [26]. Distance traveled during one foraging event, and consequently during which pollination is performed, can reach up to 50 m. However, midges mostly deposit pollen from a certain cocoa tree on flower stigmas of neighboring cocoa trees [31, 62]. It has been shown that there are 5–7 times more *Forcipomyia* specimens above the cocoa canopy than below the

canopy [26]. Since wind speed above the canopy is higher than below, it can be expected that wind could play an important role in horizontal cocoa pollinator distribution over the cocoa field.

Besides feeding on flower nectar, adult ceratopogonids also suck the blood of other insects and mammals. In general, pollinating activity is very limited in time during the lifetime of these pollinators.

Ceratopogonid pollinator populations can be abundant and exceed one million individuals per ha [3]. Moist environments favor ceratopogonid midge abundance. In fact, there is a positive correlation between soil moisture and ceratopogonid population levels [26]. Stable moist conditions are indispensable for successful development of eggs and larvae [63]. It is suggested that the West African harmattan (dry, hot wind from the north) results in withered breeding places, rendering them unsuitable for insect breeding [26]. Pollinator populations thus increase with each rainy period, to decrease again with the onset of a drier period [31].

3.3. Pollination gap in cocoa

The yield gap in cocoa (i.e., the difference between yield at optimal, experimentally determined growing conditions and the current cocoa farm yield) is caused by multiple factors including disease, pest and weed pressure as well as inadequate phytosanitary practices, lack of improved varieties, low soil fertility, etc. [64]. However, there is increasing evidence that the present yield gap is also linked with inadequate pollination. This so-called pollination gap was already observed in the late 1970s when it was found that during the dry season, the number of ceratopogonid pollinators, as well the relative number of pollinated flowers were lower than in the wet season [3, 4, 26]. Because rotten, moist organic material is an ideal breeding substrate for ceratopogonid midges, attempts have been made to increase reproduction opportunities for these midges by adding such organic material in cocoa plantations. In an experiment in Ghana, banana pseudostems, cocoa pod husks and leaf litter were added as pollinator breeding substrates next to cocoa trees. It was found that midge population increased to 500% of the control tree levels whereas fruit set in treated trees was four times higher than in control trees. Cherelle wilt also increased in treated trees but was lower than increased fruit set rates so that the final number of mature fruits was twice as high for all substrate-treated trees compared to the control trees [65]. A more direct proof of the pollination gap was found when cocoa trees in Sulewesi (Indonesia) were artificially pollinated. Optimum dry bean yield was achieved when 40% of flowers were hand-pollinated [14]. The latter treatment increased dry bean yield by 350 kg per ha as compared to a pollination intensity of 10%, which concurs with natural pollination intensities observed over the past 20 years [30, 66]. In North Queensland (Australia), it was recently shown that adding cocoa pod husks as a pollinator breeding substrate considerably increased fruit set (110 times more cherelles) and yield (60 times more fresh fruit production). However, hand pollination in fields where breeding substrate had been added did not result in extra yield, indicating that breeding substrates had already increased pollination intensities to optimum levels [16].

http://dx.doi.org/10.5772/intechopen.75361

4. Constraints to cocoa pollination in Côte d'Ivoire

4.1. Deteriorating pollinator environment

4.1.1. Cocoa monoculture

Cocoa is a shade-tolerant tree. Traditionally, cocoa is grown in shaded, agroforestry systems where it is intercropped with forest trees that were spared when the forest was cleared for cocoa cultivation. However, it was shown that—provided soil nutrition levels are adequate—cocoa production with shade trees is lower when compared to full-sun production [31, 67–69]. As a consequence, agroforestry systems have globally been replaced by monoculture systems with low shade provision [70]. Over the past few decades, cocoa cultivation has intensified not only by removing shade trees but also by extensive application of fertilizers and pesticides. As a result, the insect assemblage of cocoa cultivation systems has changed considerably. When compared to agroforestry systems or natural forests, insect biodiversity has decreased in present-day cocoa plantations, often at the expense of predators, leading to increased pest outbreaks and pollinators [71–75].

4.1.2. Landscape degradation

In Côte d'Ivoire, the cocoa sector is largely responsible for landscape degradation [19]. Over the past few decades, cocoa was typically cultivated on freshly cleared land where its production rapidly expanded, after which the land was abandoned 10–15 years later due to declining yields. Since the 1970s, such continuous so-called boom-and-bust cycles, as well as cocoa expansion from the southeast to the southwest of Côte d'Ivoire, have led to massive deforestation in the country [9, 22, 76]. In the 1960s, total tropical primary forest cover amounted to around 8.14 million ha. In the 1980s, that area had dropped to 2.6 million ha, whereas in the 2000s, primary forest cover was just over 1.35 million ha, meaning that since its independence, Côte d'Ivoire has lost 80% of its forest cover [77].

Almost all cocoa plantations in Côte d'Ivoire have less than 50% of shade, meaning that the majority of trees are fully exposed to sunlight, leading to biodiversity loss and soil deterioration, often resulting in reduced addition of organic matter to the cocoa plantation soils [78]. It has been extensively shown that *Forcipomyia* spp., which are the predominant pollinating midges, require moist and decaying organic material to breed [15, 28, 52, 79]. Also, the vicinity of natural forest and moist refuges promote diversity of *Forcipomyia* spp. and cocoa pollinators in general [52, 80]. It is therefore fair to assume that in Côte d'Ivoire, massive landscape degradation has led to decreased breeding opportunities and consequently to lower population levels of cocoa pollinating midges.

4.2. Pesticide use in the Ivorian cocoa sector

4.2.1. Target pests and insecticide products used

The major cocoa pest problem in West Africa is caused by mirids (Order: Hemiptera, Fam. Miridae). *Sahlbergella singularis* and *Distantiella theobromae* suck the sap from cocoa pods

and young shoots, causing commercial cocoa losses of up to 30% [81, 82]. In West Africa in general, more than 75% (in some areas 100%) of cocoa farmers use chemicals to control mirid infestation [83]. Nowadays, most frequently used insecticides in cocoa cultivation are the pyrethroids bifenthrin, cypermethrin, deltamethrin and lambda-cyhalothrin, and the neonicotinoids acetamiprid, imidacloprid and thiacloprid [84]. In Côte d'Ivoire, almost all farmers who use insecticides, apply commercial products containing a systemic neonicotinoid insecticide, usually in combination with a contact pyrethroid insecticide two times per year (July–August and January–February). The pyrethroid would thereby kill the mirid adults as well as the nymphal instars, whereas the systemic neonicotinoid would ensure that mirids that hatch after insecticide applications are also killed (personal communication with local pesticide dealers) (**Table 1**). However, the precise impact of these specific insecticides on cocoa pollinators in Côte d'Ivoire is unclear and should be further investigated.

4.2.2. Impact of pesticides on cocoa pollinators

Broad-spectrum insecticides (such as β-hexachlorocyclohexane and dichlorodiphenyltrichloroethane), which were historically widely applied in cocoa crop production, did not affect pollinator population levels [26]. It is suggested that breeding sites are protected from

Pesticide brand	Neonicotinoid	Conc. (g/L)	Pyrethroid	Conc. (g/L)
Thiodalm Super	Acetamiprid	20	Bifenthrin	20
Callifan Super BD	Acetamiprid	20	Bifenthrin	20
Gourou Super 45 EC	Acetamiprid	25	Cypermethrin	25
Onex Super 40 EC	Acetamiprid	20	Cypermethrin	20
Caomine 40 EC	Acetamiprid	20	Cypermethrin	20
Blinde 20 EC	Acetamiprid	10	Lambda-Cyhalothrin	10
Gawa 30 SC BTE	Imidacloprid	30	—	—
Thiosulfan 60 EC	Imidacloprid	60	—	—
Caostar 60 EC	Imidacloprid	60	—	—
Gawa Pro 80 SC	Imidacloprid	60	Bifenthrin	20
Koumabana	Imidacloprid	30	Bifenthrin	20
Grosudine Super 50	Imidacloprid	30	Bifenthrin	20
Tropinex Ultra	Imidacloprid	30	Lambda-Cyhalothrin	20
Actara 240 SC BTE	Thiamethoxam	240	—	—
Azudine 50 SC	Thiamethoxam	30	Deltamethrin	20
Boradyne 45 ZC	Thiamethoxam	30	Lambda-Cyhalothrin	15

Table 1. Insecticides, designed for application in cocoa cultivation, randomly collected by the authors from pesticide shops in Abidjan, Côte d'Ivoire in October 2016.

insecticide sprayings by leaves and other organic material. However, residual effects of insecticides might affect cocoa pollinators [3, 54]. A study in West Africa on the effect of large-scale insecticide treatments (against mirids; Fam. Miridae) on both pollinator population levels and cocoa pod production showed that there is only a short-term negative impact of insecticide treatments on pollinator population levels [31]. Also in West Africa, it was shown that fogging instead of spraying insecticides is less harmful for pollinators, as fogging only negatively influences the population level for 2 days compared to 8 days with spraying [85]. Alternative approaches are to (i) reduce insecticide dosages during the period that pollinator population levels are low, and (ii) use narrow-spectrum insecticides.

5. Recommendations

5.1. Integrated pest management (IPM) options in the Ivorian cocoa sector

Despite the currently widely applied spraying programs, mirid infestation remains the most severe cocoa production limitation factor [81]. Although the precise impact of pyrethroids and neonicotinoids on cocoa pollinators in Côte d'Ivoire is unknown, it cannot be excluded that apart from these regular pests, pollinators are also affected by these products. Therefore, novel and more integrated pest management (IPM) approaches should be tested against mirids. The latter approaches might include: (i) further development and testing of mirid pheromones [86]; (ii) increasing shade levels by planting shade trees to avoid so-called "mirid pockets" (i.e., mirids particularly occurring in non-shade areas of the plantations) [81]; and (iii) enhancing ant populations as they are most probably natural mirid predators [87].

5.2. Enhancing cocoa pollinator environment

In cocoa plantations, pollinator population levels can be increased by augmenting the amount of natural pollinator breeding sites or by adding artificial breeding substrates. Since it is known that *Forcipomyia* spp. breed in moist and rotting organic material, introducing such material in the cocoa field will most likely enhance pollinator breeding and subsequently their population levels. Banana pseudostems are preferred as a pollinator breeding substrate over cocoa husks, because the latter are a possible source of black pod disease [88]. Intercropping with fruit trees will not only provide shade, but (provided that not all fruit is harvested), will also introduce rotting fruit in the plantations as potential pollinator breeding sites. As shown in **Figure 2**, in Côte d'Ivoire, we currently investigate, together with the cocoa farmers of the local cooperatives, the effect on pollination levels of squared pits (0.5 × 0.5 m and 0.3 m deep) that are spaced in 10 × 10 m squares and in which organic material such as fresh empty pod husks, cut banana pseudostems, and fruits from intercropped trees such as *Citrus* spp. will be deposited to enhance pollinator breeding.

5.3. Pollinator mass breeding and mass release

Mass breeding and subsequent mass release of *Forcipomyia* spp. at times when cocoa flowering peaks, might also have a significant effect on effective cocoa flower pollination. The idea



Figure 2. Midges of *Forcipomyia squamipennis* in the family Ceratopogonidae are believed to be the most important pollinators of cocoa globally, based on field observations and laboratory rearings [53, 96]. Indeed, early on, scientists figured out that most *Theobroma cacao* trees are not able to self-pollinate, but for years, they could not figure out what moved cocoa pollen between trees. It turned out that cocoa flowers are pollinated by midges not much bigger than tiny specks of airborne dust. Midge populations are greatest in the rainy season. Adult midges spend the day in shady spots such as between the buttress roots of large trees, in crevices in logs, in hollow stumps or in piles of husk debris. They emerge at variable times of the day to swarm near their hiding locations, and disperse in the early morning and late afternoon. Most midges do not move further than about 6 m. The females lay batches of eggs on damp piles of plant debris, on moist decomposing wood, cocoa husks and other plant debris, in batches of 40–90 eggs. Eggs hatch after 2–3 days and the larvae pass through four instar stages before pupating at about 12 days; the pupal stage lasts 2–3 days. The adults survive for about a week and there are thought to be about 12 midge generations per year. Adult females require liquid plant food for survival and oviposition, although ovary maturation is independent of adult food intake or mating. In a joint project between Ghent University and Barry-Callebaut, and in collaboration with local cocoa smallholders and their cooperatives, we introduced squared pits of 50 × 50 cm and 30 cm deep, filled with organic material such as cut banana pseudostems, fresh empty pod husks and fruits from intercropped trees such as *Citrus* spp., at a density of 1 pit per 100 m^2 (spaced at 10 × 10 m as based on presumed midge flight radius of the midges) to enhance the establishment of the cocoa pollinating midge populations in the field (main picture is a photo by Guy Smagghe in cocoa plantation at Tiassalé, Côte d'Ivoire, 15/01/2018; inset photo is of a mating pair of *Forcipomyia* midges by Christophe Quintin, https://www.flickr.com/photos/34878947@N04/).

is based on similar practices commonly applied in the horticultural sector where bumblebees (*Bombus terrestris*) are commercially bred and subsequently released in tomato (*Solanum lycopersicon*) greenhouses for tomato flower pollination [89]. As compared to the earlier used vibrating sticks to induce pollen release from tomato flowers, bumblebees increase tomato fruit set by 45%. Another example is the black soldier fly (*Hermetia illucens*) (Order: Diptera, Fam: Stratiomyidae) that is used to enhance composting of food waste and reduction of organic manure volumes, and which can be mass bred prior to release on organic material [90]. To our knowledge, no mass breeding attempts for *Forcipomyia* spp. have been undertaken up to date. The hematophagous nature of *Forcipomyia* midges can be a constraint to their mass breeding success [91]. Laboratory experiments showed that *F. townsvillensis* eggs will not develop without complete blood meals [92]. Research is needed to test the most appropriate midge rearing conditions (temperature, humidity and feeding).

Forcipomyia spp. mostly pollinate flowers neighboring the ones where they have collected pollen [93]. We assume therefore that they do not swarm further than 10 m from their breeding sites. Under that assumption, mass release should be performed at least each 20 × 20 m in cocoa plantations (25 releases per ha). Given the wide diversity of *Forcipomyia* spp. that have been

identified as cocoa flower visitors and the fact that some are restricted to either Africa, Central America, or South America (only one cocoa flower pollinator, *F. fuliginosa* was observed in all regions), it can be assumed that specific pollinating midges are restricted to certain areas [4]. It is therefore recommended that *Forcipomyia* spp. mass breeding for use in a certain cocoa area would start with locally sampled *Forcipomyia* midges, as exotic midges might disturb local biotic equilibria. Obviously, as a precondition to adoption of commercial mass breeding of pollinating midges by resource-poor smallholders in Côte d'Ivoire, the technology should be cost-effective.

6. Conclusion

Since cocoa production essentially depends on insect pollination, any threat to pollinators will have a negative impact on cocoa production. There is evidence that currently, cocoa pollination is below the optimum level and that enhancing pollinator populations in cocoa fields could increase cocoa production [14–16]. It is clear that cocoa pollinators are threatened by the currently predominant cocoa production system, which consists of full-sun cultivation on often deforested land with degraded soils and chemical pest control. Pest control, shade tree planting, and landscape management all influence cocoa pollinator presence, making pollination management very complex.

Many research questions on cocoa pollination remain. They include: (i) quantification of the pollination gap (only in [14] attempts have been made, but just by comparing hand-pollination treatments with unpollinated controls); (ii) evolution of the pollination gap throughout the year (e.g., in West Africa, the gap might be narrower during the dry season when flowering is less abundant); (iii) the relation between pollination and cherelle wilt (can cherelle wilt be decreased by improving pollination efficiency?); (iv) success rates of artificial pollination (a difficult task requiring a lot of agility and experience); (v) influence of insecticide applications on pollinator and other insect population levels; (vi) role of landscape and cocoa cropping systems (agroforestry, intercropping, soil mulching) on pollinator species composition and abundance; (vii) pollen load and pollination efficiency of cocoa flower visitors other than *Forcipomyia* spp.; (viii) evaluation of pollinator roles in self-compatible as compared to self-incompatible cocoa trees; (ix) promotion of self-pollinating self-compatible trees; and (x) effectiveness of enhancing ant populations to improve cocoa pollination.

As final conclusion, we believe that the answers to these research questions will undoubtedly lead to decreasing the current cocoa yield gap, which is the only sustainable solution to increasing global cocoa supplies.

Acknowledgements

The authors acknowledge support from the local cooperatives of Ivorian cocoa producers in Côte d'Ivoire as well as Barry-Callebaut SA for financing cocoa pollination research in Côte d'Ivoire. Guy Smagghe also thanks the Special Research Fund of the Ghent University and the Research Foundation-Flanders (FWO-Vlaanderen) in supporting research with pollinators.

Conflict of interest

The authors have no conflict of interest.

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