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REVIEW ARTICLE

# Rehabilitation and renovation of cocoa (*Theobroma cacao* L.) agroforestry systems. A review

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**Abstract**

Cocoa farmers must decide on whether to rehabilitate (Rh) or to renovate (Re) a cocoa orchard when its productivity declines due to ageing, disease outbreaks or other causes. Deciding on Rh/Re is often a complex, expensive and conflictive process. In this review, we (1) explore the diversity of contexts, driving forces, stakeholders and recommended management practices involved in Rh/Re initiatives in key cocoa-producing countries; (2) summarise the often conflicting views of farmers and extension agents on Rh/Re programmes; (3) review the evidence of age-related changes in planting density and yield of cocoa, given the weight of these variables in Rh/Re decision processes; (4) describe the best known Rh/Re systems and their most common management practices; (5) propose an agroforestry Re approach that overcomes the limitation of current Rh/Re diagnosis protocols, which do not consider the regular flow of food crop and tree products, and the need to restore site soil quality to sustain another cycle of cultivation of cocoa at the same site; and (6) explore the effects of climate change considerations on Rh/Re decision-making and implementation processes.

Each Rh/Re decision-making process is unique and highly context-dependent (household and farm, soil, climate, culture). Tailored solutions are needed for each farmer and context. The analysis, concepts and models presented for cocoa in this paper may also apply to coffee orchards.

**Keywords** Site restoration · Climate change · Shade canopy · Early intercropping · Timber · Fruit · Natural mortality · Coffee · Yield · Density

## 1 Introduction

Tree crops include a long list of commercially important species in both tropical (e.g. coffee, cocoa, oil palm, rubber, etc.) and temperate climates (e.g. olives, peaches, apples, etc.). Tree crops share two key features: (1) they are perennial plants with long life cycles and declining yields with age, and (2) they are expensive to establish and have long waiting periods (several years) before starting to reap benefits from the harvest of their products (e.g. pods, fruits, latex, etc.). Tree crops can be classified into two classes: (1) tall tree crops, such as rubber or oil palm, whether associated with other crops or not, that have their crowns in a dominant position in the vertical profile of the shade canopy. In this privileged position, they are the first ones to capture incoming solar radiation and cast shade on the other plant species in the understory, and (2) short tree crops such as cocoa (and coffee) that are usually cultivated under a shade canopy and consequently their growth and yield are partially dependent upon the nature and management of the taller plants that constitute the shade canopy. Irrespective of the class of tree crop, after several decades of cultivation, farmers must face the need to rehabilitate (Rh), which involves restoring the productive capacity of a yet potentially productive orchard, or to renovate (Re), which involves removing all existing trees—at once or staggered over time—and planting new ones at the same site in the orchard (Fig. 1).

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**Fig. 1** Heavy pruning to reduce tree height and open the canopy of cocoa in coastal Ecuador (photograph by Eduardo Chavez, ESPOL, Guayaquil, Ecuador).

**Fig. 2** Replanting an old cocoa agroforestry system, Obala, Cameroon (photograph by Patrick Jagoret).

Rehabilitation and renovation (Rh/Re) of a cocoa orchard (either a no-shade monocrop or a shaded agroforestry system) is a complex decision-making process that involves diagnosis, design of innovations, and the formulation and implementation of an action plan. Cocoa agronomists have devised methods and protocols to help to decide when and how to Rh/Re an orchard (Fig. 2). Most methods are based on the assessment of whether three key variables have reached or passed critical threshold levels: (1) age of cacao (e.g. more than 40 years), (2) yields (e.g. less than 500 kg ha$^{-1}$ year$^{-1}$), and (3) planting density (e.g. less than 800 plants ha$^{-1}$). Quiroz and Amores (2002) also consider pest and disease status, the height of the cocoa tree, and shade levels when deciding on Rh/Re interventions. Critical levels for each variable are site and context specific and must be determined for each locality. For example, in the case of small Nigerian producers, an unproductive tree is the one whose yield is 25% of the average highest yield of an adult cocoa plant, i.e. about 125 kg ha$^{-1}$ year$^{-1}$ (Olaiya et al. 2006). The main limitation of these protocols is that only the age–yield–density relationships of cocoa are taken into consideration in the Rh/Re decision-making and implementation process, disregarding the contributions and influence that the production of other agroforestry products from the same orchard (Cerda et al. 2014) have on Rh/Re diagnosis, design and implementation.

In this review we (1) explore the diversity of contexts, driving forces, stakeholders and recommended management practices involved in Rh/Re initiatives in key cocoa producing countries; (2) summarise the often conflicting views of farmers and extension agents on Rh/Re programmes; (3) review the evidence of age-related changes in planting density and yield of cocoa, given the weight of these variables in Rh/Re decision processes; (4) describe the best known Rh/Re systems and their most common management practices; (5) propose an agroforestry Re approach that overcomes the limitation of current Rh/Re diagnosis protocols; and (6) explore the effects of climate change considerations on Rh/Re decision-making and implementation processes.

## 2 Rh/Re examples in cocoa-producing countries

Rh/Re decision-making and implementation processes are highly context specific. There are no general recipes, so each process needs tailored solutions, as exemplified by Rh/Re initiatives in the Dominican Republic, Ecuador, Peru, Brazil, Cote d'Ivoire, Ghana and Indonesia.

- Dominican Republic. Recurrent hurricanes and the availability of new technologies to increase crop yield (improved genetics, new grafting techniques, etc.) have been the two major driving forces in Rh/Re initiatives in the Dominican Republic. Government, private companies and major farmers' organisations have engaged in Rh/Re initiatives. For example, in the late 1960s, a government-led Rh/Re programme introduced selected, high-yielding clones from Trinidad, Ecuador, Jamaica and Costa Rica (Batista 2009). In 2006, the government promoted side grafting to rehabilitate old and unproductive cocoa trees in pioneer cocoa fronts (Siegel and Alwang 2004), and in 2017 launched a 10-year National Action Plan in partnership with the UNDP's Green Commodities Program (Cuello et al. 2015). CONACADO, an emblematic, small farmers' organisation, in partnership with Equal Exchange (an NGO), and with funding from USAID, is currently engaged in Rh/Re their organically grown cocoa orchards (https://equalexchange.coop/sites/default/files/INFORMEParcelasDemostrativasCONACADO2018.pdf).

- Ecuador. Most Rh/Re interventions have been part of a government-backed programme with local financial institutions as lenders (Quiroz and Amores 2002). The Ministry of Agriculture claimed to have rehabilitated or renovated more than 100,000 ha of low-yielding cocoa plantations heavily affected by pest and diseases or reaching the end of their life expectancy over a 10-year period (2006–2015) (https://www.agricultura.gob.ec/productividad-rendimientos-cacao/).
- Peru. Rh/Re initiatives have been linked to USAID's financial and logistic support to both eradicate coca plantations (*Erythroxylon coca*) and to promote cocoa as a licit, alternative crop to sustain rural livelihoods (Kieck et al. 2016; Scott et al. 2015), for instance, the Peru Cacao Alliance (Alianza Cacao Perú) programme, USAID's 10-year programme in the Provinces of San Martin, Ucayali and Huanuco (http://www.alianzacacaoperu.org/).
- Brazil. The devastating outbreak of Witches' Broom (*Moniliophthora perniciosa*) in the late 1980s (Teixeira et al. 2015; Poelmans and Swinnen 2016) triggered several Rh/Re initiatives aimed at restoring yields and production, and the promotion of a set of good management practices, including the replacement of the traditional, susceptible cocoa genotypes by new, disease- and drought-resistant, high-yielding, and fine flavour cocoa cultivars, combined with integrated pest management practices, agroforestry and low carbon cultivation practices (Pekic 2014; van der Kooij 2013; Schroth et al. 2016a).
- Cote d'Ivoire and Ghana. Pest and disease outbreaks (e.g. cocoa swollen shoot virus, CSSV) have been a major driving force in Rh/Re decisions in the two major global cocoa producers (Ameyaw et al. 2014; Andres et al. 2017). In Côte d'Ivoire, the Quantity-Quality-Growth (2QG) programme (2014–2023) was set up by the Ministry of Agriculture and Rural Development (MINADER) and the Conseil Café-Cacao (CCC) to rehabilitate and renovate 800,000 ha of degraded cocoa plantations, including 150,000 ha destroyed by the CSSV. Recommended practices include the introduction of new cocoa varieties (high-yielding, drought-resistant, good-quality chocolate), maintenance pruning, fertiliser application, regeneration by grafting and crop protection measures (Dzahini-Obiatey et al. 2010; Andres et al. 2018). The CSSV outbreak was also the driving factor that led to the Government of Ghana and the World Bank to invest USD 100 million to rehabilitate and renovate 17,900 ha of CSSV-infected cocoa farms (Kwaw-Nimeson and Tian 2019). Rehabilitation and renovation is recommended in current projects under Cote d'Ivoire and Ghana's Cocoa and Forestry Initiative (CFI), in partnership with the major cocoa and chocolate companies (represented by the World Cocoa Foundation), international NGOs (IDH, in this case), and other stakeholders. The CFI simultaneously targets increasing incomes from increased cocoa yields, preventing deforestation, and promoting the cultivation of cocoa in agroforestry systems to diversify and sustain rural incomes and to restore previously deforested land (Kroeger et al. 2017; Schroth et al. 2015a). Renovation of cocoa orchards poses a risk to deforestation, given the preference of farmers to establish new cocoa orchards in forest areas to take advantage of high soil fertility (Clough et al. 2009; Vaast and Somarriba 2014; Somarriba and López-Sampson 2018).
- Large-scale Rh/Re programmes have been implemented across West Africa (Ivory Coast, Cameroon and Ghana) in two main waves (1970 and 1990) but with low success rate due to farmers' lack of financial resources to entirely implement such interventions (Longworth 1963; Are 1970b; Lockwood 1976). Such programmes have typically integrated research and extension services to transfer improved planting materials and dissemination of best agronomic practices. The financing of such programmes has been heavily or entirely subsidised (Jagoret et al. 2011; Dalberg 2015). Currently, the cocoa private sector is supporting several Rh/Re programmes to improve yields and secure a steady supply of cocoa beans (https://www.worldcocoafoundation.org/initiative/african-cocoa-initiative-ii/). These programmes are being implemented on over 1.2 million ha of cocoa orchards and focus on two areas: (1) providing a Rh/Re package including inputs, high-quality planting material (high yield, disease and drought resistant, good chocolate quality) and high-quality agronomical training and (2) setting up a business-driven provision of extension services.
- Indonesia. Aging plantations, low yields and disease incidence triggered Rh/Re interventions on more than 0.8 million ha of cocoa orchards. Between 2000 and 2010, the Government of Indonesia became heavily involved in Rh/Re programmes by providing loans and subsi-

dised inputs. Since 2010 onwards, private companies, several development agencies and other public–private partnerships have been implementing ambitious Rh/Re programmes to build up and complement former efforts (Lockwood and Yin 1996; Thau Yin 2004). The overall goal of these Rh/Re interventions is to increase yields from the current average of 400–450 kg $ha^{-1}$ to 1.5 Mt $ha^{-1}$ to outcompete alternative cash crops such as palm oil.

## 3 To Rh/Re or not to Rh/Re? Extension agents versus farmers

At least five major factors have been found to drive cocoa farmers into Rh/Re. First is the fall in cocoa yields due to the combined effect of plant ageing, the reduction in cocoa population density (linked to accumulated natural mortality), and increased incidence of pests and diseases (Aikpokpodion and Adeogun 2011; Jagoret et al. 2011; Mahrizal et al. 2014; Wessel and Quist-Wessel 2015; Adebiyi and Okunla 2013; Akinnagbe 2015; Dias et al. 2000; Adeogun et al. 2010). Second is the need to restore the productive capacity of a cocoa orchard that is still productive after a period of abandonment that may be due to the prolonged falling of cacao prices, the invasion of pests and diseases (Dzahini-Obiatey et al. 2006; Quiroz and Amores 2002; Are 1969b, 1970a; Danquah 2003; Laryea 1969; Longworth 1963; Tresh and Lister 1960), wars and other social–political causes (Krauss and Soberanis 2002; Ofori-Bah and Asafu-Adjaye 2011; Assiri et al. 2003; Laryea 1969), and difficulties in the transmission of hereditary rights over the orchard (Jagoret et al. 2018). Third is farmers' expectations of good cocoa prices (or access to incentives) for a sufficient length of time (Akinnagbe 2015; Trivedi 1988) that prompt them to replace their old, low-yielding orchard with a new, high-yielding one (Trivedi 1988). Fourth is incentives and subsidies, including technical, financial and operational support, as well as other incentives (Adebiyi and Okunla 2013; Akinnagbe 2015, 2017; Aneani et al. 2017; Asare et al. 2018; Dalberg 2015; Laryea 1969; Murray and Jones 1969; Obiri et al. 2007; Wessel and Quist-Wessel 2015). Fifth is social processes linked to migration and labour availability. For example, in Ghana, when the main family labour force of a household (the sons and daughters) have emigrated, their parents turn to sharecropping their land with young immigrants who are interested in high and rapid returns and usually choose to renovate the old, traditional cocoa orchards (Amelonado variety, mixed shade canopy, no use of agrochemicals, low yields) and replace it with hybrid cocoa, in full sun, and using agrochemicals to achieve higher yields (Ruf 2011; Ruf and Zadi 1998).

Rehabilitation or renovation of a cocoa orchard is a risky and costly task (Akinnagbe 2015; Dalberg 2015), so it is no wonder that farmers are usually reluctant to engage in Rh/Re (Aneani and Padi 2016; Lass 1985). Farmers' most common reasons for not rehabilitating or renovating their orchard include the following:

- There is a significant loss of earnings for several years before the new orchard starts production (Riedel et al. 2019; Laryea 1969).
- High investments must be made in the removal of the old orchard and the establishment and management of the new one (Asare et al. 2018).
- Distrust of the (yet unknown) performance of new technology, especially under a changing climate (Akinnagbe 2015).
- Family, cultural or personal values that outweigh the value of economic losses from cocoa. For example, indigenous cocoa farmers in Talamanca, Costa Rica will not cut down the old cocoa orchard planted by their grandfather 60 years ago, even if it does not produce any cocoa and it is a source of inoculum and disease affecting the rest of the farm (E. Somarriba, personal observations).
- Farmers and agronomists differ in their definition of 'acceptable yields' (Danquah 2003). For example, a cocoa orchard 30–35 years old may still be considered productive by a farmer because the production cost involved is essentially the cost of harvesting, and as long as the yield covers this minimum cost and generates some surplus they will keep the orchard as it is (Laryea 1969; Olaiya et al. 2006; Upton 1966). Farmers believe that extension agents do not understand their household and cocoa farming reality (Andres et al. 2017).

Quite often the reluctance of farmers to Rh/Re is overridden by incentives and subsidies. There is a rich literature on the adoption, micro-economics and politics involved in Rh/Re programmes (see Adeogun et al. 2010; Ogunniyi and Osuolale 2015; Gotsch and Burger 2001; Obiri et al. 2007; Trivedi 1988; Adebiyi and Okunla 2013).

## 4 Cocoa age–yield–density relationships

Understanding the relationships between yield, density and age is central to Rh/Re diagnosis and design. Cocoa agronomists base their Rh/Re diagnosis and design protocols on combinations of these three variables (Olaiya et al. 2006; Quiroz and Amores 2002; Vaz 1995; Matlick et al. 1999). Three questions must be answered to understand these relationships: (1) how does yield per hectare change with density? (2) Given an initial planting density, how will density change with age? (3) How does yield per plant change with age? These questions are addressed below.

Cocoa yield per hectare ($Y$) has two components: the population density of cocoa trees (for brevity, 'density', $n$ = plants ha$^{-1}$) and the yield (of dry cocoa beans) per plant ($y$). Both components vary with age ($t$) (Eq. 1):

$$Y_t = y_t * n_t \tag{1}$$

where

$$y_t = f_1(t) \tag{2}$$

and

$$n_t = f_2(t) \tag{3}$$

and $f_1$ and $f_2$ are two unknown functions.

### 4.1 How does yield per hectare change with density?

Determining the optimal planting density to achieve maximum yield per hectare ($Y$) and finding the most appropriate mathematical expression for this relationship have been central research topics in ecology, forestry, agronomy and agroecology (Bleasdale and Nelder 1960; Mead 1970; Panik 2013; Vandermeer 1984; Willey and Heath 1969; Yahuza 2011). These studies typically show that at low density, individual plants do not compete with their neighbours, yield per plant ($y$) is at its maximum, unencumbered yield, and $Y$ increases linearly when density increases until competition sets in, depressing yield per plant. Crop species are classified as depicting 'asymptotic' or 'parabolic' patterns (Yahuza 2011; Panik 2013). Optimal density is usually determined when the curves of yield per hectare ($Y$) and yield per plant ($y$) intersect (Fig. 3).

Remarkably few studies have explored the relationship between cocoa yield and planting density. The scarce experimental evidence indicates that cocoa yield per hectare increases with planting density (Armstrong 1976; Charles 1961; Dias et al. 2000; Pacheco et al. 2003; Kowal 1959; Smith 2015; Spaggiari Souza et al. 2009; Mooleedhar and Lauckner 1990). Lockwood and Yin (1996) found no differences in yields in the density range evaluated. In Trinidad, Mooleedhar and Lauckner (1990) observed increasing yield per hectare when cocoa density in young cocoa orchards increased from 748 to 2990 cocoa trees ha$^{-1}$. An experiment in Ghana testing yields in orchards planted at densities between 474 and 6726 trees ha$^{-1}$ showed that the optimal density for yield performance per hectare was 1977 trees (Alvim 1964; Smith 2015). At densities above 4448 trees ha$^{-1}$, competition suppressed many trees and depressed fruit production in residual trees (Wood 1964). In Central Cameroon, Jagoret et al. (2017a) showed that the highest cocoa yields (more than 1 Mg ha$^{-1}$) were obtained with 1568 cocoa trees ha$^{-1}$. In these cocoa farms, yield decreased as the density of cocoa trees increased, but it also appeared to be highly dependent on the density of the associated trees, which was of 155 trees ha$^{-1}$ in the most productive cocoa farms. In Bahia, Brazil, higher yields were obtained at higher densities in the range of 1000–5000 trees ha$^{-1}$. However, using the maximum cocoa planting density is not always possible because it also increases the incidence of diseases (Dias et al. 2000; Spaggiari Souza et al. 2009).

### 4.2 Plantation and farmer cocoa production models

Typical cocoa planting densities differ between cocoa geographies. Historical reasons explain observed patterns. There are two basic cocoa production models: (1) low planting density in the 'Plantation Model' and (2) high planting density in the 'Farmer Model' (Urquhart 1961; Vernon 1971). The Plantation Model was developed in the Antilles and spread to Sri Lanka, Southeast Asia, the Pacific Islands and other localities during the Spanish colonial era (fifteenth to eighteenth centuries). It was the only cacao production model until the nineteenth century. This model uses nursery seedlings and planting density between 400 and 1200 plants ha$^{-1}$ (Urquhart 1961; Freeman 1929), regular pruning to control plant size and shape, regular and frequent removal of suckers, and planted shade. For instance, in the Plantation Model in Brazil, cacao was planted at 600–700 trees ha$^{-1}$ until the beginning of the twentieth century, but then planting density was increased to 1111 plants ha$^{-1}$ (3 × 3 m), a system that is still in use today. In agroforestry models in Brazil, cacao plantation density does not exceed 400 trees ha$^{-1}$ (Spaggiari Souza et al. 2009). Cocoa plantations in Central America (Panama, Costa Rica, Nicaragua, Honduras, Guatemala, Belize) have an average of 625 (ranging between 450 and 800) plants ha$^{-1}$. New plantings in Central America are established at 1100 plants ha$^{-1}$ at a recommended spacing of 3 × 3 m (Orozco-Aguilar et al. 2015).

The Farmer Model is typical of Africa. In its origins in the nineteenth century, cocoa was planted under heavily thinned primary forests or under old secondary forests through the direct sowing of closely spaced cocoa planting sites and 2–4 seeds per planting site to compensate for expected substantial mortality losses at the establishment of the orchard (Lass 1985). Planting sites were not rigorously demarcated due to the presence of big roots and trunks of the shade canopy trees; cocoa planting density varied between 3,141 and 10,000 trees ha$^{-1}$ (Vernon and Morris 2015). Nowadays, farmers in Ghana prefer planting cocoa trees without lining and pegging to reduce labour costs, typically planting at close spacing and reducing density by thinning after natural mortality during establishment has taken its toll (Asare et al. 2018). In Cameroon, the average density is

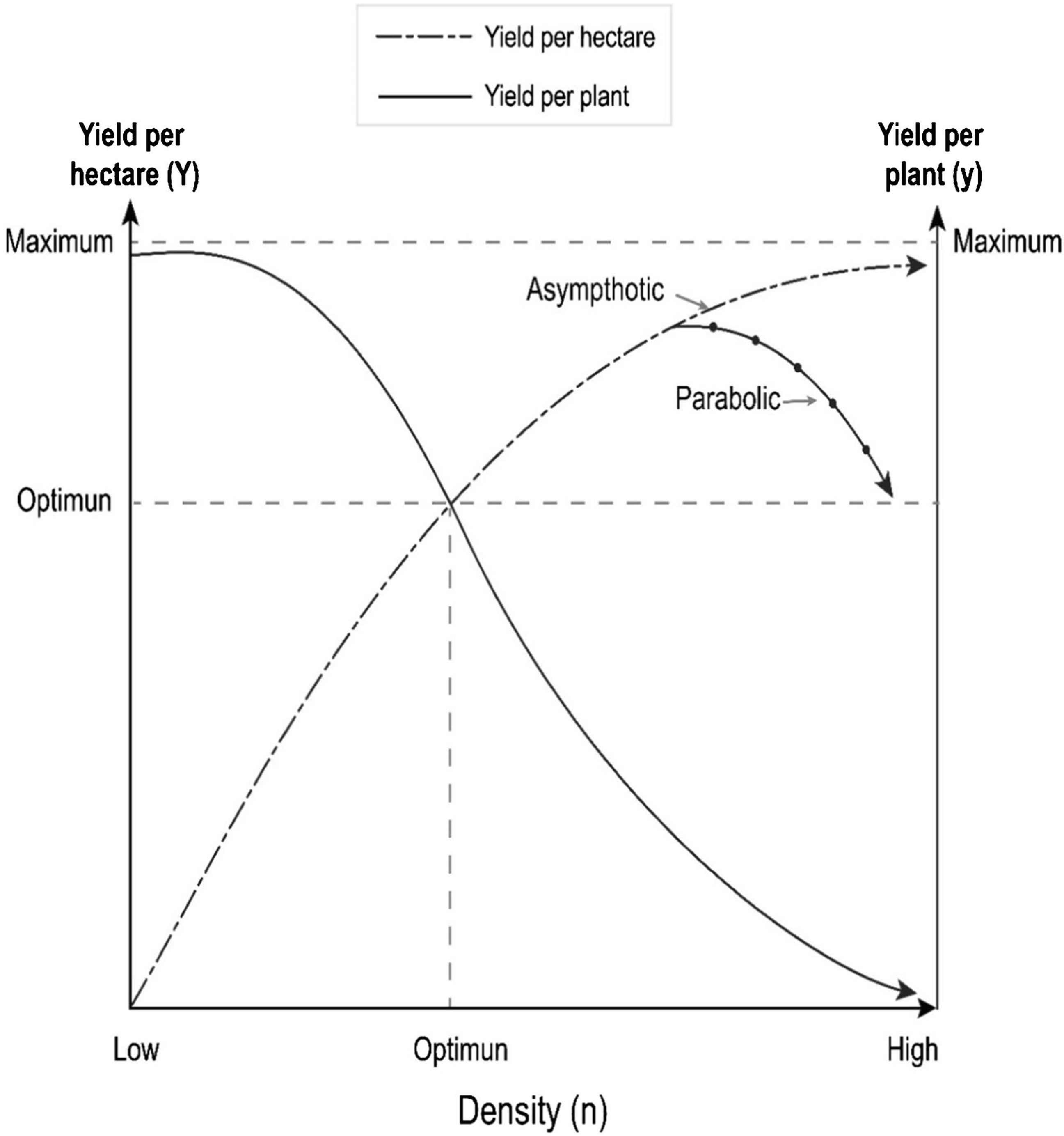


**Fig. 3** Yield–density relationships in plant populations. Yield per hectare (*Y*) and yield per plant (*y*) are both affected by plant population density ($n$ = plants ha$^{-1}$).

1644 plants ha$^{-1}$, but it varies significantly between cocoa-growing regions and orchard life cycle trajectories (Jagoret et al. 2011, 2018).

A planting density of 1680 trees ha$^{-1}$ appears to be the preferred planting density for cocoa in West and Central Africa because the canopy of cocoa closes rapidly, reducing the cost of weeding and facilitating harvesting and fumigation against capsids (*Sahlbergella singularis* Hagl. and *Distantiella theobroma* Dist.) (Charles 1961; Smith 2015). Climate change is now prompting farmers to plant drought-resistant cocoa at higher planting densities to compensate for higher plant mortality rates due to excessive heat and drought (Asante et al. 2017). Planting cacao at high densities in poor soils, such as those in West Africa, seems to be a sound strategy (Charles 1961). At high planting density, cocoa pods are concentrated on the trunk and not on the branches (Kowal 1959; Pacheco et al. 2003), and because of the tight closure of the cocoa canopy, there is no need for regular, intensive pruning or removal of suckers. Similar findings have been reported for Malaysia (Blencowe and Hubbard 1972).

### 4.3 Yield plasticity, minimal critical density and the 'evolving cocoa planting density' concept

In fully stocked cocoa orchards (using the representative cocoa population densities of either the Plantation or the Farmer Model), the elimination (as a result of prescribed thinning or natural mortality) of a number of trees (i.e. a decrease in density) may not result in a decrease in yield per hectare because the canopy space freed up by the cocoa trees removed is rapidly exploited by residual, neighbouring cocoa trees, which attain higher per plant yields that compensates for the yield loss from removed/dead trees (Bastide et al. 2008; Smith 2015; Vernon 1971). This compensatory pattern is maintained until the crowns of the residual trees can no longer utilise the space freed up by reductions in density, yield per plant stagnates and no longer compensates the yield loss due to removed trees. Below this 'minimal critical density', yield per hectare decreases as density decreases (Laryea 1969; Smith 2015). The actual minimal critical density is context specific. For instance, in an industrial cocoa plantation in Indonesia, initially planted at 1250 trees ha$^{-1}$, the compensatory effects are still operational at 20 years of age, when the density has fallen to 835 trees ha$^{-1}$ (Bastide et al. 2008). Vernon (1971) cites 950 trees ha$^{-1}$ as the minimal critical density. In Nigeria, this figure is 1450 trees ha$^{-1}$ (Kowal 1959). Below the minimal critical density, the cocoa canopy of the orchard will have permanent 'holes' that become foci for weed invasion, attacks of pests and diseases, thus creating unfavourable microclimate conditions for the growth and yield of the cacao trees in their vicinity. The maintenance of a closed canopy is the most important factor in the life of a cocoa orchard (Vernon 1971).

The 'evolving cocoa planting density' concept has been proposed to denote a management model that prescribes reductions in planting density at various plantation ages both to increase per plant area (larger crowns) and keep low levels of inter-plant competition (at the soil level) to maintain high yields (Lachenaud 2003; Lass 1985). There is some evidence of gains in yields with this cocoa density management model (Armstrong 1976; Wood 1964). For instance, thinning of 50% at 10 years of age in plantations established initially at 1666 trees ha$^{-1}$ produced favourable responses in yields both per plant and per area (Bastide et al. 2008).

### 4.4 How does density change with age?

Cocoa plants in a new orchard are all same-aged (a cohort) and will pass through the same life cycle stages, but not all will die at the same time. After an initial period of zero natural mortality ($z$, the length of this zero-mortality period, is variable), the population size of the cohort will decrease with age at an annual, compound rate of less than 2% due to natural or random mortality (Lass 1985; Vernon 1971). The density of the initial cocoa cohort in any year ($P_t$) can be described with Eq. (4).

$$P_t = \begin{cases} P_0(1-r)^{t-z} \, if \, t \geq z \\ P_0 \, otherwise \end{cases} \tag{4}$$

where $P_t$ is the surviving trees at time $t$, $P_0$ is the initial planting density at time zero, $r$ is the mortality rate, $z$ represents the age at which the natural mortality starts affecting the tree population.

Long-term studies (say, 60 + years) of changes in cocoa density in orchards with different cocoa genotypes and in different agro-environments are extremely rare. We can use Eq. (4), field data and expert knowledge to model cocoa mortality patterns in different agro-environments, to predict cocoa density and to estimate mortality rates from published studies. For instance, at a mortality rate of 2% and an initial period of 10 years of zero mortality, an orchard starting with 1000 plants ha$^{-1}$ will have 552 plants ha$^{-1}$ when 40 years old. Mortality rates can be estimated from cocoa density and age data reported in several studies. For example, a 22-year-old cacao plantation in Ghana still had 100% of the individuals from the initial cohort. However, at 30 years, 84% of the initial population remained; at 40 years, 50% remained and at 50 years, only 26% of the initial cohort remained (Laryea 1969; Vernon and Morris 2015). In Costa Rica, a 40-year-old cacao orchard retained 70% of the trees from the initial cohort (Martin 1957). In West Papua, Indonesia, an industrial cocoa plantation, initially planted at 1250 cocoa plants ha$^{-1}$, had 835 plants ha$^{-1}$ at the age of 22 years (Bastide et al. 2008). If the relationship between population size and age follows Eq. (4), the estimated average annual rate of mortality ($r$, for $t > z$) is 0.887% for Costa Rica, 4.697% for Ghana and 1.817% for Indonesia. Natural mortality affects cocoa yields very differently, depending on the initial planting density, i.e. high impact in yield in the Plantation Model and low impact on yield in the Farmer Model cocoa orchard. An annual, natural mortality rate of 2% has insignificant effects on a Farmer Model orchard (Charles 1961), but it has a devastating impact on a Plantation Model orchard.

### 4.5 How does yield change with age?

Although biologically a cacao tree can live for more than 100 years, the economic life of a cocoa orchard (if not rehabilitated) lasts typically 30–40 years (Akinnagbe 2017; Gotsch and Burger 2001; Obiri et al. 2007; Montgomery 1981; Lass 1985). However, the economic life of an orchard is highly variable and context specific. Site quality, germplasm and orchard management have important effects on the form of the yield–age curve of cocoa (Wessel 1969). For instance, traditional orchards in Ghana have an economic life cycle of 50–80 years, but for hybrid cocoa, with or without timber shade, the economic optimum has been estimated at 29 and 18 years, respectively (Obiri et al. 2007; Mahrizal et al. 2014). There is no single yield–age curve for cocoa that applies everywhere (Dias et al. 2003; Spaggiari Souza et al. 2009; Vigneri 2007; Ahenkorahh et al. 1987; Upton 1966; Laryea 1969; Lass 1985; Ruf 2011; Smiley and Kroschel 2009; Montgomery 1981). For example, in Malaysia, cocoa starts yielding in the third year of age (400 kg ha$^{-1}$), rising to an average (typical) yield by year 15 (950 kg ha$^{-1}$); yields are maintained until 30 years of age and then decline rapidly until 40 years of age, when they are barely 200 kg ha$^{-1}$ (Gotsch and Burger 2001). In some cocoa-growing areas, without rehabilitation practices, drops in yields were reported over time. Laryea (1969) estimated a 20% drop in yields in cocoa orchards over 30 years of age. Other studies report yield decline after 20 years of age in Nigeria (Vernon and Morris 2015), and after 15 or 20 years of age in Ghana (Ofori-Bah and Asafu-Adjaye 2011; Aneani et al. 2017). In Cote d'Ivoire and in Ghana, cocoa orchards planted in sites with low fertility degrade at 10–15 years of age (Ahenkorahh et al. 1987; Assiri et al. 2003). On good soils, production stabilises at 10 years of age and yields start declining at 30 years of age, at an average rate of 1% per year. Some cocoa orchards maintain acceptable yields up to 40 years of age in Cameroon when rehabilitation practices are applied (Jagoret et al. 2011).

A few yield–age functions have been published for cocoa. For instance, Ryan et al. (2009) used

$$y_t = e^{(-1.1-0.125t+\ln(t))} \tag{5}$$

where $y$ = dry cocoa bean yield (kg tree$^{-1}$), $e$ is the base of natural logarithms, ln is natural logarithm and $t$ = age in years.

Obiri et al. (2007) used the model developed by Ryan et al. (2009) and re-scaled it to an 80-year cycle for traditional cocoa cultivation in Ghana.

$$Y_t = e^{(-1.822-0.166t+3.931*\ln(t))} \tag{6}$$

where $Y_t$ = dry cocoa bean yield (kg ha$^{-1}$), and adjusted regression parameters for two plantation models using hybrid cocoa, with shade,

$$Y_t = e^{(1.6399-0.18t+2.924\ln(t))} \tag{7}$$

and without shade,

$$Y_t = e^{(0.0992-0.4t+4.745\ln(t))} \tag{8}$$

The graphical representation of Eqs. (6), (7) and (8) is given in Fig. 4.

Most cocoa farmers continuously rejuvenate their orchard by both replanting empty planting sites and managing the trees' live tissues. The latter includes stumping, pruning, and grafting old and diseased cocoa plants to regulate the crown shape and tree size (Jagoret et al. 2011, 2017b). These practices transform the single-cohort orchard initially planted into a multi-cohort orchard (with each cohort yielding according to its age) with young, productive tissue (Jagoret et al. 2011, 2017b). As a result of these plant and tissue age structures, the $y(t)$ curve is 'lifted upward', extending the economic life of the orchard (see Fig. 5). $R_{\min}$ is the minimum acceptable yield tolerated by farmers, which usually depends on context conditions, including markets and production cost. $R_0$ is the maximum attainable yield of the orchard with current technology.

## 5 Rehabilitation and renovation practices

Cocoa agronomists and farmers have at their disposal an extensive list of practices for rehabilitation and renovation (Lass 1985). This list includes complete replanting of the orchard, replanting in stages, selective replanting of trees, planting new cacao under old cacao used as temporary shade, reconstructing cocoa tree crowns using basal suckers, with or without grafting them, various types of pruning and pollarding to regulate cocoa crown's shape and size, replanting, stumping, propagating elite trees, shade regulation, early intercropping, etc. (Akinnagbe 2017; Are and Jacob 1971; Ogunniyi and Osuolale 2015; Wessel and Quist-Wessel 2015; Asare and David 2010). Several authors have provided lists of the different models for rehabilitation and renovation, and their variants, in different cocoa-growing regions (Assiri et al. 2003; Ampofo and Osei-Bonsu 1987; Ogunniyi and Osuolale 2015; Olaiya et al. 2006; Are 1969b, 1970a; Quiroz and Amores 2002; Lass 1985).

Rehabilitation practices include (1) stumping and sucker selection to regenerate the crown of the cocoa tree (Akinnagbe 2017; Riedel et al. 2019); (2) stumping combined with top or patch grafting (with a new cocoa genotype) on the regenerated suckers; (3) restocking the orchard by direct seeding, planting nursery seedlings, rooted stakes or grafted plants at empty planting sites

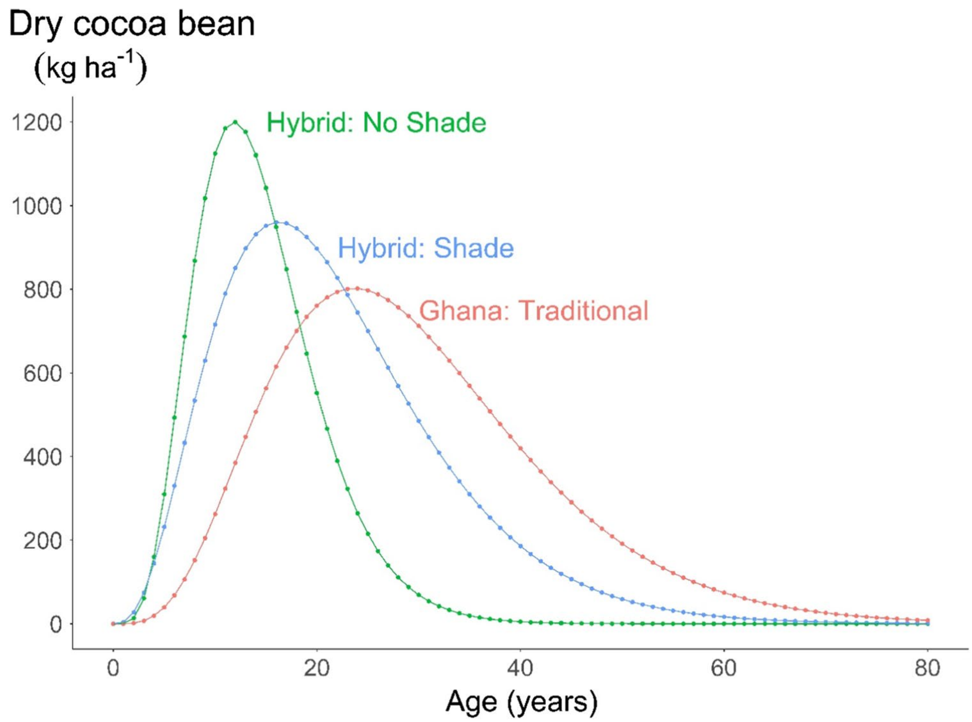


**Fig. 4** Age × yield curves for different cocoa systems (Obiri et al. 2007).

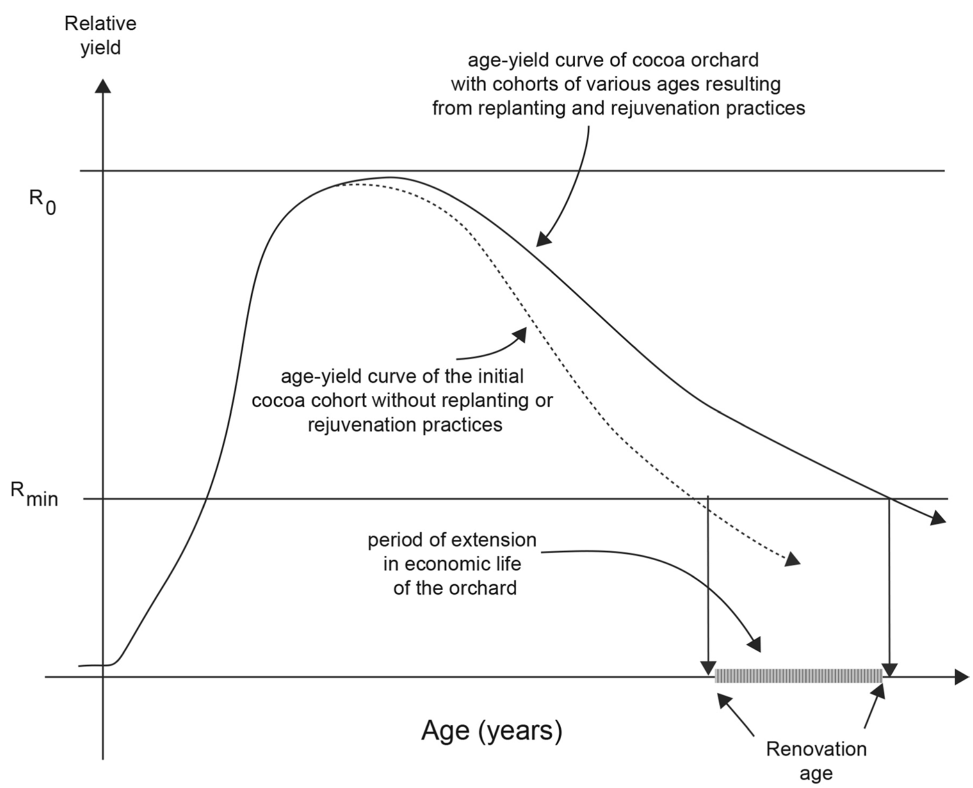


**Fig. 5** Impact of continuous rejuvenation of cocoa tissue plants in the age of renovation of a cocoa orchard. $R_{min}$ is the minimum acceptable yield tolerated by farmers, which usually depends on context conditions, including markets and production cost. $R_0$ is the maximum attainable yield of the orchard with current technologies.

(Asare et al. 2018); and (4) complete removal of the crown by pollarding to remove diseased tissue or to reduce tree height (Are 1969b; Grisales and Cubillos 1985; Quiroz and Amores 2002; Olaiya et al. 2006). In Central Cameroon, the rehabilitation practices adopted by farmers are largely responsible for the presence of very old cocoa agroforestry systems that continue to be exploited today. The continuous replacement of dead cocoa trees and the cutting back of senescent cocoa trees rejuvenate the cocoa stand (Jagoret et al. 2018). Farmers' management of shade trees is in continuous evolution, in terms of both density and species composition. Species selection is based on minimising competition and promoting complementarity between cocoa trees and associated tree species (loc. cit.). The rehabilitation of a commercial, clonal, open-sun cocoa plantation in Malaysia using agroforestry and soil amendments has been documented by Vanhove et al. (2016).

Renovation typically seeks the construction of a new cocoa orchard, with cocoa cohorts and a shade canopy that may be very different from the original. Three major categories of renovation models can be identified: (1) selective (or partial) renovation; (2) staggered (or phased) renovation, when a fraction of the orchard is replaced periodically; (3) total renovation, cutting and eliminating everything at the same time to establish the new cocoa orchard (Olaiya et al. 2006; Lass 1985). Most available information focuses on types 2 and 3 renovation models.

In selective or partial renovation, farmers replace all poor-yielding trees over the entire life cycle of the cocoa orchard (Lass 1985). The disadvantages of this method (possible spread of cocoa swollen shoot virus and other diseases from the existing trees to the new plantings and high labour requirement) seem to outweigh its advantages (income generation can continue while replanting is in process and no new land is required) (Mahrizal et al. 2014). In the staggered model, a fraction of the cocoa plants are renovated periodically, aiming at achieving an age-structured cocoa population that both results in a constant annual flow of benefits and spreads investments over the renovation period (Ampofo and Osei-Bonsu 1987; Obiri et al. 2007; Mahrizal et al. 2014). In this model, cocoa yields from the residual plants increase in response to the thinning of the neighbouring cocoa plants, pruning and management (Enríquez and Paredes 1981; Soria and Garcia 1968). Weeds are not a problem because the soil is always shaded by residual cocoa trees. Also, there is no need to plant and manage temporary shade, and shading by the yet-to-be-removed cocoa plants may reduce capsid or mirid attacks (Laryea 1969; Vello et al. 1971) or increase attack by viruses and fungi (Dzahini-Obiatey et al. 2006). However, the shading of the new plants may be irregular (Are 1969a, 1970a) and the opportunities for early intercropping are reduced. Many variations on the temporal model (to distribute risk, financial investment and secure a constant flow of income) and the spatial staggering model (by rows, by sectors, by groups of trees, etc.) have been presented (Lass 1985). In the total renovation model, the financial investment is high (Vello et al. 1971; Martin 1957). No income from cocoa sales is obtained for up to 5 years until cocoa production resumes, but significant income may be obtained from both the sale of timber and early intercropping.

## 6 The cocoa agroforestry renovation approach

The life cycle of a cocoa agroforestry orchard involves four components (Fig. 6). First is the period of site restoration (e.g. soil fertility and health) to sustain a new cultivation cycle of cocoa. Second is site preparation, planting of cocoa and early intercropping with short-term crops to generate early revenues and reduce the need for investment capital to establish the new orchard. Third is the cocoa stand, with its various cohorts, varied genetic compositions and its context-dependent age–yield–density behaviour. Fourth is the shade canopy, with varied botanical compositions and three-dimensional spatial structures. Two or more cultivation cycles can take place in one site. In Fig. 6, the yields of all components are scaled to any locally determined maxima (on an ordinal, relative scale). The *x*-axis is the age in years. Three cocoa yield threshold levels are represented: (1) minimum acceptable yield level, which tells farmers when to renovate ($R_{min}$); (2) maximum yield level with current technology ($R_0$); (3) maximum yield level with new technology ($R_1$). In the following sections, we explore in more detail each component of the model.

Figure 6 represents a cocoa agroforestry model that includes (1) a 5-year period to restore the fertility of the site; (2) a 3-year period for land preparation, planting cocoa and early intercropping with food crops; (3) cocoa over the entire cultivation cycle; and (4) the shade canopy (over the entire cultivation cycle), made up of fruit and timber trees, which are all planted and removed at the same time, at age 35 years. Timber trees are planted at low density when cocoa is planted, and then no intermediate thinning is required. The evolution of cocoa yields over time has been explored in previous sections of this review. A more detailed description of the other components of the approach is presented in what follows.

### 6.1 Site restoration

Farmers prefer to establish new cocoa orchards on recently cleared forest land because of better soil fertility and to avoid the burden of both removing the old cocoa orchard and restoring soil fertility when attempting to replant at the same site. The term ‘forest rent’ has been coined to describe the high soil fertility levels experienced when cocoa is established in recently cleared forest lands (Asare et al. 2018; Laryea 1969; Ruf and Zadi 1998; Trivedi 1988). Cocoa is usually cultivated without the application of fertilizers (organic or inorganic) to replace the nutrients exported in the cocoa beans; thus, the soil nutrient pool of

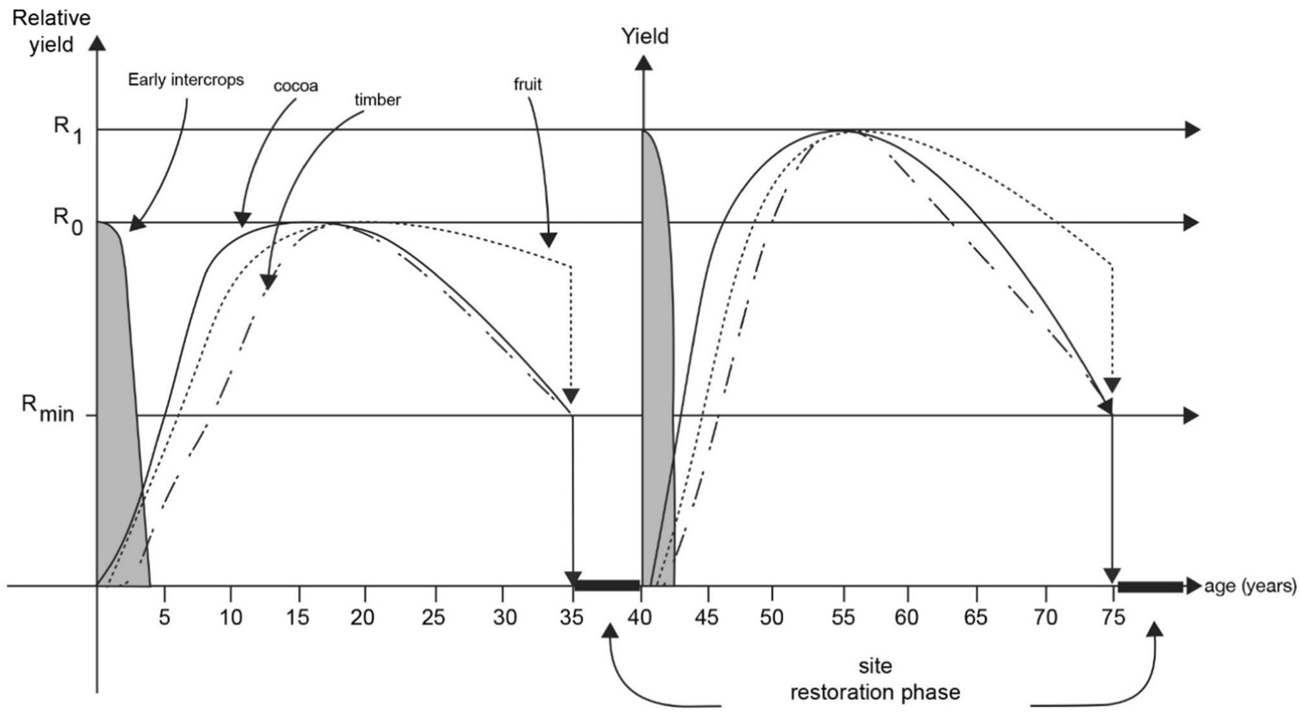


**Fig. 6** Age-dependent trends in all components of the cocoa agroforestry renovation model that includes three components: (1) a 5-year period to restore the fertility of the site and to prepare the site for the planting of an agroforestry system; (2) a period of 1–3 years of early intercropping where short-term crops are cultivated; (3) cocoa, fruit and timber trees are all planted and removed at the same time, at age 35 years. Fruit and timber trees are used for shade. In the second cycle, an improved agroforestry model replaces the original cocoa agroforestry orchard. The *x*-axis is the age in years. Three threshold levels are depicted: (1) minimum acceptable yield level ($R_{min}$)—it tells farmers when to renovate; (2) maximum yield level with current technology ($R_0$); (3) maximum yield level with new technology ($R_1$).

the site is mined out during the cultivation cycle of cocoa (Ahenkorahh et al. 1987; Wessel and Quist-Wessel 2015; Jagoret et al. 2011). Various studies document both the difficulty experienced by farmers when attempting to replant cocoa after a 40-year cycle of non-fertilized cocoa, and the need to restore the fertility of the soil before a new cocoa orchard is planted (Asare and David 2010; Assiri et al. 2012; Wessel 1969). The difficulties are notorious in poor soils, which may require the planting of improved fallows, cover crops and other soil fertility remediation measures for several years before cacao can be planted again (Assiri et al. 2003; Anim-Kwapong and Osei-Bonsu 2009; Anim-Kwapong 2003; Anim-Kwapong and Teklehaimanot 1995; Are 1969b, a; Are and Longworth 1965; Ayanlaja 1983; Petithughenin 1995).

## 6.2 Early intercropping

Early intercropping with short-term crops is a well-established practice in cocoa cultivation worldwide, with proven benefits in household food consumption, early financial returns resulting in a better long-term financial performance, and enhanced survival and early growth of the cocoa seedlings. Weeding, fertilisation and other amelioration practices applied to the intercrops directly benefit the early establishment of both cacao and planted shade trees (Adeyemi 1999; Egbe and Adenikinju 1990; Mahrizal et al. 2014; Oladokun 1990; Melendez 1991). The financial impact of early intercropping is rarely (if ever) considered in Rh/Re decision-making; with some notable exceptions (Mahrizal et al. 2014; Obiri et al. 2007).

## 6.3 The shade canopy

Cocoa shade canopies are structurally and functionally diverse, with one or many tree species, each with its own population size, age and size frequency distribution, yields (timber, fruit, firewood, maintenance of soil fertility, store carbon, protect the soil from erosion, etc.), temporal dynamics, spatial planting patterns, vertical stratification of tree crowns and use-values (Wessel and Quist-Wessel 2015; Jagoret et al. 2014). Cocoa shade canopies are usually grouped into six broad typologies (Somarriba and Lachenaud 2013), each one reflecting the goals and needs of the farmer, e.g. to produce only cocoa (as is the case in open sun orchards and in shaded systems in which the shade species only produces shade) or also to produce fruit, timber, medicine, etc. (Obiri et al. 2007).

## 7 Climate-smart cocoa agroforestry Rh/Re

A growing body of research describes how much and where air temperature, rainfall, wind, $CO_2$ concentration, and other atmospheric and meteorological variables will change over the next 30 or 50 years in all cocoa production regions (Schroth et al. 2016b; Bunn et al. 2019a; Läderach et al. 2013). Expected climatic changes in cocoa regions include a rise in temperature, changing precipitation levels and patterns, and recurrent stressful events (e.g. drought or flooding) leading to tree death, changes in phenology, shortening of the life cycle of important cocoa pests and diseases, and decrease in yields (Leandro-Muñoz et al. 2017; Bertolde et al. 2012; Gateau-Rey et al. 2018; Granados Ramírez and Pérez Sosa 2020). Knowledge of cocoa physiology and agronomy dictates what is possible in terms of cropping cocoa under climate change (Lahive et al. 2018). Impacts of climate change on current and future cocoa production areas and supply chains in key cocoa geographies have been predicted and mapped to help farmers, extension services, land-use planners and decision-makers transition to a climate-smart cocoa sector at various scales (Bunn et al. 2019b). There is room for improving predictions by taking into consideration the physiological plasticity of cocoa to changing climatic conditions as well as the untapped potential of genetic diversity in the response of cocoa to climate change stresses (Lahive et al. 2018).

The impacts of climate change on cocoa cultivation areas create a patchwork of situations. At some locations, currently suitable cultivation areas may become marginal or completely inadequate for growing cocoa, forcing farmers to shift to other crops (Schroth et al. 2016b; Read 2019). At other locations, areas previously unsuitable may become acceptable or even optimal for growing cocoa. For instance, in Cote d'Ivoire and Ghana, increasing temperatures will shift optimal elevations for cocoa (Läderach et al. 2013) and force farmers to use shade trees wisely as a key adaptation measure (Schroth et al. 2016b). Pest and disease outbreaks, now powered by climate change, have led to the downfall of entire cultivation areas and have shaped the global geography of the cultivation of cocoa (Cilas and Bastide 2020). Increasing temperatures are forcing coffee farmers in Central America to shift cultivation areas to higher elevations, opting for cocoa to replace lowland coffee (Läderach et al. 2017; de Sousa et al. 2019).

Adoption of climate-smart cocoa farming strategies and practices that simultaneously address (at least) profitability, resilience and low GHG emissions is much needed. Farm diversification, agroforestry, the use of improved genotypes of both cocoa and associated crops, irrigation, fertilisation, soil organic matter and cover, integrated pest management, intensification and other good crop husbandry practices have all been recommended as key adaptation and mitigation measures to cope with climate change (Gusli et al. 2020; Denkyirah et al. 2017; Jagoret et al. 2012). The use of shade trees (i.e. agroforestry) stands out as a widely recommended adaptation and mitigation measure (Andres et al. 2018; Schroth et al. 2016b; Kroeger et al. 2017). Other studies have assessed farmers' perceptions and coping measures in the face of climate change such as the application of innovative crop management practices (Asante et al. 2017; Denkyirah et al. 2017; Oyekale and Adepoju 2012; Jacobi et al. 2013; Codjoe et al. 2013; Oluwatusin 2014), the estimation of the right amount of subsidies to compensate farmers for the risks involved when adopting climate-smart practices (De Pinto et al. 2013), and the need for certification and better prices to promote the use of shade (Middendorp et al. 2018).

Recommendation domains, based on the level of expected change in land suitability and the degree of transformation in cocoa farming needed to cope with these changes, have been proposed as an analytical and planning tool to help design optimal transition pathways for cocoa under climate change (Bunn et al. 2019b). Transitions in land suitability from optimal to acceptable to marginal (or vice versa) will require climate-smart cocoa agroforestry Rh/Re models, strategies and practices (Kroeger et al. 2017; Read 2019). It is proposed that a climate-smart cocoa agroforestry Rh/Re decision-making and implementation process, which identifies threats and response measures, should be tailored to the four components of the cocoa cultivation cycle: (1) site restoration; (2) plantation establishment and early intercropping; (3) cocoa; (4) shade canopy. For instance, the erratic onset of rains may be fatal to cocoa seedlings during the establishment and early intercropping phase, so the use of improved cocoa genotypes has been recommended to reduce seedling mortality during the dry period (Padi et al. 2013). Fires are especially fatal for young cocoa. In the forest–savanna transition zone in West Africa, farmers losing a young cocoa plot to fires may shift to other crops, giving up cocoa cultivation (Asante et al. 2017). Droughts can also kill adult cocoa trees (Gateau-Rey et al. 2018).

The threats posed by climate change and the adaptation measures needed during the productive phase (cocoa and shade canopy) of the cocoa cultivation cycle are manifold and poorly understood. For example, in their summary of 80 years of CSSVD research and eradication campaigns in Ghana, Andres et al. (2017) concluded that the 'effects of commonly used shade tree species on mealybug populations and CSSVD infection have not been investigated so far, and they may vary depending on shade tree species. It is difficult to identify adequate shade levels and tree species composition that minimise mealybug populations and thus likelihood of CSSVD infection while ensuring favourable growing conditions for cocoa trees. This is because optimal shade levels for cocoa trees and mealybug populations vary over the year. Therefore, more research on effective agroforestry designs to combat CSSVD is needed'. Recent studies have looked at the effect of the spatial distribution of shade trees on the spatial distribution of cocoa mirids (Babin et al. 2010; Gidoin et al. 2014) or the role of shade trees as barriers to the dispersal of mealybugs transmitting CSSV (Andres et al. 2017).

Few studies have been published on the long-term changes in the botanical composition, total biomass, value, timber stock, etc. of cocoa shade canopies, with some notable exceptions. For instance, Frimpong et al. (2003) and Obiri et al. (2007) reported reductions in total carbon stock with shade canopy age in Ghana. Jagoret et al. (2017a) and Jagoret et al. (2018) documented increments in cocoa basal area and a decline in the basal area of shade trees with the aging of the orchard. Standing carbon seems to increase as the plantation ages in Cameroon (Saj et al. 2013, 2017). Equally unknown is the yield–age function of most shade tree species in cocoa orchards in different agro-environmental and cultural contexts. More research is warranted.

A growing body of research focuses on the development and use of methodologies and tools to aid in the optimal design of cocoa shade canopies (Somarriba et al. 2018, 2020; Álvarez-Carrillo et al. 2012; Malézieux 2012; Guharay et al. 2001; Tscharntke et al. 2011). This is a most welcome development since most cocoa shade canopies are sub-optimal in terms of species composition, stand density and homogeneity in the spatial distribution of canopy cover (Somarriba et al. 2018). Preliminary evidence suggests that, with proper design, it is possible simultaneously to achieve livelihood goals (profit and reduced financial vulnerability, food security) at the same time as environmental goals (e.g. store significant amounts of carbon in shade tree biomass, reduce input-related emissions, mostly from fertilizers) (Schroth et al. 2015b; Somarriba et al. 2013; Middendorp et al. 2018). Six rules for shade management in cocoa agroforestry systems have been proposed, involving the inclusion of N-fixing legumes, periodic pruning, diverse botanical composition with multiple vertical strata, and combining food and cash crops, for which optimal shade design and management is required (Tscharntke et al. 2011). Others suggest the use of basal area ratios between shade canopy trees and other components. A Cameroonian cocoa agroforestry system has been proposed as an indicator of long-term sustainability (Saj et al. 2017). This review suggests that the synchronisation in time of yields of all products from the orchard (food crops, cocoa, shade tree products) is a central design goal in cocoa agroforestry systems. This is not an easy task since several factors militate against synchrony. For instance, the life cycle of cocoa and shade canopy plants differ, trees may be planted or recruited from natural regeneration in different years, and even when cocoa and shade canopy trees are planted simultaneously (as in Fig. 6), they may not be harvested simultaneously due to differences in their yield–age relationships. For instance, fruit trees may start fruiting between 3 and 5 years of age and sustain productivity for decades. Timber trees may be harvested at the same time cocoa trees are renovated (30 years in Fig. 2, also see Obiri et al. 2007) or not. For instance, timber trees in cocoa shade canopies in Central America have size (and age) structured populations because recruitment, natural mortality and harvest occur continuously (Somarriba et al. 2014).

## 8 Conclusions

Rehabilitation and renovation (Rh/Re) are essential elements in the cocoa cultivation cycle. Cocoa agronomists have devised methods and protocols to assess the Rh/Re needs of a cocoa orchard, and to make decisions regarding whether to rehabilitate, renovate or not at all, as well as how much and when to do it. Current Rh/Re decision-making processes are based on the assessment of the age, planting density and yield of only the cocoa component of the orchard. The regular flow of food crop and tree products for sale or family consumption, and the need to restore site (soil) quality to sustain another cycle of cultivation of cocoa at the same site, are not considered in current Rh/Re diagnosis and design protocols. Furthermore, farmers are usually reluctant to follow technical recommendations to engage in Rh/Re because of the financial burden involved, and the uncertainty and risks of adopting new, yet unproven, climate-smart production practices.

In this review, we propose an agroforestry Re approach that overcomes these limitations by incorporating not only the production of cocoa but also of food crops and tree products, and the need to restore site quality to enable another cultivation cycle of cocoa at the same site (and hence reduce pressure on natural forests). Intercropping with short-term food crops, agroforestry, and site restoration are three common practices in cocoa farming worldwide, but their contributions to the Re decision-making and implementation process are rarely (if ever) considered. This review sheds light on these important issues and shows how to overcome current limitations.

Rehabilitation and renovation of cocoa agroforestry systems is central to any transition towards profitable, climate-smart cocoa production. Our review shows that Rh/Re decision-making and field implementation processes are complex, context-specific (agronomic, social, climate, etc.) and hence unique processes. To guide farmers, extension agents, land use planners and decision-makers in this complex process, we need a solid body of science- and expert-based knowledge to support decisions and innovation design at every step of the transition towards profitable and climate-smart cocoa production. Unfortunately, we have only a rudimentary understanding of the processes and interactions between cocoa and the shade canopy. We need more research on (at least).

- The optimum amount of aboveground carbon that each typology can store (without sacrificing profits) along cocoa cultivation altitudinal, latitudinal, rainfall and soil quality gradients.
- The critical rainfall thresholds that determine whether the presence, kind and amount of shade trees in a cocoa agroforestry system is beneficial or detrimental to the output of the system. Regulation of shade canopy biomass (by pruning, thinning, planting) have direct effects on air temperature (and heat stress) and water use.
- How yield-losses to pests and diseases vary with shade canopy design. Interactions between shade, microclimate, pests and disease dynamics are complex and poorly understood.
- How primary productivity of cocoa shade canopy typologies affect the rate of restoration of site quality, in different soil, climate and culture contexts.
- The effect of synchrony (or lack thereof) on yields among shade trees, and between them and cocoa, on the optimisation of the Rh/Re process.
- The density–yield–age curves for the most common species of shade trees used in different cocoa agroecological and cultural contexts.

The analysis of the factors influencing Rh/Re, the agroforestry Re approach herein presented, and the best practices and interactions with climate change described for cocoa may also be applicable to coffee agroforestry systems.

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## Declarations

**Data availability (data transparency)** Not applicable.

**Code availability (software application or custom code)** Not applicable.

**Conflict of interest** The authors declare no competing interests.

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

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