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Cocoa Cultivation: New Challenges for the 21st Century*

by

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KEYWORDS. — Sustainability; Botany; Ecology; Phenology; Agronomy; Pests; Diseases; Pollination.

SUMMARY. — Together with oil palm, coconuts and coffee, cocoa belongs to the most important perennial export commodities from South-Saharan Africa (SSA). Despite efforts from both the cocoa industry and third parties to increase cocoa sustainability, the SSA cocoa sector continues to be linked with poverty and environmental degradation. This paper deals with cocoa botany, phenology, ecology and cultivation aspects. Then three cocoa cultivation challenges are highlighted for the 21st century: *i*) improvement of cocoa landscapes, which are degraded as a result of deforestation, monocropping and climate change; *ii*) increase of pest and disease management sustainability which suffers from excessive or inappropriate pesticide use, leading to disturbed cocoa-pest-predator equilibria; *iii*) closing of the pollination gap which is caused by a decline in the natural cocoa pollinators, and which causes are linked to the former two challenges. Only when these challenges are addressed our chocolate will be given a sustainable future.

TREFWOORDEN. — Duurzaamheid; Botanie; Ecologie; Fenologie; Agronomie; Plagen; Ziektes; Bestuiving.

SAMMENVATTING. — *Nieuwe uitdagingen voor de cacaoteelt in de 21ste eeuw*. — Cacao behoort samen met oliepalm, kokosnoot en koffie tot de grootste meerjarige exportteelten van Sub-Sahara Afrika (SSA). Ondanks inspanningen van zowel de cacao-industrie als van derden om de cacaosector te verduurzamen, blijft die in SSA gelinkt aan armoede en milieudegradatie. In dit artikel introduceren we de botanie, fenologie, ecologie en teeltaspecten van cacao. Vervolgens stellen we drie uitdagingen voor, voor een duurzame cacaoteelt in de 21ste eeuw: *i*) verbetering van cacaolandschappen die gedegradeerd zijn door ontbossing, monocultuur en klimaatverandering; *ii*) verduurzaming van het beheer van ziektes en plagen, dat te lijden heeft onder overvloedig of verkeerd pesticidegebruik, wat leidt tot verstoring van de evenwichten tussen cacao, plagen en predatoren; *iii*) het dichten van de bestuivingskloof die het gevolg is van een terugval in de natuurlijke bestuivers van cacao en waarvan de oorzaken zijn gelinkt aan de eerste twee uitdagingen. Enkel wanneer deze uitdagingen worden aangepakt is een duurzame chocoladetoekomst verzekerd.

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Mots-clés. — Durabilité; Botanique; Écologie; Phénologie; Agronomie; Ravageurs; Maladies; Pollinisation.

Résumé. — *Nouveaux défis pour la culture de cacao au XXI^e^ siècle*. — Le cacao, avec le palmier à huile, la noix de coco et le café, est l'une des plus grandes cultures d'exportation pérennes d'Afrique subsaharienne. Malgré les efforts déployés à la fois par l'industrie du cacao et des tiers pour en accroître la durabilité, la culture de cacao est toujours liée à la pauvreté et à la dégradation de l'environnement en Afrique subsaharienne. Cet article aborde les aspects botaniques, phénologiques, écologiques et culturels du cacao. Sont ensuite proposés trois défis pour la culture durable du cacao au XXIe siècle: *i*) améliorer les paysages de cacaoyers altérés par la déforestation, la monoculture et le changement climatique; *ii*) augmenter la durabilité de la gestion des maladies et des ravageurs, qui souffre d'une utilisation excessive ou inappropriée de pesticides, entraînant une perturbation de l'équilibre entre le cacaoyer, les ravageurs et les prédateurs; *iii*) combler le déficit de pollinisation résultant de la diminution des pollinisateurs naturels du cacao, et dont les causes sont liées aux deux premiers défis. Ce n'est que lorsque ces défis seront résolus que l'avenir du chocolat durable sera garanti.

1. Introduction

The tropical cash crop cocoa (*Theobroma cacao* L.) is well known to consumers of industrialized countries as the raw product from which chocolate is made. In 2016, global cocoa acreage was around ten million ha (FAOSTAT 2018), which is just 0.7 % of global agricultural land surface but 7 % of the global area of perennial crops. Global cocoa production in 2018 was five million two hundred and fifty-two thousand million tons (FAOSTAT 2020). In 2018, 66.7 % of all cocoa was produced in just three countries (tab. 1).

Table 1

Cocoa production data from 2018 in the seven most cocoa-producing countries in the world

Country	Cocoa area (mio ha)	Production (mio tons)	Share in global production	Yield (kg ha^{-1})
Ivory Coast	4.015	1.964	37.4 %	489
Ghana	1.788	0.948	18.0 %	530
Indonesia	1.678	0.594	11.3 %	354
Nigeria	1.182	0.333	6.3 %	282
Cameroon	0.751	0.308	5.9 %	410
Brazil	0.577	0.239	4.6 %	415
Ecuador	0.502	0.235	4.5 %	469

Source: FAOSTAT 2020.

The main cocoa consumers are the European Union (1.81 ton in 2014) and the United States (0.78 ton in 2014) (Fountain & Heutz-Adams 2018).

Cocoa demand is on the rise, particularly due to newly-emerging consumer markets such as India and China (Squicciarini & Swinnen 2016). Increasing cocoa demand is met by increasing cocoa production. In the past, cocoa production increase was achieved at the expense of tropical forest. In all cocoa production areas around the globe, and particularly in West Africa, cocoa is produced by around 4.5 million farming families, most of which live in (extreme) poverty. In Ivory Coast, for instance, 77 % of cocoa growers live in poverty whereas 58 % live in extreme poverty (according to World Bank definitions) (TruePrice 2018). Despite cocoa industry-led efforts such as sustainability or fair trade certification schemes, deforestation and poverty continue to be linked to cocoa production (Higonnet *et al.* 2017, TruePrice 2018). Cocoa production increase will be more sustainably achieved by increasing cocoa's agricultural yield, rather than by growing cocoa on more — and possibly deforested — land, by a growing number of poor farmers. Increased cocoa yield enhances cocoa production without threatening tropical forests. Moreover, if cocoa production growth per surface area exceeds increase in production costs, increased cocoa yield will increase farmer income (provided that cocoa prices remain constant).

In 2016, global average cocoa yield was 438 kg dry beans per ha (FAOSTAT 2020), whereas it was shown in research stations that cocoa bean yield could reach up to 2,000 kg ha^{-1} yr^{-1} (Goenaga *et al.* 2015). In the present paper, cocoa botany, phenology, ecology and cultivation aspects will be briefly dealt with, followed by an exploration of the constraints to increasing cocoa yield in a sustainable way, *i.e.* leading to improved cocoa farmer livelihood and cocoa ecosystem conservation. Although we highlight cocoa productivity aspects in general, we will focus on West Africa, since almost two thirds of global cocoa supplies are produced in that region and since productivity constraints are most challenging there. More specifically, the often extreme poverty of West African cocoa smallholder farmers is limiting the likelihood of West African farmers to adopt yield-increasing farm practices and technologies. Moreover, contrary to most other cocoa-growing regions, the West African climate has a pronounced dry season (December-February), limiting cocoa production. Climate change will likely decrease and is already decreasing annual precipitation and disturbing rainfall distribution throughout the year, creating additional challenges to West African cocoa production (Ofori-Boateng & Insah 2014).

2. Botany and Phenology

T. cacao is one of the four out of twenty *Theobroma* spp. with a known food use, either as fruit pulp juice or chocolate-like goods produced from the seeds (cocoa beans) (Hernández Bermejo & León 1994). The origin of *T. cacao* is the South-American upper Amazon area (northwest Brazil, east Peru). From that area, cocoa has spread in pre-Columbian times to the lower Amazon region (east Brazil), where together with the upper Amazon cocoa varieties they form the 'Forastero group'. A second centre of diversity is Meso-America, where cocoa beans were introduced (to Mexico, Guatamala), probably as early as 1900 BC (Crown 2013), and where cocoa developed into separate variety groups (Criollo and Lower Amazon Forestero, respectively) (Wood & Lass 1985). Criollo cocoa is considered to be more fine-flavoured (Lachenaud & Motamayor 2017) than cocoa belonging to the Forastero group (Wood & Lass 1985). The latter group, and particularly the Amelonado variety (Cheesman 1944), is now widely cultivated in West Africa. Nevertheless, hybrids of Amelonado with Upper Amazon, Trinitario and Criollo varieties also frequently occur on West African cocoa fields (Aikpokpodion *et al.* 2009). Recent genetic analysis using microsatellites (Motamayor *et al.* 2008) has revealed that the global cocoa germplasm can be subdivided into ten genetic cluster groups, including the formerly distinguished Lower Amazon Amelonado and Criollo varieties, but also the fine-flavoured Nacional variety (Solorzano *et al.* 2012) from Ecuador.

Cocoa trees can reach heights of up to 15 m in the wild. Three to four years after the seedling stage, cocoa starts producing its first fruits, the so-called cocoa pods*. Full production is achieved after approximately ten years (Urquhart 1955, Braudeau 1969, Wood & Lass 1985). The taproot is 0.8 to 1.5 m long (only 0.4 m in poorly-drained soils). Up to ten lateral roots occur in the 10-40 cm soil layer. Root hairs can cover an area with a radius of 5 to 6 m around the tree (Braudeau 1969, Wood & Lass 1985). Seeds develop orthotropically. After eighteen months, the terminal bud ceases and three to five plagiotropic branches (the so-called 'jorquette') develop simultaneously more or less 1.5 m above the ground level (Aikpokpodion *et al.* 2009). The jorquette can contain an orthotropic shoot that develops in a second jorquette. In cocoa plantations, the second jorquette should be pruned to maintain tree height below 4 m, which keeps the cocoa pods and canopy within farmer reach for harvest and phytosanitary management, respectively (Urquhart 1955, Aikpokpodion *et al.* 2009). Orthotropic branches can also develop as suckers (called 'chupons') on the main stem, just above ground level (Wood & Lass 1985). Leaves develop in a series of discontinuous, unstructured outgrowths of the terminal bud, producing three to six leaves (the so-called 'flushes'). A cocoa tree can have four to five flushes per year. Young leaves are soft and pale green, to pink, to deep purple in colour. Later on they become dark green and rigid. Lamina is entire, simple, oblong, pointed and pinnately veined. Average leaf size is 20 cm long and 8-10 cm wide (exceptionally 50 cm long). The upper epidermis is heavily cutinized and the (very small) stomata occur only on the underside of the lamina (Urquhart 1955, Wood & Lass 1985).

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* In botany, a 'pod' is normally exclusively used for leguminous fruits. Although, botanically speaking, a cocoa fruit is an indehiscent drupe (Wood & Lass 1985), cocoa fruits are generally referred to as 'pods'.

Fig. 1. — Cocoa flower morphology and cauliflory.

Cocoa flowers are hermaphrodite. They are produced in clusters directly on the trunk and older branches (this is known as cauliflory) (fig. 1) and are small, 1-2 cm in diameter, with a pink calyx. Cocoa flowers are pentamerous. The floral formula is ✶ K5 C5 A(5° + 5) G(5) (Wood & Lass 1985). There are two flowering seasons per year, which yield around one hundred flowers per year. A petal consists of a pouch, which conceals the anthers, and a wide tip. The style is surrounded by an outer whorl of purple staminodes (Young *et al.* 1987).

The number of flowers per tree varies throughout the season and depends on climatic factors, such as photoperiod and temperature, while being cultivar-dependent (Wood & Lass 1985). Furthermore, in a given year, flower production is determined by fruit production in the previous year. Years of high pod production alternate with years with a low level of flowering (Adjaloo *et al.* 2012). In most tropical countries, flowering occurs all year round. Flowering peaks are often preceded by increased temperature and rainfall, and occur at the onset of the rainy season, after which lower numbers gradually decline (Omolaja *et al.* 2009). In West Africa, the major rainy season commences in April and climaxes in June, a period characterized by intense flowering (Goenaga *et al.* 2015). In the minor rainy season (September-November), flowering intensity is lower. Few flowers are observed during the dry season (December-March) (Adjaloo *et al.* 2012). When pods develop and thus work as an increasing sink, new flower production decreases (Valle *et al.* 1990).

Cocoa flowers are pollinated by tiny (no longer than 3 mm) flies: *Forcipomyia* midges in the family Ceratopogonidae (Forbes & Northfield 2017, Toledo-Hernández *et al.* 2017). A complete *Forcipomyia* sp. life cycle covers about twenty-eight days (Wood & Lass 1985). 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) (Kaufmann 1974, 1975; Winder 1977a,b). Ceratopogonids pick up cocoa pollen grains on their thoracic hairs after foraging for cocoa flower nectar. During subsequent flower visits, the pollinating midges move around on the inner side of the staminodes, thereby rubbing their pollen grain-carrying bodies against the style. The receptive period of the stigma is about two to three days after anthesis. Ceratopogonid pollinator populations can be abundant and can exceed one million individuals per ha (Winder 1978). Moist environments favour ceratopogonid midge abundance and there is a positive correlation between soil moisture content and ceratopogonid population levels (Winder 1977a,b). Stable moist conditions are indispensable for successful development of eggs and larvae (Soria 1975). 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 (Winder 1977a,b). Pollinator populations thus increase with each rainy period, to decrease again with the onset of a drier period (Wood & Lass 1985). While foraging and pollinating cocoa flowers, *Forcipomyia* sp. can travel distances of up to 50 m (Winder 1977a,b). Nevertheless, midges mostly deposit pollen from a certain cocoa tree on flower stigmas of neighbouring cocoa trees (Wood & Lass 1985, Yamada & Guries 1998). Unsuccessful pollination leads to flower abscission. Reported lower abscission rates vary from 63 % on the main trunk and 81 % on the fan branches to over 90 % for all flowers (Asomaning *et al.* 1971, Young *et al.* 1987, Mohanaramya 2013).

After successful pollination and fruit set, cocoa fruits can develop into mature, harvestable pods in one hundred and thirty to one hundred and sixty days (Mohanaramya 2013) (fig. 2). However, even after cocoa flowers are successfully pollinated and led to fruit set, not all young fruits (cherelles) (fig. 3) 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 (Wood & Lass 1985). 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 a hundred days after fruit set (McKelvie 1956). Poor soils and impeded photosynthesis result in increased cherelle wilting (Nichols & Walmsley 1965, Valle *et al.* 1990). Wilting in an early stage saves energy that can be invested in the development of the remaining fruits (Wood & Lass 1985, Falque *et al.* 1995). Apart from resource limitation, inadequate pollination (insufficient pollen grains deposited on the stigma surface) and incompatible pollen may cause cherelle wilting (Kigel & Galili 1995).

Fig. 2. — Mature coco fruit (‘pod’) and flowers on a cocoa tree branch.

Fig. 3. — Cocoa cherelles and mature fruits on a cocoa tree in Ivory Coast.

Most cocoa trees are self-incompatible but mostly cross-compatible (Wood & Lass 1985). Incompatibility takes place at the stage of gamete fusion, meaning that incompatible gametes are unable to fuse. The underlying mechanism is of genetic nature (Cope 1958, Mohanaramya 2013). Following unsuccessful fertilization due to incompatibility, the cocoa flower drops off after two to three days. Self-compatible hybrids produce larger fruits with a higher dry bean yield (Lockwood 1977).

3. Crop Ecology

Cocoa only grows in areas with temperatures that are always between 21° C and 30° C. The tree does not tolerate mean monthly minimum temperatures below 15° C. For that reason, most cocoa areas occur at an altitude below 300 m above sea level (m.a.s.l.). In rare cases, cocoa is produced at elevations of 1,400 m.a.s.l., *e.g.* on mountain slopes or in valleys with a specific microclimate in Uganda and Colombia (Urquhart 1955). According to the Köppen climate classification (Geiger 1954), most cocoa production areas have a tropical rainforest, tropical monsoon or tropical savannah climate. Relative atmospheric humidity in the latter areas is usually very high, reaching 100 % at night and falling to 70-80 % during the day (Wood & Lass 1985, Young 1994, Van Himme & Snoeck 2001). More than any other climate parameter, precipitation is the most yield-determining factor (Zuidema *et al.* 2005). Cocoa is very sensitive to soil water deficiency. It grows best in areas with annual precipitation of 1,500 to 2,000 mm (Wood & Lass 1985, Young 1994, Van Himme & Snoeck 2001). Zuidema *et al*. (2005) showed that cocoa yield is negatively affected when, during the driest three months, monthly precipitation is below 100 mm.

Cocoa soils are mostly acrisols (FAO classification) (corresponding with ultisols in the USDA soil classification system). Sandy soils are less suitable for cocoa cultivation as cocoa cultivation soils should be able to retain as well as drain water well. Soil pH is ideally 6.5, but cocoa grows well in soils with a pH ranging 5-8. Soil organic matter (SOM) is crucial in sustainable cropping systems as it has a high capacity to retain moisture and nutrients and improves the structure of the surface layer. In cocoa cultivation SOM is best > 3.5 % (Wood & Lass 1985).

4. Cultivation

4.1. Propagation

In West Africa, cocoa is exclusively propagated by seed. Seeds are distributed by the government and are produced in biclonal seed gardens (Laliberté & End 2015). In other cocoa growing areas, clonal propagation is performed either by top grafting on rootstock seedlings (Wood & Lass 1985), using orthotropic or plagiotropic budwood (Laliberté & End 2015), or by micro-propagation methods such as somatic embryogenesis (Traore *et al.* 2003, Maximova *et al.* 2008, Henao Ramírez *et al.* 2018). Rooted cuttings were used in the 1950s-1960s (Urquhart 1955, Braudeau 1969), but have today lost importance as a cocoa propagation method (Laliberté & End 2015). Cocoa seedlings, grafted or not, are maintained in nurseries, in most cases in polyethylene (PE) bags. Eighty square metres of nursery surface can provide planting material for 1 ha of cocoa (Wood & Lass 1985).

4.2. Agroforestry

In the Amazon basin, cocoa's region of origin, cocoa trees thrive under the (dense) canopy of large tropical forest trees (Wood & Lass 1985, Young 1994). The usefulness of applying shade in cocoa plantations, however, has been debated for many decades. The mainstream paradigm on shade in cocoa plantations is that cocoa yield increases when no shade is applied, but only when soil fertility is optimum. Scholars often refer to the work of AHENKORAH *et al*. (1974) to underpin this claim. During a fourteen-year experiment at the Cocoa Research Institute (CSIR) in Ghana, cocoa plants were subjected to four treatments in which shade/no shade and fertilizers/no fertilizers were combined.

In the Ghanian experiment, shade removal increased cocoa yield, even when no fertilizers were applied (fig. 4). However, after ten years, yield of unfertilized cocoa trees without shade became lower than yield of shaded and fertilized cocoa (AHENKORAH *et al.* 1974).

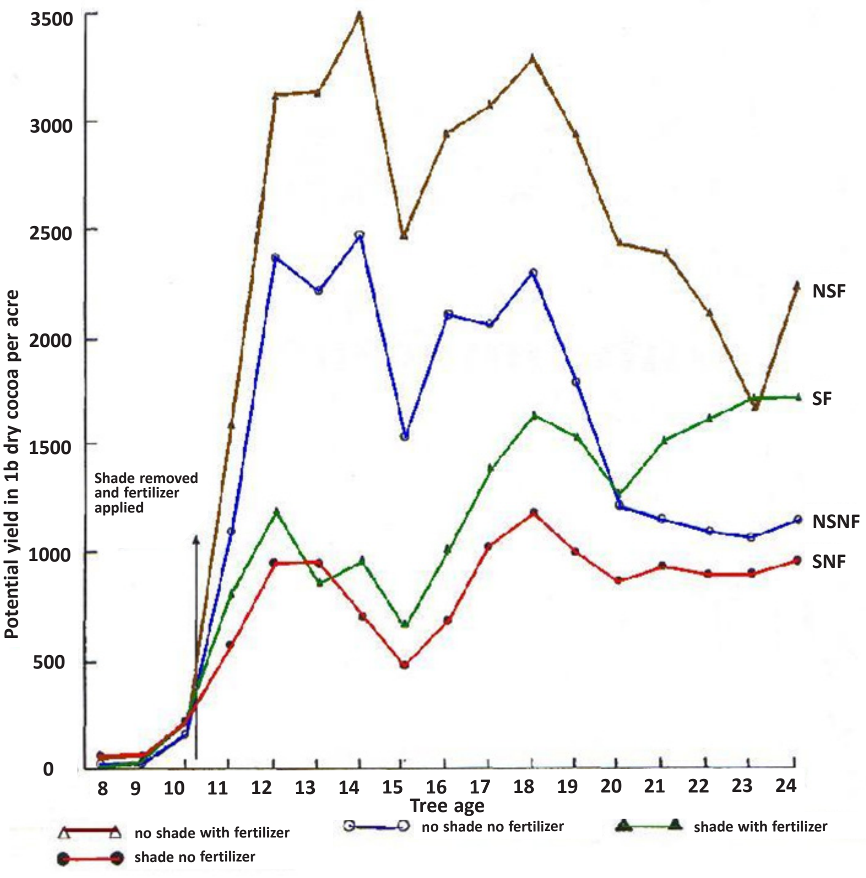

Fig. 4. — Effect of shade removal and fertilizer application on cocoa dry bean yield (lb) in Ghana (1956-1971). Adapted from AHENKORAH *et al.* (1974).

Shade trees in combination with cocoa trees form a so-called agroforestry system in which these trees dynamically interact (fig. 5). In agroforests, cocoa production is more sustainable because of the following factors: reduction of high air and soil temperatures and reduction of wind speed (Beer *et al.* 1998); reduction in fruit abortion (Bos *et al.* 2007); protection against windborne spores of fungal diseases (Rice & Greenberg 2000); buffering of humidity and soil moisture availability (Beer *et al.* 1998, Schwendenmann *et al.* 2010); improvement and maintenance of soil fertility including erosion reduction (Beer *et al.* 1998, Rice & Greenberg 2000, Duguma *et al.* 2001); improvement of light regulation and nutritional status of trees (Isaac *et al.* 2007); reduction of excessive vegetative growth (flushing) (Beer *et al.* 1998); reduction of nutritional imbalance and dieback (Beer *et al.* 1998); weed growth inhibition (Rice & Greenberg 2000); increased insect biodiversity, which improves yield through natural control of pest populations and increased pollination services (Sperber *et al.* 2004, Zuidema *et al*. 2005, Bos *et al.* 2007, Bisseleua *et al.* 2009).

Fig. 5. — Cocoa agroforestry system with coconut palm (*Cocos nucifera*) and banana (*Musa* sp.) as shade trees in Sumatra, Indonesia.

The latter benefits come at a cost. Shade trees compete with cocoa for sunlight and soil nutrients. Excessive shade thus limits cocoa yield (Abdulai *et al.* 2018). Reported optimum shade intensities vary from 40 % (Steffan-Dewenter *et al.* 2007) to 90 % (Groeneveld *et al.* 2010). The latter variation is caused by the interactions of shade trees with soil nutrient status, tree age and genotype in the effect on cocoa pod production (Duguma *et al.* 2001). However, nitrogen-fixing leguminous shade trees can enrich soils in cocoa agroforests with 70 kg ha^{-1} yr^{-1} (Dechert *et al.* 2005, Bos *et al.* 2007) to 340 kg N ha^{-1} yr^{-1} (Beer *et al.* 1998). Young cocoa trees are more vulnerable to drought and heat than mature trees. As a result, shade trees provide more benefits to early cocoa growth than it causes growth limitation due to competition for nutrients and sunlight (Isaac *et al.* 2007).

4.3. Cocoa Nutrition

Large amounts of nutrients are cycled within cocoa systems, mostly through 5-10 t ha^{-1} yr^{-1} litter fall. Still, harvesting and small nutrient losses such as leaching lead to nutrient exports causing gradual soil nutrient depletion (van Vliet & Giller 2017). N, P and K are mostly removed by pod harvest, whereas Ca and Mg are mainly lost as a result of leaching (Dechert *et al.* 2005). Removal of Mg and Ca by cocoa pod harvesting is considerably higher than P removal (Thirion 1950, Hartemink 2005). K is a major nutrient in mature cocoa. Its stocks in the topsoil can vary from 100 to 550 kg ha^{-1}, depending on soil type. Since K is very mobile, high K levels in the soil correspond to high K levels in the cocoa vegetation (Hartemink 2005). Nutrient demands under shade are primarily for P and K, while increased sunlight exposure causes an immediate demand for N (van Dierendonck 1959). Given the large diversity in the rates of cocoa soil nutrients, nutrient leaching and nutrients exported through harvest across the diverse cocoa cultivation areas, providing generally applicable cocoa fertilizer recommendations, are difficult (van Vliet & Giller 2017).

4.4. Water Management

Cocoa yield is negatively affected by water shortage. Rather than total annual rainfall, cocoa yield variability is more strongly affected by total rainfall in the two driest months. When the latter two-month precipitation is as low as 40 mm, annual cocoa yield is 20 and 40 % lower than when total rainfall in the two driest months is 300 mm, on loamy and clayey or sandy soils, respectively (Zuidema *et al.* 2005). Shade trees will prevent soil moisture evaporation, but might as well compete with cocoa trees for soil water. Moreover, competition for soil water resources is limited by shade tree root mass which is predominantly situated between 0.5 and 1.5 m below surface, whereas cocoa roots mostly occur at the surface between 0.1 and 0.3 m below the ground (Schwendenmann *et al.* 2010).

In areas with a marked and long dry season (*e.g.*, the coastal plains of Ecuador or the north-east of Brazil, with almost no rain for six months), water is supplied to cocoa by (drip) irrigation (Carr & Lockwood 2011).

4.5. Other Cocoa Cultivation Management Practices

A number of cocoa cultivation practices have little or no links with the challenges that will be highlighted further in this paper and will not be discussed. They include planting, pruning and harvesting (Thirion 1950, Braudeau 1969, Wood & Lass 1985, Mossu 1992, Van Himme & Snoeck 2001). Also post-harvest activities (fermentation, drying, quality control, shipping, roasting and the subsequent processing into chocolate products) will not be further discussed. Phytosanitary management will be discussed in further sections.

5. Challenges

5.1. Improvement of Cocoa Landscapes

It is estimated that since 1900, West Africa has lost 83.3 % of its forest area (Aleman *et al.* 2018). This dramatic deforestation rate is mostly linked to logging and agricultural activities (Ruf *et al.* 2015). New cocoa plantings are often done in primary or secondary forest, where plants develop well due to the highly fertile soil and where some forest trees are left as shade trees. When in subsequent years, yield starts to decline due to soil nutrient depletion, shade trees are cut down and pest and disease problems increase due to ecological imbalance. When cocoa yield decreases to a point where the plot is no longer profitable, farmers encroach new forest land to start another cocoa cultivation cycle (Ruf *et al.* 2015). This typical so-called cocoa 'boom-and-bust cycle' (Clough *et al.* 2009) contributes significantly to deforestation in Ghana and Ivory Coast. In these countries, deforestation for cocoa cultivation has affected most of the national parks and protected areas (Higonnet *et al.* 2017).

Over the past hundred years, the West African tropical forest ecosystem has drastically been transformed into a forest-agriculture mosaic where small patches of forest occur in a landscape dominated by agricultural systems and fallow land, characterized by a decrease in plant and animal biodiversity (Norris *et al.* 2010). The latter changes are a major cause of soil erosion and soil degradation and have disturbed plant-pest-predator equilibria (Rice & Greenberg 2000). There is therefore an urgent need to stop deforestation and restore forests. The United Nations REDD+ programme (Reducing Emissions from Deforestation and forest Degradation) can help achieve this goal as it not only conserves and enhances forest carbon stocks, but also restores a natural ecosystem and the concomitant ecosystem services from which cocoa agro-ecosystems can benefit (Malhi *et al.* 2013). However, carbon stocks in (cocoa) agroforestry systems cannot always be directly targeted into REDD+. If this is not the case, (cocoa) agroforestry might still be included in REDD+ strategies, as ways to (1) shift demand for land (land sparing) and (2) provide alternative sources of products otherwise derived from forest overexploitation or conversion (Minang *et al.* 2014).

Soil organic carbon (SOC) plays an important role in West African cocoa production. It supplies plant nutrients and enhances cation exchange capacity, which is generally low (< 1 cmol kg^{-1}) in the mostly kaolinite soils of tropical West Africa. SOC further improves soil aggregation and water retention and supports soil biological activity (Dudal & Deckers 1993). It is therefore recommended that cocoa soils have a SOC content of at least 1.75 % in the top 0-15 cm soil layer (Alvim 1977, Wood & Lass 1985). However, most soils under cocoa have SOC levels below that value (van Vliet & Giller 2017). Improving SOC in cocoa can be achieved by mulching (*i.e.*, addition of organic amendments such as crop residues), which is often not applied because cocoa farmers often use crop residues as fuel or fodder (Bationo *et al.* 2007). It is well known that agroforestry systems can accumulate large amounts of SOC (Smiley & Kroschel 2008, Jacobi *et al.* 2014, Monroe *et al.* 2016). Optimized cocoa agroforestry systems might therefore play a major role in addressing SOC decline in cocoa systems in West Africa.

West African cocoa cultivation landscapes are also affected by climate change. Climate change is expected to cause a reduction in annual rainfall in the region, resulting in a shift southwards of the northern cocoa boundary. Furthermore, it can be expected (and it has already been observed) that the current bimodal rainfall distribution pattern will be considerably disturbed (Masih *et al.* 2014, Sylla *et al.* 2015). Growth and development of plants and crops (such as cocoa) with limited drought tolerance are likely to be negatively affected by prolonged periods of drought, certainly in areas where precipitation is already a cocoa yield limiting factor (Ofori-Boateng & Insah 2014). In some areas a shift to more drought-tolerant crops will be necessary, whereas in more moderately affected areas, crop diversification and agronomic adjustments (such as agroforestry) (Mbow *et al.* 2014) to the cocoa cropping system will be necessary as a climate change adaptation strategy (Schroth *et al.* 2017).

5.2. Increase Pest and Disease Management Sustainability

5.2.1. Major Pests and Diseases in Cocoa

In this section only the most important (*i.e.* devastating) cocoa pests and diseases are commented briefly. The most commonly (and pantropically) prevailing cocoa disease is Black Pod Disease (BPD) (fig. 6). It is caused by three different *Phythophthora* spp. (Oomycetes): *P. palmivora*, *P. megakarya* (only in West

Africa) (Bailey *et al.* 2016) and *P. capsici.* Symptoms are the progressive rotting and subsequent necrosis of cocoa pods. BPD spores are spread by wind, insects, pruning material, etc. (Bailey & Meinhardt 2016, Surujdeo-Maharaj *et al.* 2016). *Phytophthora* sp. chlamydospores germinate in humid conditions, resulting in zoospore releasing sporangia. Soil is a potentially huge reservoir for BPD (Ten Hoopen *et al.* 2017). Stem canker — diseased or dead (discoloured) areas seen as sunken lesions on woody tissue — is also caused by *Phytophthora* spp., often as a secondary infection after physical or pest damage (Bailey & Meinhardt 2016, Surujdeo-Maharaj *et al.* 2016).

Fig. 6. — Cocoa pod affected by Black Pod Disease.

Vascular Streak Dieback (VSD) is a fungal disease caused by the basidiomycete *Ceratobasidium theobromae* (P.H.B. Talbot & Keane). It is today the most important disease affecting Southeast-Asian cocoa production. VSD basidiospores germinate on leaves after which hyphae ramify through the xylem tissue to lower plant parts (Samuels *et al.* 2012). Since basidiospores are formed after evening rainfall and spread early, the following morning (Guest & Keane 2007), there is a critical link between rainfall peaks and infection periods (Keane 1981, Dennis *et al.* 1992). VSD symptoms include: *i*) green spotted leaf chlorosis; *ii*) necrotic leaf blotches with yellow chlorotic edges (fig. 7); *iii*) blackening of xylem tissue, apparent on leaf scars from abscissed leaves (three dots) or on dark streaks when stems are split; *iv*) rough bark as a result of swollen lenticels immediately below the petiole of the affected leaf; and *v*) 'broomstick' symptoms as a result of proliferation and subsequent death of axillary buds following leaf abscission (Keane *et al.* 1972, Keane 1981, Guest & Keane 2007, Samuels *et al.* 2012).The endophytic character of VSD hampers its easy control. Systemic fungicide application has proved ineffective due to its high cost and side effects such as cacao seedling growth inhibition (Prior 1977, Guest & Keane 2007). Rehabilitation of diseased trees by grafting of scions obtained from VSD-tolerant clones can be used as a control measure, but no fully resistant cocoa clones have been identified up to now (McMahon *et al.* 2010, Osman 2013).

Fig. 7. — Cocoa leaf with Vascular Streak Dieback infestation symptoms (Malaysia).

Witches Broom Disease (WBD), caused by *Moniliophthora perniciosa* (Basidiomycota) is a cocoa disease which is restricted to Latin America. It particularly affects cocoa production in Bahia state, Brazil, where in some cases, production has decreased by 70 %. Basidiospores attack growing tissue and cause branch production without fruits and pods with distorted growth and green patches. Control efforts by fungicide applications, pruning of diseased plant material and introduction of resistant clones deliver poor results. New molecular techniques like genetic linkage maps and Quantitative Trait Loci (QTL) might lead to new, WBD-resistant clones (Evans 2016b).

Also Frosty Pod Rot (FPR), caused by *Moniliophthora roreri*, is a disease restricted to Latin America. The fungus attacks (young) pods and covers the pod surface with a white fungal mat. Systemic fungicides can control FPR, but are expensive. There is to date no evidence of genetic resistance in cocoa to FPR (Evans 2016a)

Cacao Swollen Shoot Virus (CSSV) is the only virus disease of cacao that is prevalent and damaging. It is a dsDNA virus of the genus Badnavirus and the family Caulimoviridae and is transmitted by several mealybug species (Pseudococcidae). CSSV symptoms include red veins, leaf chlorosis (interveinal), small mottled pods, and stem and root swelling followed by die-back. Mealybugs have a mutualistic relationship with attendant ants which protect mealybugs from natural enemies in return for their sugary exudates (honeydew) (fig. 8). CSSV is difficult to control. Removing diseased plant parts and all (healthy) trees adjacent to diseased trees has been used as a strategy in eradication campaign programmes in Ghana, which were unsuccessful due to the large amount of manpower the campaign required and farmers resistance to cutting down healthy trees (Muller 2016).

Fig. 8 — Ants attending mealybugs on a cocoa pod.

In West African cocoa cultivation, mirids (Hemiptera, Miridae) are considered to be the most important pest problem (ANIKWE 2010a, BABIN *et al.* 2010, ANIKWE & OTUONYE 2015, AWUDZI *et al.* 2016a,b). Mirid problems in West Africa are caused by two species, *Distantiella theobroma* Dist. and *Sahlbergella singularis* Hagl. (LESTON 1970; YOUDEOWEI 1973; WHEELER 2001; BABIN *et al.* 2010; AWUDZI *et al.* 2016a,b). Mirid damage on cocoa trees is caused by the feeding activities of both mirid nymphs and adults on cocoa pods and young shoots (ANIKWE 2010a; BABIN *et al.* 2010, 2011). Mirids suck sap from these plant parts and inject histolytic saliva causing dark markings (lesions) on the tissue, leading to destruction of foliage and young pods (ANIKWE 2010a; BABIN *et al.* 2010, 2011; ADU-ACHEAMPONG *et al.* 2017) (fig. 9). Mirid attacks are usually lethal to cocoa pods which are less than three months old (WHEELER 2001, ANIKWE & OTUONYE 2015). Parasitic fungi may invade the lesions, leading to secondary infections such as cankers (BABIN *et al.* 2010, 2011). Mirid damage, particularly in combination with secondary diseases, causes physiological dieback and — when severe — can lead to a delay in first pod production or even death of young trees (WOOD & LASS 1985, BABIN *et al.* 2011, ADU-ACHEAMPONG *et al.* 2017). Because of the latter pest-disease complex, it is difficult to estimate the precise impact of mirid infestation. It is often claimed that yield losses as a result of mirid infestation can be as high as 30-40 % (WHEELER 2001; ANIKWE *et al.* 2009a,b; KOUAMÉ *et al.* 2014; ANIKWE & OTUONYE 2015; AWUDZI *et al.* 2016a,b; BAGNY BEILHE *et al.* 2018), although it is not clear how these estimates were made. Although mirid population numbers in West Africa vary between countries or regions and between years, mirid population peaks are reported for the July-November period (ANIKWE 2010a,b; ADU-ACHEAMPONG *et al.* 2014;

Kouamé *et al.* 2014; Awudzi *et al.* 2016a,b), which in West Africa concurs with the most abundant cherelle and mature pod production of the main harvesting season. In Ivory Coast, in the region of Haut-Sassandra, a second peak in mirid populations was observed in January, which concurs with a peak in cherelle production for the secondary harvesting season (with smaller volumes) (Kouamé *et al.* 2014). In West African cocoa agroforestry systems, a negative correlation between shade density and mirid numbers was observed (Babin *et al.* 2010, Bisseleua *et al.* 2013, Gidoin *et al.* 2014). As a result, more severe mirid damage can be concentrated in sunny patches inside a cocoa plantation, the so-called mirid pockets (Wood & Lass 1985, Anikwe & Otuonye 2015).

Fig. 9. — Cocoa pod damaged by mirid infestation (black lesions).

Cocoa Pod Borer (CPB), *Conopomorpha cramerella* (Snellen) (Lepidoptera: Gracillariidae), is the most important pest in Southeast-Asian cocoa production (Shapiro *et al.* 2008, Rosmana *et al.* 2010). CPB is held responsible for cocoa crop losses that range between 30 % (Zhang *et al.* 2008) and 50 % (Wielgoss *et al.* 2012). Female *C. cramerella* lay between sixty and two hundred eggs on the furrowed cocoa pod surface during their lifetime (Azhar & Long 1996, Santoso *et al.* 2004). Newly-hatched larvae bore perpendicularly through the pod surface until reaching the sclerotic layer of the husk (Ooi *et al.* 1987). Larvae subsequently feed on the pulp and placenta until reaching maturity (Rosmana *et al.* 2010), resulting in premature ripening of pods, containing flat, small beans that are often stuck together in a mass of dried mucilage and make bean extraction for commercial purposes impossible (Beevor *et al.* 1993, Rosmana *et al.* 2010). CPB management relies heavily on pesticide applications (Wood *et al.* 1992, Beevor *et al.* 1993), which are neither environmentally sustainable nor economically effective. More integrated CPB control can be achieved by mass trapping, mating disruption or an attract-and-kill strategy using *C. cramerella* specific pheromone traps (Beevor *et al.* 1986a,b; 1993; Vanhove *et al.* 2015) (fig. 10).

Fig. 10. — Pheromone-based trap (KoppertTM Delta Trap), mounted above cocoa canopy for *C. cramerella* population monitoring in Malaysia.

5.2.2. Pesticide Use in West Africa

In the 1950s and 1960s, organochlorides (lindane, dieldrin, DDT) were widely used in cocoa pest control (Entwistle 1972) in West Africa until mirid resistance to these products was reported (Dunn 1963, Gerard 1964). Later (1960s-1990s), carbamates (*e.g.,* propoxur, promecarb) and organophospates (*e.g.,* chlorpiryfos, diazinon) were used until they were banned because of environmental and health hazards (Bateman 2015). Today, pest management control in West African cocoa cultivation is almost exclusively done with pyrethroids (such as bifenthrin, deltamethrin, cypermethrin and lambda-cyhalothrin) and neonicotinoids (such as imidacloprid and thiamethoxam) (Anikwe *et al.* 2009a,b; Asogwa & Dongo 2009; Bateman 2015). West African cocoa producers apply an array of insecticides at frequencies that vary between zero to eleven times per year (Mahob *et al.* 2011, Antwi-Agyakwa *et al.* 2015) (fig. 11). Since the

1950s, West African governmental agencies have recommended (Adu-Acheampong *et al.* 2014; Ahoutou *et al.* 2015; Antwi-Agyakwa *et al.* 2015; Awudzi *et al.* 2016a,b) a calendar-based insecticide application scheme, targeting mirid populations when they are most abundant (August-November).

Fig. 11. — Cocoa farmer preparing a mistblower tank with insecticides to treat a cocoa field in Ivory Coast.

5.2.3. Integrated Pest Management Options for West African Cocoa Farmers

Although the most frequently prevailing insecticides used today in West Africa (see chapter 5.2.2.) have a lower (acute) toxicity than the earlier-used organochlorides, organophosphates and carbamates (Bateman 2015), their widespread use continues to pose human health hazards and risks to terrestrial and aquatic wildlife (Williamson 2011, Jepson *et al.* 2014, Diakite *et al.* 2018). Moreover, the massive and general insecticide applications have led to disturbances of the natural balance between pests and predators (Van Mele 2008, Alagar 2015) and might be responsible for a decline in cocoa pollinator numbers (Entwistle 1972, Claus *et al.* 2017). Scrutiny of the calendar-based spraying schemes of mirid targeting insecticides in Ivory Coast (own data, unpublished) reveals that pesticide dosage can be lowered to a third of the currently recommended dosages without any significant difference in the impact on mirid-infested cherelles. Also, it was found that no significant differences in mirid damage and pod production parameters prevail when insecticides are applied early or late in the recommended application period, suggesting a lower seasonality of mirid populations in Ivorian cocoa cultivation systems than assumed by *e.g.* the *Conseil Cacao-Café* (CCC). This government body regulating the commercialization of cocoa and coffee recommends two applications per year (July-September and December-January) (Ahoutou *et al.* 2015).

Together with the labour and product costs of pesticide applications, the latter findings urge for a more rational pesticide application in West African cocoa farming. Experiments in Ghana have shown that mirid monitoring can be easily done by using pheromone-based monitoring traps (Mahob *et al.* 2011, Awudzi *et al*. 2016a, Sarfo *et al.* 2018). Mirid monitoring systems might in the future be used by West African cocoa smallholders as a tool guiding insecticide applications, following *e.g.* Cruz *et al*. (2012) who used pheromone traps as a decision tool for insecticide applications against the fall armyworm (*Spodoptera frugiperda*) in Brazil. It might be that pheromone-based pesticide monitoring systems are too difficult (too technical or complicated) to apply. Even if that were the case, farmers could step away from calendar-based pesticide application schemes and perform pesticide treatments only when there is clear visual evidence of pest incidence.

In West Africa, application of systemic insecticides by mistblowers is common practice. However, it might not be the most appropriate treatment against all cocoa pests. Especially for pest problems such as stem borers that often occur on just a few trees a local knockdown (spraying stem borer tunnels with a pyrethroid, own unpublished data) or physical control treatment (such as poking stem borer tunnels with wire) (Anikwe 2010b) might be more effective pest control measures, while consuming considerably less pesticides.

Phytosanitary pruning is recommended as an effective practice against a number of common West African cocoa diseases, especially against Black Pod Rot (Urquhart 1955, Braudeau 1969, Wood & Lass 1985). Cocoa agroforestry systems restore the balance between pests and predators (Sperber *et al.* 2004, Bos *et al.* 2007, Bisseleua *et al.* 2009). Recent research highlights that cocoa agroforestry systems increase ant populations which perform biocontrol of mirids (Bisseleua *et al.* 2017, Bagny Beilhe *et al.* 2018). Cocoa agroforestry systems also reduce incidence of CSSV in West Africa (Andres *et al.* 2018).

In West Africa, despite the availability of alternatives for chemical pest control, the adoption of these integrated pest control methods, which predominantly rely on changing or intensifying farming practices, is low. Today, insecticide applications by West African cocoa farmers are influenced by socio-economic, farm-specific and institutional factors but also by pest incidence perceptions (Danso-Abbeam & Baiyegunhi 2018). As a result, integrated pest control methods such as rigorous phytosanitary pruning, monitoring-based insecticide applications, and the creation or enhancement of agroforestry systems, will require farmer training and technical support. When successful, such integrated mirid control will decrease overall pesticide use in the West African cocoa sector, increase cocoa farm profitability (also by potentially increasing cocoa pollinator pollination levels; see chapter 5.3.) and improve farmer health and environmental sustainability.

5.3. Closing the Cocoa Pollination Gap

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. (Aneani & Ofori-Frimpong 2013). However, there is increasing evidence that the present cocoa yield gap is also linked to inadequate pollination. During the dry season, the number of ceratopogonid pollinators, as well as the relative number of pollinated flowers, are lower than in the wet season, because cocoa pollinators require rotten, moist organic material as a breeding substrate (Winder 1977a,b, 1978). Attempts have been made to increase reproduction opportunities for these midges by adding organic material to 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 had 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 initial number of mature fruits was twice as high for all substrate-treated trees compared to the control trees (Adjaloo *et al.* 2013).

A more direct proof of the pollination gap was found when cocoa trees in Sulawesi (Indonesia) were artificially pollinated. Optimum dry bean yield was achieved when 40 % of flowers were hand-pollinated (Groeneveld *et al.* 2010). The latter treatment increased dry bean yield by 350 kg per ha as compared to a pollination intensity of 10 %, which corresponds with natural pollination intensities observed over the past twenty years (Falque *et al.* 1995, de Almeida & Valle 2007). In North Queensland (Australia), it was recently shown that adding cocoa pod husks as a pollinator breeding substrate considerably increased fruit set (one hundred and ten times more cherelles) and yield (sixty 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 (Forbes & Northfield 2017).

It is questionable whether adding (importing) organic material to cocoa fields can be sustained from an economic and logistic perspective. Own experiments in Ivory Coast (unpublished) in which chopped banana pseudostems were added to one hundred pits (50 cm x 50 cm, 30 cm wide, spaced at 10 m x 10 m) per ha required the import of 7.5 m^3 of organic material per ha of cocoa. Agroforestry systems are therefore a more feasible way for cocoa smallholders to increase organic material in their cocoa plantations (Rice & Greenberg 2000, Tscharntke *et al.* 2005), which — when dead or pruned agroforestry tree branches, leaves and fruits are left to rot — will enhance cocoa pollinator breeding opportunities.

The impact of reducing pesticide applications on cocoa pollinator levels is unclear and requires more investigation. Given the short reproductive cycle of *Forcipomyia* spp. (around twenty-eight days), it is expected that calendar-based annual bimodal insecticide applications only temporarily reduces pollinator levels, after which they rapidly recover (Claus *et al.* 2017). Cocoa pollinator decline is therefore more likely explained by landscape degradation than by pesticide applications.

Following practices that are 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 (Velthuis & van Doorn 2006), similar mass breeding and subsequent mass release of *Forcipomyia* spp. at times when cocoa flowering peaks, can be explored as a cocoa pollination enhancement strategy. However, the hematophagous nature of *Forcipomyia* midges can be a constraint to their mass breeding success (Gibson & Torr 1999). Laboratory experiments showed that *F. townsvillensis* eggs do not develop without complete blood meals (Cribb 2000). Research is needed to test the most appropriate midge rearing conditions (temperature, humidity and feeding).

Forcipomyia spp. mostly pollinate flowers adjacent to those where they have collected pollen (Young 1983). 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, it can be assumed that specific pollinating midges are restricted to certain areas (Winder 1978). 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 the local insect populations.

As is the case with integrated pest management (see chapter 5.2.3.), farmers might not easily adopt agroforestry systems or pollinator mass-breeding techniques. A precondition to the adoption of commercial mass breeding of pollinating midges by resource-poor smallholders in Ivory Coast is at least the cost-effectiveness of the technology.

6. Conclusion

As is the case with most tropical cash crops, cocoa cultivation is a facing increasing demand on the global market as well as production increase and sustainability constraints. Average cocoa yield is far below potential levels due to a combination of historically-grown cocoa management decisions (full-sun, monoculture systems), cocoa landscape degradation (deforestation and soil erosion), but also the vicious circle of poverty and low farm productivity. Climate change puts additional stress on cocoa productivity, especially in West Africa, where it is likely to lead to a decrease in the area suitable for cocoa growing. As a result of decreasing precipitation in the whole of West Africa, the South-North annual precipitation gradient will reach the most northern cocoa cultivation limit earlier than is the case today.

We have identified some specific challenges of the agricultural cocoa sector that are directly linked to the aforementioned production and sustainability constraints. They include:

— Improvement of the cocoa landscapes;
— Integrated pest and disease management;
— Enhancement of cocoa pollination.

It cannot be expected that the West African resource-poor cocoa smallholders, who produce the majority of cocoa worldwide, are capable of addressing these challenges by themselves. It can only be achieved if an ambitious partnership is built between farmers, politicians and economic actors. If successful, not only future cocoa supplies will be sustainably secured, but also cocoa farmers, as a result of a higher income and healthier working conditions (due to reduced hazardous pesticide use), will face a brighter future.

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