Chapter

Impact of Illegal Mining Activities on Cocoa Pollinator Abundance in Ghana

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Abstract

Cacao (*Theobroma cacao* L.) is mainly pollinated by Ceratopogonid midges (Forcipomyia spp.). Wild pollinators are important to both cocoa production and natural ecosystems, and are threatened by land-use change, intensive agricultural management, fragmentation from mining activities, and climate change. Despite the massive expansion of cocoa production in Ghana, it may now be of secondary economic importance to gold due to its increased environmental impact and the economic importance exercised by cocoa communities. However, very little attention has been paid to pollination management as a factor of production, as pollination is often not considered an important process for crop yield. The Ghana Cocoa Board takes a closer look at the impact of illegal mining on cocoa productivity and trusts farmers to destroy their farmland for illegal gold mining. In this chapter we briefly describe the cocoa sector, cocoa flower and pollinator biology and phenology as presented. What follows is an overview of the current environmental threats and social issues posed by unregulated mining affecting pollinator abundance and diversity in the context of Ghana. Finally, we examine ways to improve pollination and deforestation in Ghana's small cocoa sector.

Keywords: pollinators, illegal mining, habitat fragmentation, deforestation, cocoa, Ghana

1. Introduction

Pollination services are an essential element to maximize production in sustainable agriculture [1–3]. They are critical to food production and human livelihood, directly connecting wild ecosystems to agricultural production systems [4]. Wild pollinators are important in both agricultural and natural ecosystems and are threatened by land-use change [5], intensive agricultural management and pesticide use [6], pathogens [7] and climate change. The most important cocoa pollinators are midges. In cocoa, pollination occurs almost exclusively by ceratopogonid midges (order Diptera) of the genus Forcipomyia [8, 9]. The midges species that pollinate cocoa belong to the genus Forcipomyia. Most researchers studying cocoa pollination assume that Forcipomyia, which is common in cocoa plantations in Ghana, is Forcipomyia squamipennis I.

Demand for cocoa, the third largest trade commodity globally [10], is increasing in China, Russia, India, and Brazil by 2.5% per year [11], while production has declined by an average 1.5% annually for the past decade [12]. The three major cocoa producing countries are Ivory Coast, Ghana, and Indonesia. In West Africa, it is predicted that 89.5% of current cocoa growing areas will experience a decline in cocoa suitability by 2050 [13]. Businesses and governments are advocating sustainable cocoa initiatives to prevent deforestation and promote ecosystem services, biodiversity and sustainable livelihoods [14]. Cocoa production in Ghana is exclusively concentrated in the country's Ashanti, Brong, Ahafo, Central, Eastern, Western and Volta agroecological forest areas where the climatic conditions are ideal for cocoa production. The first cocoa farm was mostly established in south-east Ghana. Since then, the epicenter of production has gradually shifted west. In the early 1980s, the Ashanti and Brong Ahafo regions accounted for 35.5 and 18.5% of total production, respectively. Today, the western region alone supplies 56.5% of the total annual cocoa harvest. The cocoa industry generates about US$2 billion in foreign exchange annually and plays an important role in the national economy. The sector employs around 800,000 farming families in six of the country's ten regions [15]. Ghana is the second highest cocoa producing country in the world after Ivory Coast, with the sector producing approximately 970,000 tonnes of cocoa in 2017 [16].

Ghana's cocoa sector continues to make a significant contribution to the country's economy. In 2014 it accounted for 21.5% of the country's GDP and between 2009 and 2014 it averaged 25.6% [17], representing a large share (16.9%) of the agricultural sector's contribution to GDP. The environmental impacts of gold mining are wide-ranging and severe. A recent USAID study found that despite the massive expansion of cocoa production in the country, cocoa production may now be of secondary economic importance to gold due to its increased environmental impact and economic importance, even if mining is not practiced by all [15]. While Ghana has developed action plans to end deforestation in the cocoa sector and restore forest lands, actions to address the rapid expansion of artisanal and small-scale gold mining have so far been quite limited, jeopardizing potential gains in reducing deforestation in the cocoa sector.

In this chapter, we examine how habitat loss, fragmentation, deforestation, and climate effects affect the abundance and diversity of cocoa pollinators. We will first introduce the global cocoa sector and then focus on Ghana, the second largest cocoa producing country in the world. Next, we provide background on the biology and phenology of cocoa flowers and pollinating midges (Forcipomyia spp.), followed by a discussion of the impact of illegal mining on pollinator abundance and diversity (environmental and management) in Ghana. Finally, we discuss some options for easing restrictions on cocoa pollination.

2. The cocoa crop sector

2.1 Global cocoa production and economic value

Cocoa is a cash crop for many West African smallholder farmers. Although global annual cocoa production quantities are below those of other tropical crops such as sugar cane, rice, soybeans, oil palm, cassava or bananas, it is a unique crop as more than 90% of its production comes from smallholder farmers [18]. Cocoa production is estimated to be around 10 million hectares, which accounts for only 0.7% of the total global arable land but 7% of the global permanent land [19]. Therefore, cocoa cultivation and especially cocoa agroforestry systems play an important role in carbon sequestration and therefore have a significant mitigation potential [20]. Climate change, deforestation, diseases and low world market prices threaten global cocoa production. Global annual cocoa production has doubled in recent decades, reaching 3.6 million tonnes in 2009–2010, increasingly being concentrated in a handful of countries. Africa has established itself as a leading cocoa supplier over the past 10 years. According to the International Cocoa Organization, Africa's production has increased at an average annual rate of 2.7% since 2000. Farmers throughout the cocoa belt of West and Central Africa account for more than two-thirds of the world's cocoa production. World annual production reached 4.5 million tons in 2013 and growth came mainly from West Africa [18].

2.2 The cocoa sector in Ghana

Cacao is an important source of income for the provision of various public infrastructures and a profession mostly loved by farmers in Ghana and other countries. Cocoa dominates the agricultural sector and is an important source of income for approximately 800,000 farmers and many others involved in the trade, transport and processing of cocoa [21]. Ghana's cocoa sector has seen an impressive recovery in recent years. Ghana can boast of over 1,000,000 tons of cocoa in the 2010/2011 harvest year. Ghana is the second largest cocoa producer in the world [22, 23]. Together with Ivory Coast, it produced almost 52% of the world's total cocoa production in 2016. About 800,000 cocoa households produce 75 percent of all cocoa in Ghana [24]. The Ghanaian government generates most of its income from the export of cocoa [19]. Cocoa provides resources for poverty alleviation as well as food, money, employment and industrial raw materials [25]. The small size of farms in Ghana may be due to cocoa farm agreements where the farm is sometimes shared between the landowner and the caretaker [26]. The inheritance system in Ghana often leads to fragmentation of farmland when a farmer share his farm to several sons. Smaller farms result in decreased yields as small farms are a disincentive to invest, leading to reduced use of fertilizers and fungicides/pesticides [27]. The average cocoa acreage fell from 9.6 to 7.5 ha between 2008 and 2014 [28].

Ghana faces the problem of poor farm maintenance in terms of pest and disease control and low soil fertility. This is due to the low adoption of improved agricultural practices. For example, farmers only weed their farms twice a year on average, instead of the recommended four times. In addition, control of capsids and black pod disease occurs only twice a year instead of the recommended four or nine times a year [29]. Ghana has implemented the Hi-Tech program (fertilizer distribution via COCOBOD) to increase fertilizer use as fertilizer use in Ghana is low compared to Ivory Coast [30]. Timing of pesticide application is critical to maximize effectiveness in controlling mirids. The mirid population in West Africa begins to build up in July and peaks between August and September, while black pod occurrence increases from June and peaks in August and October. Therefore, it is recommended that cocoa plantations in Ghana are sprayed between July and September. Tetteh Quershie is the oldest variety still used in Ghana. It was named after the Ghanaian farmer who introduced cocoa to Ghana. The pods introduced by Tetteh Quarshie are of the Amelonado variety, which is a Forastero subspecies [31]. New introductions were made in 1944 from Forastero materials collected by F. J. Pound from the upper Amazon at the West African Cocoa Research Institute headquarters in Tafo, Ghana and Ibadan in Nigeria. Due to the earliness of these materials, they were widely used for replanting deforested plantations and by the late 1950s about 11 select species of the upper Amazon were being used to produce second and third generation Amazons, known as F3 Amazons or mixed Amazons, which were distributed to farmers. Several hybrid varieties have also been developed from these materials in Ghana, involving crosses with local Amelonado, Trinitario and some Criollo materials [32].

3. Cocoa pollination

The intensity of pollination and fruit set largely determine the cocoa yield [33]. However, very little attention has been paid to pollination management as a factor of production, as pollination is often not considered an important process for crop yield. Even when pollination is acknowledged, its management is often not considered. This is because most people believe that there are enough pollinators in the wild to carry out pollination without active human intervention.

3.1 Biology and phenology of cocoa fruit set

3.1.1 Biology

Cocoa flowers are hermaphrodite (male and female parts). Group of flowers (inflorescence) and pods are produced by the mature tree on the main stem and branches. This type of flowering is called cauliflory. The flowers are produced at the same defined areas on the tree and these swell with time to form flower cushions. 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. Flowers that are well pollinated develop to form fruits called pods. The main pod development stage is the cherelle or immature pod. A mature cocoa tree can produce over 10,000 flowers every year of which 1–50% are pollinated with 10–50 pods reaching maturity. The flowers first appear as small green or white buds at the flower cushion. The buds reach maturity and open within 28 days. The flower is small (0.5–1 cm), white, non-scented and borne on long pedicel or stalk. The female part consists of stigma, style and ovary which contains ovules (female sex cells) and the whole structure is surrounded by staminodes. The male part is made up of long stalk (filament) and anther with pollen grains (male sex cells) at the tip. The anther is hidden in a pocket- like structure called the petal sac or porch. Unlike most flowers where only the stigma is receptive to pollen, both the stigma and style are receptive to pollen. Most of the pollens are deposited on the style during pollination. Open flowers may remain on the tree for 48 to over 72 hours depending on the season, after which the unpollinated ones drop.

The sepals and petals of pollinated flowers start drying up giving it a brownish appearance. Greenish cherelles then emerges from the swollen ovary at the base of the female part. The presence of staminodes and petal porch prevent most insects from effectively pollinating the cocoa flower. Unlike most insect pollinated flowers, the color of the flower does not appear to attract its main pollinator, midges. However, there are purple colored lines called guide lines on the inner surface of the staminodes which guide them after landing on the flower. The midges upon landing on the staminode, move towards the base of the staminode as they feed along the guide lines and finally enters the porch which contains the pollen. There are hairs on the upper part of midges' thorax which are designed to pick pollen as they move within the porch.

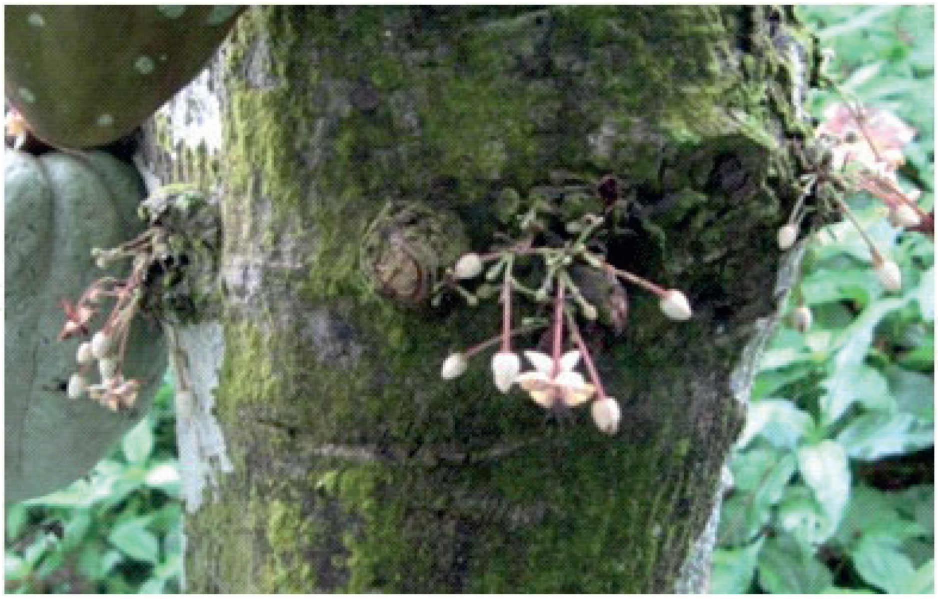

Figure 1.
Stem of cocoa tree showing developed flower cushions with buds and flowers.

The insect then fly to another flower where the pollens are dropped on the stigma and style. This is made possible by brushing the thorax against the style as it moves to the base of the staminode (**Figure 1**).

3.1.2 Bud development

Flower bud development from meristem to receptive flower takes at least 20 to 30 days [34]. Prolonged dry (<125 mm per month) or cold (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 [34]. Pollen grains are only able to germinate on a receptive stigma [36]. 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 [34].

Anthesis starts around 2–4 pm. 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 [37]. However, pollen release is maximum between 8 am and 2 pm [38]. 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 (**Figure 2**).

3.1.3 Cherelle wilt and pod maturation

Not all young fruits (cherelles) will grow to mature cocoa fruits, even after cocoa flowers are successfully pollinated and led to fruit set. 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

Figure 2.
Flower buds about to open and fully open flowers.

the fruits are naturally thinned to balance nutrient allocation in the tree. Cherelles can wilt up to day 100 after fruit set [39]. Poor soils and impeded photosynthesis result in increased cherelle wilting [35]. Leguminous shade trees, which supply nitrogen to the soil, can therefore lower cherelle wilt [40]. Wilting in an early stage saves energy that can be invested in the development of the remaining fruits [37].

It takes 5–6 months for pollinated flowers to become ripe pods. Different sizes or growth stages of flowers and pods can be found on the tree at any given time. Mature pods grow up to 30 cm long and 10 cm wide, and contain 20–60 beans (seeds) [37]. 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 [40].

3.1.4 Flower phenology

Cocoa bears fruits all year round, and the developmental stages start after pollination of the cocoa flowers occurs. However, only 1–5% of the flowers can successfully produce as a cocoa bud [39]. Some authors [41, 42] argued that the spatial arrangement of staminodes around the style of the cocoa flower affects pollination success and hence may limit fruit set. Others [43–45] also believed that cocoa flowers are nectarless and odorless. Young et al. [46] have demonstrated the presence of microscopic nectaries on the pedicels, sepals, and guide lines of the petals and staminodes that produce odor. These characteristics of the cocoa flower seem to make it unattractive to many potential pollinators, and therefore only insects that have evolved with the plant will successfully pollinate it. 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 [47]. 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) [48].

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) [49]. When pods are developing and this sink for assimilates is increasing, new flower production diminishes [26].

3.2 Biology and phenology of cocoa pollinators

3.2.1 Overview of cocoa pollinating species

Due to their viscosity, pollen grains form clumps and become too heavy to move independently [49]. Pollination of cocoa has the potential to overcome yield deficits in climate-resilient and sustainable production systems [12]. Pollination rates are generally poor for cacao and inconsistent throughout the year, so better pollination can increase yield. Experiments have been conducted in Ghana to increase the production of cocoa through hand pollination, which has been shown to increase fruit set, matured pods and the number of seeds per pod [49]. The Cocoa Research Institute of Ghana (CRIG) in Tafo used additional (artificial) hand pollination to increase yield and also breed new cocoa varieties [16, 49]. This aims to achieve maximum pollination, which is crucial for optimal yield in crop production, allowing for a bountiful harvest and increasing the export of cocoa beans, which will encourage farmers to increase production in the country [16].

Insect pollinators play an essential functional role in supporting ecological stability as well as food security worldwide [50]. Pollinating insects are vital to the world's food supply, pollinating more than 80% of the world's wild plant species [51]. The cocoa crop requires cross-pollination, which is mainly carried out by midges of the genera Ceratopogonidae and Cecidomyiidae [42]. Ceratopogonids are biting midges with a length of 14 mm [52]. It is believed that the females visit cacao flowers to feed on the protein-rich pollen grains necessary for egg maturation. Therefore, insufficient midges population leads to insufficient pollination and this deficiency has been reported as the main cause of low fruit set in some cocoa plantations [33, 53, 54]. In addition to midges, there are also wild bees Lasioglossum sp. and Hypotrigona sp., which visit cocoa flowers that bloom at tree canopy level to collect pollen. Lasioglossum in particular has been found to be effective at pollinating cacao flowers through its characteristic movement in and out of the petal porch. The role of Hypotrigona sp., which has been regularly identified on cocoa flowers in Ghana, has yet to be fully investigated. In general, more work needs to be done to fully understand the mechanisms of cocoa pollination globally and particularly in tropical Africa. In addition, 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 likely very small. So far, pollen grains have been collected from insects other than Forcipomyia spp. not detected by microscopic observation. In some cases, observations suggest that cecidomyiids (in Cameroon) and drosophilids (in Ghana) may contribute to pollination to some extent [8]. Only Diptera and in particular the genus Forcipomyia (Fam. Ceratopogonidae) are morphologically capable of pollinating cocoa. Forcipomyia hosts the largest number of cocoa pollinators. Within this genus, the most commonly reported pollinators belong to the subgenera Euprojoannisia, Thyridomyia, and Forcipomyia [8].

These small midges, 2–3 mm long, prove to be excellent pollinators due to their frequency of visits and the massive deposition of pollen grains on the stigma [55].

Therefore, in order to maintain their population, pollinator abundance can be synchronized through environmental manipulation by providing suitable breeding sites in the cocoa field [56]. Providing breeding media in portable breeding containers can contribute to population increase in cocoa cultivation. Choices of growth media include cocoa pod husk (CPH), banana stumps; and combining cocoa pod shells with the availability of insect-infested pods in the cocoa field. Additional substrates provided must be easy to find in the cocoa field and will increase the population of Forcipomyia sp. increase [57]. However, the substrate must be replaced regularly as the moisture content decreases over time. Declining trends in pollinator populations can occur on various spatial and temporal scales [58], including reductions in floral resources. A lack of floral diversity, particularly in monoculture ecosystems, can limit the provision of resources needed by these midges [59].

3.2.2 Biology and phenology of Forcipomyia spp.

Adult midges can be found between the buttresses of large shade trees, in cracks of decayed old tree trunks, in hollow tree stumps and in piles of cocoa husks. Swarming occurs at any time of the day or in the late afternoon. Midges are present on cocoa plantations year-round, but the largest population occurs during the rainy season. Adult females lay eggs in batches of 40 to 90 on damp, rotting wood, cocoa husk, and other plant debris. The larvae hatch in 2–3 days and pupate after four molts when they are about 12 days old. The pupal stage lasts 2–3 days. Adult females require liquid plant food for survival and oviposition, although ovum maturation occurs independently of adult feeding or mating. Unfertilized eggs do not develop. The maximum life expectancy for either sex in captivity is eight days. Forcipomyia goes through at least 12 generations per year. Due to its abundance and continuous reproduction on cocoa plantations, Forcipomyia is probably the most important ceratopogonid cocoa pollinator in Ghana. According to [42], midges are attracted by the vertically aligned staminodes and use them to land. The fact that style pollination generally leads to greater fruit set than stigma pollination makes the ceratopogonid midges efficient pollination candidates [60].

The insect may then proceed into the petal hood along the purple colored guide lines where curved bristles on the thorax press against the anther, thereby picking up pollen grains. Both sexes visit cocoa flowers, but males appear to be more efficient pollinators. High numbers of Forcipomyia in the farm result in increased pod set. However, the number of pollinators depends on the availability of good breeding substrate such as cocoa pod husks, decaying plantain and/or banana stems in the farm. Ceratopogonid midge flights might cover long distances, but it is not known how far exactly [8]. Distance traveled during one foraging event, and consequently during which pollination is performed, can reach up to 50 m. It has been shown that there are 5–7 times more Forcipomyia species above the cocoa canopy than below the canopy [8]. 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. Ceratopogonid pollinator populations can be abundant and exceed one million individuals per ha [9]. Moist environments favor ceratopogonid midge abundance. In fact, there is a positive correlation between soil moisture and ceratopogonid population levels [8]. Stable moist conditions are indispensable for successful development of eggs and larvae [61]. Pollinator populations thus increase with each rainy period, and decrease with the onset of a drier period [62].

4. Impact of illegal mining on pollinator abundance

4.1 Illegal mining activities and cocoa production in Ghana

The Ghanaian government generates most of its income from the export of cocoa [63]. Threats considered that lead to low cocoa yields include old aged trees (cocoa plantations over 30 years old), predominance of low-yielding traditional cultivars, smaller farm sizes due to fragmentation of land tenure agreements, illegal mining activities, and non-compliance with good agricultural practices [64, 65]. Artisanal and small-scale mining is understood to mean mining operations by individuals, groups, families or cooperatives with minimal or no mechanization, often carried out in the informal sector. The Ghanaian government recognized the potential of the sector for job creation and legalized artisanal mining in 1989 [66]. The Minerals and Mining Act 2006 (Act 703) further defines artisanal and small-scale mining as mining operations in an area corresponding to the prescribed number of blocks. In addition, small-scale mining was legalized as the exclusive domain of Ghanaians [66].

However, foreigners with sophisticated machinery found their way into the sector, accelerating the rate of extraction in the mining communities [66]. As a result, illegal small-scale mining activities increased after legalization aimed at regulating mining activities to protect the environment [66]. Small-scale illegal gold mining is referred to as Galamsey, which derives from the jumbling Ghanaian local jargon "gather-am-and-sell" [67]. Although illegal small-scale mining has drawn criticism from several quarters, the Ghana Cocoa Board takes a closer look at its impact on cocoa productivity and trusts farmers are destroying their farmland for illegal gold mining activities [68, 69]. In fact, the Ghana Cocoa Board has been one of the major complainers about the Galamsey threat [69–72], as Galamsey creates factors that discourage or adversely affect cocoa cultivation. First, Galamsey presents pull factors as a more attractive investment. Some people are drawn to informal mining because they believe mining offers them a get-rich-quick opportunity [73]. The farmers who have their cocoa farms close to the mining areas observe early dropping of immature pods, wilting and yellowing of leaves because the galamsey activities deplete the topsoil which supports the healthy growth of plants [74, 75]. The damaging environmental impacts associated with the unregulated mining activities include effluent damping, unrehabilitated excavations, improperly stored waste, dust emissions, deforestation, acid mine, river siltation and the release of chemicals such as cyanide and mercury [76, 77] asserted that between 1 and 20 hectares of cocoa lands are been taken over by galamsey activities in numerous Ghanaian cocoa-producing districts annually. According to GSS (Ghana Statistical Service) (2018), the GDP contribution of cocoa decreased from 3.6% in 2011 to 1.8% in 2017. The rife mining activities in the nation have been partly blamed for the reduction in cocoa production and economic contribution.

4.1.1 Landscape degradation

Habitat destruction from land-use changes such as habitat loss, fragmentation, deforestation and conversion of natural habitats to cropland is the most important driver of biodiversity loss in terrestrial ecosystems [78]. From an ecological perspective, changes in land cover involve shifts in land cover composition and variations in their spatial arrangement [79], which directly affect the composition of biological communities and pollinator-flowering plant relationships [80, 81]. Species that survive in such environments need to adapt to changing habitats and periodic disturbances. The integration of shade trees into cocoa agroforests can bring numerous economic and environmental benefits [82, 83], such as Increased Diptera visitation rates with increased canopy closure found in Indonesia [84].

Therefore, the long-term conversion of forests to mining sites in Ghana could result in agroecological disadvantages such as forest degradation, biodiversity loss, soil quality disruption associated with low yields and food insecurity [83–85]. A recent report estimates that the annual cost to the global economy of habitat loss will reach $10 trillion by 2050, making ongoing biodiversity loss as much an economic crisis as an environmental crisis. For more sustainable agriculture, three complementary strategies are envisaged that address several key drivers of pollinator decline: ecological intensification, strengthening existing diverse farming systems, and investing in ecological infrastructure [83]. These three strategies simultaneously address several key drivers of pollinator decline by mitigating the impacts of land-use change from illegal mining, pesticide use and climate change. Protecting large areas of semi-natural or natural habitat (tens of hectares or more) helps conserve pollinator habitats at a regional or national scale [84].

4.1.2 Habitat fragmentation

Habitat destruction, fragmentation and degradation, combined with conventional intensive farming practices, often result in reduced or altered pollinator food and nesting resources. It is well known that habitat destruction can reduce the population size, composition and species richness of pollinator communities [85, 86], and thereby affecting evolutionary processes at the species level. Significant declines have already been observed for some pollinator groups (e.g. Hymenoptera, Lepidoptera), which may be due in part to a history of habitat conversion [87] as well as the loss of certain habitat elements such as nesting or foraging sites [81, 88]. Differences in ecological and morphological traits (feeding adaptation, mobility, body size, behavior) can affect the response of pollinator species to changing environments and their ability to survive in poor quality environments [86]. Pollinator species that are more specialized for habitat or food requirements tend to be more vulnerable to land cover changes that alter the availability of food or nesting resources [87], leading to homogenization of pollinator communities dominated by common generalist species [89]. Gene flow has a major impact on genetic variation within populations, as it offsets the detrimental effects of genetic drift, determines effective population size, and has important implications for the management and conservation of genetic resources [82]. Since pollen movement is a key component of gene flow, density effects can be expected to alter genetic structure and, especially in small populations, increase the likelihood of extinction [86]. Therefore, given that tropical forests experience high rates of deforestation [90], knowledge of gene flow is fundamental to understanding reproductive success and management of tropical tree species.

4.1.3 Deforestation

Crop loss occur when the Galamsey operations are done directly on the farm. Cocoa crops are being destroyed by large machines such as bulldozers used to clear land on Galamsey farms. Loss of crop yield and income usually occurs when the Galamsey operators forcibly take part of the farmland from the farmers. This has several negative impacts on the environment, including water and air pollution, deforestation and land degradation. Tropical forests are the most biodiverse ecosystems and species-rich habitats in the world, but are significantly threatened by widespread ongoing deforestation [84]. Primary forests are of vital importance for the conservation of biological diversity due to their unprecedented diversity of species and habitats [82, 91]. Deforestation of primary and secondary forests can result in biodiversity loss and forest fragmentation, reducing previously uninterrupted habitat to smaller fragments [87]. This can result in forest-dependent species being isolated in small patches of forest that are not large enough to support a healthy population. However, secondary forests play a key role in providing habitat for a wide variety of species and in establishing connections between primary forest areas. Protection and restoration of primary and secondary forests are critical to improving tropical forest health [92]. Beyond habitat loss, land-use change can lead to deterioration in habitat quality, known as habitat degradation. In these cases, the species are able to survive, but their populations may decline [89]. For example, a recent study suggested that agricultural expansion has reduced the richness and composition of pollinators of bees and wasps in the UK [83].

5. Conclusions

Since cocoa production is largely dependent on pollination by insects, any threat to pollinators will negatively impact cocoa production. There is evidence that cocoa pollination is currently below optimal levels in Ghana and that increasing pollinator populations in cocoa fields could increase cocoa production [85]. This was demonstrated by the Cocoa Research Institute of Ghana (CRIG) in Tafo using additional (artificial) hand pollination to increase yield and also to breed new cocoa varieties [16]. It is noted that illegal small-scale mining (Galamsey) has actually been the major factor affecting cocoa production due to land degradation, water and air pollution, diversion of water bodies, damage to farms and farmhouses, etc. The findings from this suggest that Ceratopogonidae midges alone were probably too rare to act as the main or even sole pollinator of cocoa in Ghana, since the relative abundance observed on cocoa flowers in Ghana are low due to the operations of illegal mining activities done right in the cocoa farms [84].

The study identified the need for protection of extensive natural forest areas to protect the genetic identity of wild cacao pollinators in Ghana and, in addition, to promote genetic exchange between wild populations to maintain genetic variability of viable populations [22]. Evidence has shown that areas of secondary forest surrounding cocoa farms may provide pollinator resources similar to natural forests, and that deforestation and habitat fragmentation reduce the population size, composition and species richness of pollinator communities in cocoa farms to increase production [93]. Different pollinator species respond differently to changing environmental conditions caused by illegal small-scale mining due to their physiological, behavioral or other mechanisms [85].

6. Recommendation

6.1 Ecological intensification

Management of nature's ecological functions is needed to improve cocoa production and livelihoods while minimizing environmental damage.

6.2 Strengthening existing diverse farming systems

This includes the management of systems such as forest gardens and agroforestry to promote pollinators through scientifically and local knowledge validated practices, for example, Crop rotation, cultivation of sunflowers and edge crops to provide alternative food resources to increase pollinator abundance and diversity necessary for cocoa production in Ghana.

6.3 Policies and laws concerning Galamsey

Existing legislation should be strengthened by involving farmers in stakeholder decision-making on Galamsey, so that offenders are punished and others are deterred. To achieve this, the government should provide COCOBOD with structures that enable it to effectively and efficiently impose sanctions against illegal small-scale mining.

6.4 Strategies to conserve pollinators and biodiversity

Mining activities should be structured to strike a balance between economically driven extraction of mineral resources and the strategies needed to conserve natural resources and maintain ecosystem integrity and species viability.

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Conflict of interest

The authors have no conflict of interest.

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References

[1] Kevan PG, Clark EA, Thomas VG. Insect pollinators and sustainable agriculture. American Journal of Alternative Agriculture. 1990;**5**:13-22

[2] Knapp JL, Bartlett LJ, Osborne JL. Re-evaluating strategies for pollinator-dependent crops: How useful is parthenocarpy? Journal of Applied Ecology. 2017;**54**:1171-1179

[3] Kovacs-Hostyanszki A, Espindola A, Vanbergen AJ, et al. Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. Ecology Letters. 2017;**20**:673-689

[4] Lázaro A, Alomar D. Landscape heterogeneity increases the spatial stability of pollination services to almond trees through the stability of pollinator visits. Agriculture, Ecosystems & Environment. 2019;**279**:149-155

[5] Guzman A, Chase M, Kremen C. On-farm diversification in an agriculturally-dominated landscape positively influences specialist pollinators. Frontiers in Sustainable Food Systems. 2019;**3**:87

[6] Gaffney J, Bing J, Byrne PF, et al. Science-based intensive agriculture: Sustainability, food security, and the role of technology. Global Food Security. 2019;**23**:236-244

[7] Graystock P, Blane EJ, McFrederick QS, et al. Do managed bees drive parasite spread and emergence in wild bees? International Journal for Parasitology: Parasites and Wildlife. 2016;**5**:64-75

[8] Winder JA. Field observations on Ceratopogonidae and other Diptera: Nematocera associated with cocoa flowers in Brazil. Bulletin of Entomological Research. 1977;**67**(1):57-63

[9] Winder JA. Cocoa flower Diptera; their identity, pollinating activity and breeding sites. PANS. 1978;**24**(1):5-18

[10] Donald PF. Biodiversity impacts of some agricultural commodity production systems. Conservation Biology. 2004;**18**:17-38

[11] Squicciarini MP, Swinnen JF. The Economics of Chocolate. USA: Oxford University Press; 2016

[12] FAOSTAT. 2018. Available from: http://www.fao.org/faostat/en/#data/QC

[13] Läderach P, Martinez-Valle A, Schroth G, Castro N. Predicting the future climatic suitability for cocoa farming of the world's leading producer countries. Ghana and Côte d'Ivoire. Climatic Change. 2013;**119**:841-854

[14] IDH. Cocoa. 2018. Available from: https://www.idhsustainabletrade.com/sectors/cocoa/

[15] McDermott CL, Acheampong E, Arora-Jonsson S, Asare R, de Jong W, Hirons M, Setyowati A. SDG 16: Peace, Justice and Strong Institutions–A Political Ecology Perspective. Sustainable Development Goals: Their Impacts on Forests and People. United Kingdom: Cambridge University Press; 2019. ISBN: 978-1-108-48699-6, eISBN: 9781108765015

[16] COCOBOD. Environmental and Social Management Plan 3.1. Accra Ghana: Ghana Cocoa Board; 2018. pp. 4-5

[17] World Cocoa Foundation WCF. Cocoa & Forests Initiative 2017. Available

from: https://www.worldcocoafoundation.org/cocoa-forests-initiative/.

[18] ICCO. In: International Cocoa Organization, editor. Annual Report. Vol. 76. Abidjan, Côte d'Ivoire: ICCO; 2017

[19] Anaafo D. In pursuit of pro-poor development in Ghana: Is accessible, affordable and reliable energy supply the missing link? In: The Political Economy of Energy in Sub-Saharan Africa. Accra Ghana: Routledge (ISSER); 2017. pp. 30-46

[20] Silatsa FBT, Yemefack M, Ewane-Nonga N, Kemga A, Hanna R. Modeling carbon stock dynamics under fallow and cocoa agroforest systems in the shifting agricultural landscape of Central Cameroon. Agroforestry Systems. 2017;**91**(5):993-1006

[21] Ghana Cocoa Board (COCOBOD). Supply Chain Risk Assessment Report. Accra Ghana: COCOBOD; 2001. p. 3-7

[22] Boateng DO, Nana F, Codjoe Y, Ofori J. Impact of illegal small scale mining (Galamsey) on cocoa production in Atiwa district of Ghana. International Journal of Advance Agricultural Research. 2014;**2**:89-99

[23] Afele JT, Dawoe E, Abunyewa AA, Afari-Sefa V, Asare R. Carbon storage in cocoa growing systems across different agroecological zones in Ghana. Pelita Perkebunan (a Coffee and Cocoa Research Journal). 2021;**37**(1):32-49

[24] Maguire-Rajpaul VA, Khatun K, Hirons MA. Agricultural information's impact on the adaptive capacity of Ghana's smallholder cocoa farmers. Frontiers in Sustainable Food Systems. 2020;**4**:28

[25] Peprah K. Sustainability of cocoa farmers' livelihoods: A case study of Asunafo District, Ghana. Sustainable Production and Consumption. 2015;**4**:2-15

[26] Barrientos SW, Asenso Akyere K. Mapping Sustainable Production in Ghanaian Cocoa, Report to Cadbury. Ghana: Institute of Development Studies & University of Ghana; 2012

[27] Steijn CPA. Towards Sustainable Cocoa Production: A Mixed Method Assessment of the Influence of Local Governance Modes on the Farm Level Impact of Private Cocoa Certification Standards in Ghana [Thesis]. The Netherlands: Utrecht University; 2016

[28] Tulane University. Survey Research on Child Labor in West African Cocoa Producing Regions, 2013/14. USA: School of Public Health and Tropical Medicine, Tulane University; 2015

[29] Aneani F, Anchirinah VM, Asamoah M, Owusu-Ansah F. Analysis of economic efficiency in cocoa production in Ghana. African Journal of Food, Agriculture, Nutrition and Development. 2011;**11**(1);123-137

[30] Baah F, Anchirinah V. Looking for convergence: Stakeholders' perceptions of cocoa extension constraints in Ghana. Journal of Science and Technology (Ghana). 2010;**30**(3):1-13

[31] Kuapa Kokoo. Ghana and cocoa. 2017. Available from: https://www.kuapakokoo.com/about/ghana-and-cocoa [Accessed: November 29, 2017].

[32] Addae S. The Cocoa Certification Program and its Effect on Sustainable Cocoa Production in Ghana: A Case Study in Upper Denkyira West District [Thesis]. KUMASI: KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY; 2014

[33] Young AM. Habitat differences in cocoa tree flowering, fruit-set, and pollinator availability in Costa Rica. Journal of Tropical Ecology. 1986;**2**:163-186

[34] Mohanaramya M. Studies on Floral Biology, Hybridization and Performance of Elite Clones of Cocoa (Theobroma cacao L.) in Different Locations of Tamil Nadu. India: Horticultural College & Research Institute. Coimbatore: Tamil Nadu Agricultural University; 2013

[35] Asomaning E, Kwakwa R, Hutcheon W. Physiological studies on an Amazon shade and fertilizer trial at the cocoa research institute, Ghana. Ghana Journal of Agricultural Science (Ghana). 1971;**4**(1):47-64

[36] Sanzol J, Rallo P, Mar H. Asynchronous development of stigmatic receptivity in the pear (Pyrus Communis; Rosaceae) flower. American Journal of Botany. 2003;**90**(1):78-84

[37] González MV, Coque M, Herrero M. Papillar integrity as an indicator of stigmatic receptivity in kiwifruit (Actinidia Deliciosa). Journal of Experimental Botany. 1995;**46**(2):263-269

[38] Schroth G, Lehmann J, Rodrigues MRL, Barros E, Macêdo JLV. Plant-soil interactions in multistrata agroforestry in the humid Tropicsa. Agroforestry Systems. 2001;**53**(2):85-102

[39] McKelvie AD. Cherelle wilt of cacao I. pod development and its relation to wilt. Journal of Experimental Botany. 1956;**7**(2):252-263

[40] Bos MM, Steffan-Dewenter I, Tscharntke T. Shade tree management affects fruit abortion, insect pests and pathogens of cacao. Agriculture, Ecosystems & Environment. 2007;**120**(2):201-205

[41] Glendinning DR. Natural pollination of cocoa. New Phytologist. 1972;**71**(4):719-729

[42] Kaufmann T. Studies on the ecology and biology of a cocoa pollinator, Forcipomyia squamipennis I. and M. (Diptera, Ceratopogonidae), in Ghana. Bulleting of Entomological Research. 1975;**65**:263-268

[43] Kaufmann T. Preliminary observations on a cecidomyiid midge and its role as a cocoa pollinator in Ghana. Ghana Journal of Agricultural Science. 1973;**6**:193-198

[44] Murray DB. In: Wood GAR, editor. The Botany of Cocoa in Cocoa. 3rd ed. London, UK: Longman; 1975. pp. 7-18

[45] McGregor SE. Insect Pollination of Cultivated Crop Plants. USA: US Department of Agriculture Handbook; 1976

[46] Young AM, Schaller M, Strand M. Floral nectaries and trichomes in relation to pollination in some species of Theobroma and Herrania (Sterculiaceae). American Journal of Botany. 1984;**71**(4):466-480

[47] Omolaja S, Aikpokpodion P, Oyedeji S, Vwioko D. Rainfall and temperature effects on flowering and pollen productions in cocoa. African Crop Science Journal. 2009;**17**(1):41-48

[48] Goenaga R, Guiltinan M, Maximova S, Seguine E, Irizarry H. Yield performance and bean quality traits of cacao propagated by grafting and somatic embryo-derived cuttings. HortScience. 2015;**50**(3):358-362

[49] Adjaloo MK, Oduro W, BKB B. Floral phenology of upper Amazon cocoa trees: Implications for reproduction and productivity of cocoa. ISRN Agronomy. 2012;**2012**:461674

[50] Crenna E, Sala S, Polce C, Collina E. Pollinators in life cycle assessment: Towards a framework for

impact assessment. Journal of Cleaner Production. 2017;**140**:525-536

[51] Klein AM, Vaissiere BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, et al. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society of London B: Biological Sciences. 2007;**274**:303-313

[52] Lane RP, Crosskey RW. Medical Insects and Arachnids. Netherlands: Springer; 2012

[53] Cilas C, Mississo E, Dufour B, Amefia YK. Etude des variations de la pollinisation naturelle du cacaoyer au Togo. Influence sur le remplissage en graines des cabosses - Study of the variations in natural pollination of cocoa tree in Togo. Influence on the pod seed filling rate Cafe, Cacao, the (Paris). 1987;**31**(4):283-290

[54] Ghani Ibrahim, A. (1988). ActasEffects of insect pollinators on fruit set of cocoa flowers in MalasiaProceedings. In 10. International Cocoa Research Conference17-23 May 1987Santo Domingo (R. Dominicana) (No. 633.74063 I61p 1987). Cocoa Producers' Alliance, Lagos (Nigeria)

[55] Adjaloo MK, Oduro W. Insect assemblage and the pollination system in cocoa ecosystems. Journal of Applied Biosciences. 2013;**62**:4582-4594

[56] Azhar I, Wahi SM. Pollination ecology of cocoa in Malaysia: Identification of taxonomic composition and breeding sites, ecology and pollinating activities, and seasonal abundance. In: Chew PS, Pushparajah EP, editors. Cocoa and Coconut: Progress and Outlook. Kuala Lumpur: Universiti Malaya; 1984. pp. 1-15

[57] Saripah B, Alias A. The use of transferable breeding container for population enrichment of pollinator, Forcipomyia spp. In the cocoa ecosystem. Journal of Advanced Agricultural Technologies. 2018;**5**(3):245-251

[58] Novais SMA, Nunes CA, Santos NBD, Amico AR, Fernandes GWQ, Braga RF, et al. Effects of a possible pollinator crisis on food crop production in Brazil. PLoS One. 2016;**13**(5):e0167292

[59] Blaauw BR, Isaacs R. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. Journal of Applied Ecology. 2014;**51**(4):890-898

[60] Posnette AF, Entwistle HM. The pollination of cocoa flowers. Rpt. In: Cocoa Conference. London, UK: Grosvenor House; 1958. pp. 66-69. Plant Breeding, vol. 28,no. 4,pp. 4550, 1958

[61] Soria SDJ, Abreu JM. Dinamica Populacional De Forcipomyia Spp. (Diptera, Ceratopo gonidae) Na Bahia, Brasil; 1: Flutuacao Estacional Dos Polinizadores Do Cacaueiro Relacionada Com Chuva E Balanco De Água (Thornthwaite). Revista Theobroma (Brasil). 1976;**6**(2):47-54

[62] Wood GAR, Lass RA. Cocoa. 4th ed. London & New York: Longman; 1985

[63] World Bank Group. Third Ghana Economic Update: Agriculture as an Engine of Growth and Jobs Creation. Washington, D.C: World Bank; 2018. pp. 1-63

[64] Cobbina J. Technical Efficiency of Cocoa Production in Ghana, a Case Study of Upper Denkyira East Municipality [Thesis]. Ghana: Kwame Nkrumah University of Science and Technology; 2014

[65] Anthony E, Agbongiarhuoyi O, Taiwo FB, Solomon and O. Joseph

Olumide. Perception of cocoa farmers to voluntary standard certification: An implication on cocoa transformation in Nigeria. IOSR Journal of Agriculture and Veterinary Science. 2014;**7**:17-20

[66] Ministry of Lands and Natural Resources. Project Appraisal & Implementation Document for the Multilateral Integrated Project. Accra: JMK Consulting, LLc; 2017

[67] Duodu C. How galamsey is ruining rural Ghana. New African (531). 2013. p. 38. Available from: http://search.ebscohost.com/login.aspx?direct=true&db=f5h&AN=89907230&site=ehost-live [Accessed: May 20, 2017]

[68] Yeboah S. 'Crops' or 'Carats'? Gold mining and cocoa production in Ghana. 2014. Available from: https://www.linkedin.com/pulse/crops-carats-gold-mining-cocoa-stephen/

[69] Ghana Cocoa Board. Stop destroying cocoa farms for gold. 2017. Available from: https://cocobod.gh/news_details/id/116/STOP%20DESTROYING%20COCO%20FAR MS%20FOR%20GOLD%20%E2%80%93%20COCOBOD%20WARNS

[70] Addah R. Assessing the timpacts of galamsey operations on the socioeconomic activities of Ghanaian rural mining communities: A case study of Ayanfuri (Doctoral dissertation) Ashesi University College Accra Ghana. 2014

[71] Samuel A, Oladejo N, Adetunde I. The impact and effect of illegal mining (galamsey) towards the socio-economic development of mining communities: A case study of Kenyasi in the Brong Ahafo region. International Journal of Modern Social Sciences. 2012;**1**(1):38-55

[72] Burrows E, Bird L. Gold, guns and China: Ghana's fight to end galamsey. 2017. Available from: http://www.myjoyonline.com/opinion/2017/June-13th/gold-guns-and-china-ghanas-fight-to-end-galamsey.php [Accessed: October 23, 2017]

[73] Hilson G. Poverty traps in small-scale mining communities: The case of sub-Saharan Africa. Canadian Journal of Development Studies. 2012;**33**(2):180-189. DOI: 10.1080/02255189.2012.687352

[74] Aneani F, Adu-Acheampong R, Sakyi-Dawson O. Exploring opportunities for enhancing innovation in agriculture: The case of cocoa (Theobroma cacao L.) production in Ghana. Sustainable Agriculture Research. 2017;**7**(1):33. DOI: 10.5539/sar.v7n1p33

[75] Onumah J, Leeuwis C, Boamah PO, Salifu T. Operations and frames of illegal small-scale mining in Ghana. International Journal of Agriculture Innovations and Research. 2013;**2**:307-312

[76] Eftimie A, Heller K, Strongman J, Hinton J, Lahiri-Dutt K, Mutemeri N. Gender Dimensions of Artisanal and Small-Scale Mining: A Rapid Assessment Toolkit. Washington DC: World Bank Group; 2012

[77] Boafo J, Paalo SA, Dotsey S. Illicit Chinese small-scale mining in Ghana: Beyond institutional weakness? Sustainability. 2019;**11**(21):5943

[78] Snapir B, Simms DM, Waine TW. Mapping the expansion of galamsey gold mines in the cocoa growing area of Ghana using optical remote sensing. International Journal of Applied Earth Observation and Geo-Information. 2017;**58**:225-233

[79] Fahrig L. Effects of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution and Systematics. 2003;**34**:487-515

[80] Vanbergen A, Heard MS, Breeze TD, Potts SG, Hanley N. Status and Value of Pollinators and Pollination Services – A Report to the Department of Environment Fisheries and Rural Affairs (DEFRA). UK Centre for Ecology and Hydrology. UK: University of Stirling; 2014

[81] Ollerton J, Winfree R, Tarrant S. How many flowering plants are pollinated by animals? Oikos. 2011;**120**(3):321-326

[82] Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J. Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nature Sustainability. 2018;**1**(5):234-239. DOI: 10.1038/s41893-018-0062-8

[83] Jezeer RE, Verweij PA, Santos MJ, Boot RGA. Shaded coffee and cocoa – Double dividend for biodiversity and small-scale farmers. Ecological Economics. 2017;**140**:136-145. DOI: 10.1016/j.ecolecon.2017.04.019

[84] Toledo-Hernández M, Tscharntke T, Tjoa A, Anshary A, Cyio B, Wanger TC. Landscape and farm-level management for conservation of potential pollinators in Indonesian cocoa agroforests. Biological Conservation. 2021;**257**(109106):1-8. DOI: 10.1016/j.biocon.2021.109106

[85] Winfree R, Gross BJ, Kremen C. Valuing pollination services to agriculture. Ecological Economics. 2011;**71**:80-88

[86] Hadley AS, Betts MG. The effects of landscape fragmentation on pollination dynamics: Absence of evidence not evidence of absence. Biological Reviews. 2012;**87**:526-544

[87] Bommarco R, Marini L, Vaissiere BE. Insect pollination enhances seed yield, quality, and market value in oilseed rape. Oecologia. 2012;**169**:1025-1032

[88] Kennedy CM, Lonsdorf E, Neel MC, Williams NM, Ricketts TH, Winfree R, et al. A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. Ecology Letters. 2013;**16**:584-599

[89] Fischer J, Lindenmayer DB. Landscape modification and habitat fragmentation: A synthesis. Global Ecology and Biogeography. 2007;**16**(3):265-280

[90] Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. Global pollinator declines: Trends, impacts and drivers. Trends in Ecology and Evolution. 2010;**25**(6):345-353

[91] Gyasi EA. Study of Climate Change Vulnerability and Adaptation Assessment Relative to Land Management in Ghana. Accra: Reports of the members of the study team; 2006. p. 91

[92] College BC. A guide to cocoa cultivation. In: A Hand Book for Practical Work. Ghana: Bunso Cocoa College; 1987. p. 35

[93] IPBES. Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat; 2019