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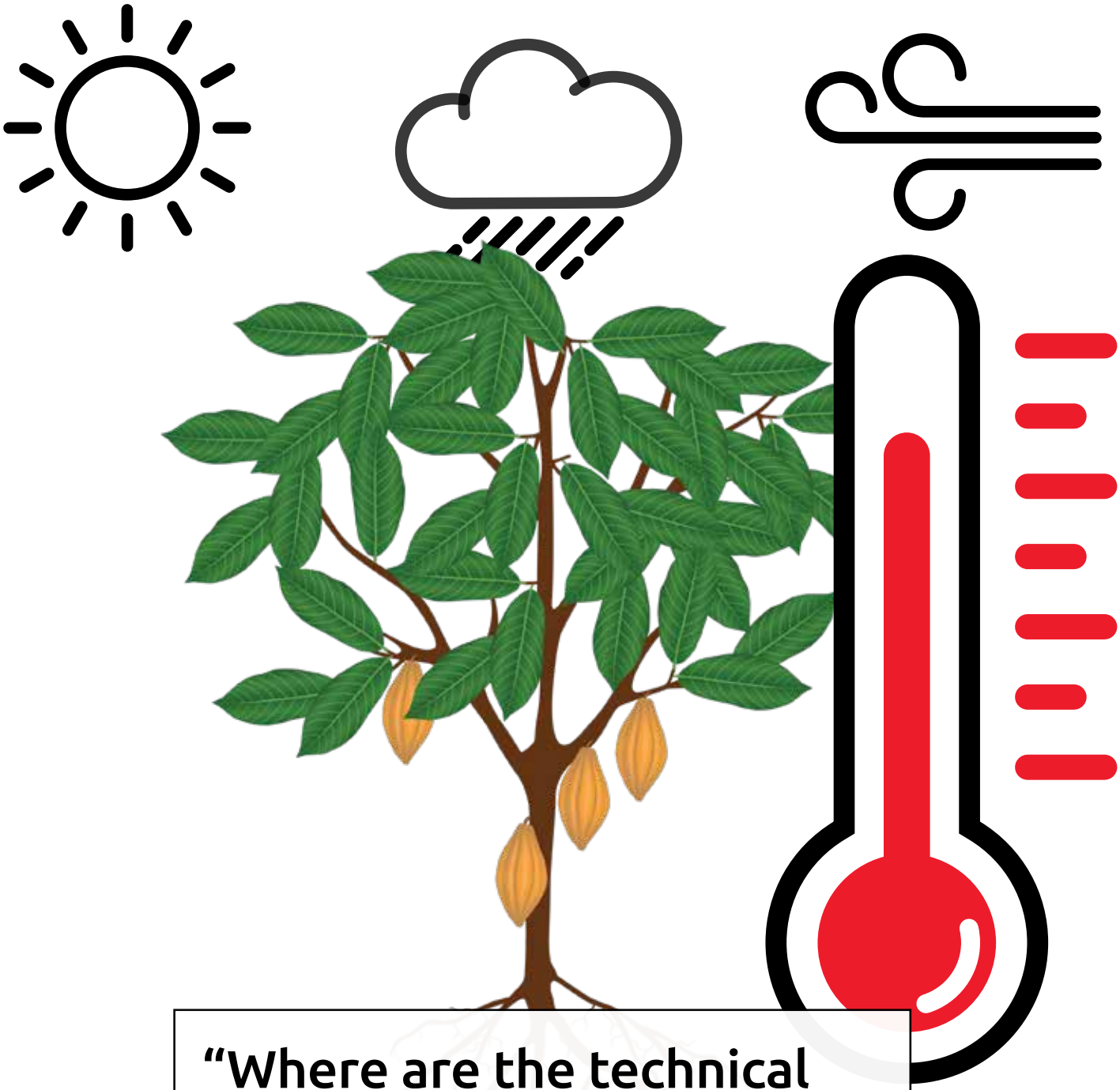

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Scientific analyses and reflections

Dr. Anja Gassner, Valentina Jüngert, Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF), Bonn, Germany

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Summary

Cocoa production, a vital global industry supporting millions of farmers, faces significant challenges due to climate change. Rising temperatures, erratic rainfall, and prolonged dry periods threaten yields and farmer livelihoods, particularly in key producing regions like West Africa, South America, and Southeast Asia. Agroforestry systems, which integrate different (ideally native) tree species with cocoa crops, offer promising solutions by improving microclimate regulation, enhancing water cycling, and increasing resilience to climate variability. However, a critical knowledge gap exists regarding optimal agroforestry designs tailored to local conditions and future climate scenarios.

This article advocates for large-scale investments in research and development to establish a “gold standard” for cocoa agroforestry systems, ensuring environmental sustainability and better livelihoods for farmers. Public-private partnerships are essential to close this gap and transform the cocoa sector into a more inclusive and climate-resilient industry. As part of this article, the authors provide an extensive literature review (including approximately one hundred studies and reports on the availability of agronomic data on cocoa production in the public domain). Ultimately, there is a lack of accessible research on adapting cocoa production to new climatic conditions through innovative agronomic practices.

One of the key challenges seems to stem from agroforestry trials with sun-tolerant cocoa varieties. Obviously, these plants may develop severe health threats in a shaded forest-like design. Also, many clonal varieties experience stress when confronted with extended periods of drought or with excessively intense and prolonged heavy rainfall that can flood entire areas. Closing the knowledge gap is crucial to transition from planting trees for compliance to mitigating production risks and improving profitability in the cocoa supply chain.

In a nutshell: Without significant investment in research, the technical levers for climate-resilient, sustainable cocoa production remain unclear – with all the consequences for farming communities, the entire cocoa supply chain and ultimately the environment.

Introduction

Chocolate production – one of the main uses of cocoa (Theobroma cacao L.) – is a multimillion-dollar global enterprise. In 2024, its turnover was an estimated US$133 billion, with predicted annual growth of 4.7 per cent. Cocoa is also widely used in cosmetics and various food industries. World cocoa production was estimated at 4,840,000 tonnes for the 2024/25 financial year, while grindings were tipped to reach 4,650,000 tonnes [1]. Native to the upper Amazon basin, cocoa is not only indispensable to European cuisine – with each person on the continent consuming an average of 5 kilogrames of chocolate per year – but also provides livelihoods for 5 to 6 million farmers across the globe [2].

Capitalising on geographical production advantages and leveraging economies of scale, sectoral actors have developed sophisticated and robust systems to establish efficient cocoa supply chains worldwide [3]. This has resulted in specialisation both in terms of producers and production, which is characterised by large cocoa-dominated landscapes in key producing countries such as Ghana, Nigeria, Cameroon, Côte d'Ivoire, Indonesia and Brazil. Ghana alone has over 800,000 cocoa farmers, while Nigeria has approximately 300,000, Cameroon around 600,000, and Côte d'Ivoire more than a million [4], [5]. For many of these farmers, cocoa represents the primary source of income, contributing 60 to 90 per cent of household earnings [6]. Such earnings are essential for covering daily expenses – including food, education, and family welfare – which highlights the sector's socioeconomic significance in these regions [7]. It is uncertain if and how higher cocoa prices in the last two years have

improved the situation for the farmers, especially in the main producing countries such as Côte d'Ivoire and Ghana.

Over the past century, cocoa production has expanded globally, with West Africa becoming the dominant producer. Sustainability was synonymous with increased efficiency of production, which implied intensification of yield production with lower consumption of land, and fertiliser [8]. From the 1920s to the 1980s, monoculture farming increased yields thanks to the development of full-sun cocoa varieties – but also led to deforestation and farmer poverty. The 1990s saw the rise of Fair Trade and sustainability certifications. By the 2010s, climate change, child labour and supply chain transparency became major concerns, prompting corporate and regulatory action. Today, deforestation-free regulations, living income initiatives, and regenerative farming are shaping the industry. Ethical consumerism is growing, pushing brands toward sustainable cocoa sourcing, while technology improves traceability and farmer livelihoods. Despite such advancements, however, sustainability remains a key challenge for the sector. Only if value chains become more inclusive and equitable, and higher cocoa prices translate into higher farmgate prices and better livelihoods for cocoa farmers, can we expect a real transformation of the sector.

Agroforestry – the use of trees in combination with crops, livestock, or both crops and livestock on the same area of land – plays an important role in the conversation about sustainable cocoa production [8]. The ecological and social benefits of agroforestry are well-documented and a number of chocolate-producing companies are committed to supporting the integration of trees into their cocoa sourcing landscapes. Yet a vast technical knowledge gap remains in terms of data and experiences to advise cocoa producers on the best agroforestry designs for their specific local contexts, especially considering changes in climatic conditions [9].

The ecological and social benefits of agroforestry are well-documented.

This paper makes a case for large-scale public and private investments into cocoa agroforestry research. The Green Revolution – an international donor-led research and development programme to create and adopt high-yielding varieties of maize, wheat and rice, and implement large-scale intensive agriculture – was phenomenally successful: it resulted in higher yields, lower food prices and better-off farmers throughout Asia [10]. Now, we need the same for shaded cocoa production systems. We must combine the best of research and development with local producer knowledge to develop a "gold standard" for cocoa production that goes beyond meeting environmental, social and governance (ESG) requirements to ensure that millions of smallholder cocoa farmers benefit from the synergies of trees within cocoa agroforestry systems and diversify their production.

The paper is structured into three sections. We first outline the state of knowledge of climate change and its widespread impacts and risks for major cocoa-producing landscapes, as summarised in the synthesis report (SYR) of the Inter-governmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). We explain how cocoa agroforestry systems reduce the risk of climate-related produc-

Key Implications for Cocoa based on SYR Projections:

1. Temperature increases and heat stress
2. Changes in precipitation patterns
3. Increased frequency of extreme climate events (flooding, heatwaves and storms)
4. Socioeconomic vulnerability
5. Urgent adaptation needs across all sectors. For cocoa this may include:
   a. Developing climate-resilient cocoa varieties.
   b. Shifting cultivation zones.
   c. Agroforestry and shade management.
   d. Improved water conservation practices.

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tion risks, and what agronomic knowledge is needed to optimise agroforestry systems. We then provide a literature review on the availability of agronomic data on cocoa production in the public domain. Ultimately, we demonstrate that there is a lack of accessible research on adapting cocoa production to new climatic conditions through innovative agronomic practices. Closing the knowledge gap is crucial to transition from planting trees for compliance to mitigating production risks and improving profitability in the cocoa supply chain.

Climate change impacts and projections for the cocoa sector

Theobroma cacao is highly susceptible to changes in temperature and rainfall, which makes it particularly vulnerable to the vagaries of climate change. As a tropical plant native to the Amazon rainforest, the species thrives in warm, humid climates with a maximum annual average of 30 to 32 °C and a minimum average of 18 to 21 °C [11]. Besides temperature, rainfall influences yield variations more than any other climatic factor [12]; soil moisture-holding capacity, for instance, is only relevant during dry spells, and is not an issue in regions where rainfall is evenly distributed throughout the year [13]. Cocoa needs plenty of rainfall – 1,500 to 2,000 mm per year – and within that range, rainfall seasonality and the length of the dry seasons significantly limits cultivation. A dry period with less than 100 mm of rainfall over more than three months is considered a critical threshold for cocoa growth and yield [14], [15].

Prolonged dry periods, like other climate-related events, can significantly reduce cocoa bean size and yield due to higher flower termination rates and increased withering [16], [17]. Extended drought periods adversely affect flower production and lead to flower abortion, thereby reducing the survival of pollinated flow-

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ers, pod sizes and dry bean yield. Drought also diminishes the number of beans per pod, as well as bean size and weight [13]. The impact of water deficit on early cocoa pod development is not well understood. Cocoa seeds convert sucrose to oil and lipids, but under water stress, it is suggested that reduced carbon uptake could limit sugar transport and lipid deposition. This may explain the lower seed weight observed in water-deficit conditions [13].

Some breeders have succeeded in producing varieties that are less susceptible to water stress; however, clones can only be optimised for specific climatic conditions, not for variation in rainfall patterns over the life cycle [18]. Cocoa trees can live up to 100 years, but are most productive for about 25 to 30 years; between three and five years, the tree reaches maturity and starts bearing fruit, with pods maturing in about six months. Full production occurs from year five onward, lasting up to 25 years before the tree enters a decline phase, requiring rejuvenation or replanting [19]. Having to change the variety due to changing climatic conditions within the productive lifecycle is a transition investment that smallholders cannot afford.

> **The impact of water deficit on early cocoa pod development is not well understood.**

Table 1, below, shows the diversity of climatic and production conditions in the main cocoa producing countries [20]. Next, we explore specific impacts of and projections for climate change in key cocoa producing regions of West Africa, South America and Southeast Asia.

Main cocoa production seasons by country

Country	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Cameroon												
Côte d'Ivoire												
Ghana												
Liberia												
Togo												
India												
Indonesia												
Philippines												
Vietnam												
Bolivia												
Brazil (Bahia)												
Costa Rica												
Dominican R.												
Ecuador												
Haiti												
Mexico												
Nicaragua												
Venezuela												
Colombia												

Table 1: Main cocoa production seasons by country (brown = main harvest, yellow = flower initiation, green = weeding and pruning) (Daymond et al., 2022)

1. West Africa: Ghana and Côte d'Ivoire
West Africa, particularly Ghana and Côte d'Ivoire, is the heart of global cocoa production, supplying over 60 per cent of the world's cocoa. However, climate change is exerting significant pressure on the region's cocoa sector, impacting yields, farmer livelihoods and economic stability.

According to the World Bank (2023), Ghana's annual rainfall increased from 1134.45 to 1315.23 mm from 2017 to 2018, then grew again to 1450.32 mm in 2019, before dropping to 1232.11 mm in 2020 [21]. In addition to such erratic rainfall patterns, rising temperatures add stress to cocoa production systems. Other challenges posed by climate change include increasing prevalence of diseases such as black pod rot and swollen shoot, which are highly destructive to ripening pods and cocoa stems, respectively [16], [22]. This phenomenon has led to reduced yields on cocoa farms across all production regions in Ghana [23].

The IPCC's 2023 report highlights that West Africa is expected to experience an increase in temperature and changes in precipitation patterns [24]. The western parts of the region are projected to experience decreased rainfall, with a shorter rainy season, while eastern parts may see an increase in precipitation. These changes are expected to exacerbate droughts and floods, posing significant risks to rain-fed cocoa farming [25].

In addition to erratic rainfall patterns, rising temperatures add stress to cocoa production systems.

In the past year, the El Niño climate phenomenon devastated crops through un-

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Common cocoa plant diseases

Black Pod (Phytophthora spp.)
Fungi-like oomycetes, especially Phytophthora palmivora and P. megakarya
- Symptoms: Dark brown to black lesions on pods; pods rot and mummify.
- Impact: Most widespread and damaging disease globally.

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Cocoa Swollen Shoot Virus (CSSV)
Virus, spread by mealybugs
- Symptoms: Leaf vein swelling, stem swellings, reduced pod production, eventual plant death.
- Impact: Devastating in West Africa, especially Ghana and increasingly in Côte d'Ivoire vastly diminishing huge cocoa harvest volumes.

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Frosty Pod Rot (Monilia)
Moniliophthora roreri (fungus)
- Symptoms: White fungal growth on pods (can cover the whole cabosse) that turns brown and mummifies; internal pod damage.
- Impact: Major issue in Central and South America.

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Cocoa Witches' Broom Disease Moniliophthora perniciosa (fungus)
- Symptoms: Abnormal shoot growth resembling a "witch's broom," malformed pods, dieback.
- Impact: Major problem in South America, especially Brazil.

usually high temperatures and rainfall. In Ghana, annual cocoa production fell to 429,323 metric tonnes, marking a decline of over 50 per cent from previous peak levels. Farmers now face increasing costs related to irrigation and pest management, as climate variability makes rain-fed farming less reliable [26], [20], [27], [25].

In the cocoa-growing regions of Ghana and Côte d'Ivoire, the IPCC (2023) projects that yearly and monthly minimum and maximum temperatures will increase significantly by 2030, and continue to climb progressively to 2050 (by up to 2.0 °C). Changes in yearly and monthly precipitation, meanwhile, are likely to be trivial, while atmospheric CO_2 is significantly increasing.

The effect of climate change on cocoa production remains uncertain because traditional species distribution models [28], which do not directly predict yield changes, need supplementing with physiological crop models that account for growth and yield processes, including the impact of increased atmospheric CO_2. Elevated CO_2 concentrations could potentially enhance cocoa yields by boosting photosynthesis rates and improving water-use efficiency, although these gains may not directly correspond to increased net primary productivity, making it difficult to predict exact yield outcomes [29].

2. South America: Brazil
Brazil is another major cocoa-producing country, with the commodity primarily cultivated in the Amazonian and northeastern parts of the country. Climate change is affecting the sector through rising temperatures, changing precipitation patterns and environmental degradation. The IPCC (2023) projects an increase in temperature across all cocoa-growing regions in the country, with significant rainfall reductions in the northeast and increased rainfall in the western Amazon, leading to both drought and flood risks [30], [31]. Changes in the onset and retreat of the rainy season are further complicating farm planning and productivity [30], [20].

These shifting climatic conditions are forcing farmers to adapt their practices to maintain productivity. Traditional cocoa farms are facing higher

incidences of pests and diseases, requiring increased pesticide use. The sector is heavily reliant on rain-fed agriculture, making it particularly vulnerable to climate variability: rising temperatures and water scarcity are increasing the need for irrigation.

3. Southeast Asia: Indonesia
Indonesia, a major cocoa-producing country in Southeast Asia, faces unique climate challenges due to its geographic location and complex weather patterns. The IPCC (2023) projects that the region will experience more frequent heavy rainfall events, leading to flooding and soil erosion, which can severely impact cocoa production [20], [32].

These extreme weather events have the potential to disrupt cocoa cultivation through soil erosion, nutrient loss and waterlogging. Rising temperatures and prolonged dry spells are also affecting cocoa tree health, making them more susceptible to pests and diseases [20], [32], [33].

How cocoa agroforestry systems can reduce climate-related production risks

Agroforestry systems are generally considered to be more resilient to climate variations than their conventional counterparts, as the synergetic effect of the different species increases the ecological functioning of the plantation, making the cocoa healthier and production more resilient over the long term. What's more, trees in agroforestry systems directly change the micro-climatic conditions of the plantation through shade regulation, temperature regulation and improved water cycling.

Benefits of cocoa agroforestry for micro-climate regulation

1. Shade regulation: Shade in agroforestry systems can lower temperatures for cocoa plants by up to 5 °C compared to exposed areas outside the canopy, creating higher humidity levels. This, in turn, reduces the vapour pressure deficit, which regulates transpiration. Studies suggest that agroforestry practices can decrease cocoa evapotranspiration, enabling cocoa plants to thrive even in sub-optimal climate conditions [34], [13].

Healthy cocoa flowers developing on a tree trunk.
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Below: Following a massive heatwave, fully burned cocoa blossoms.
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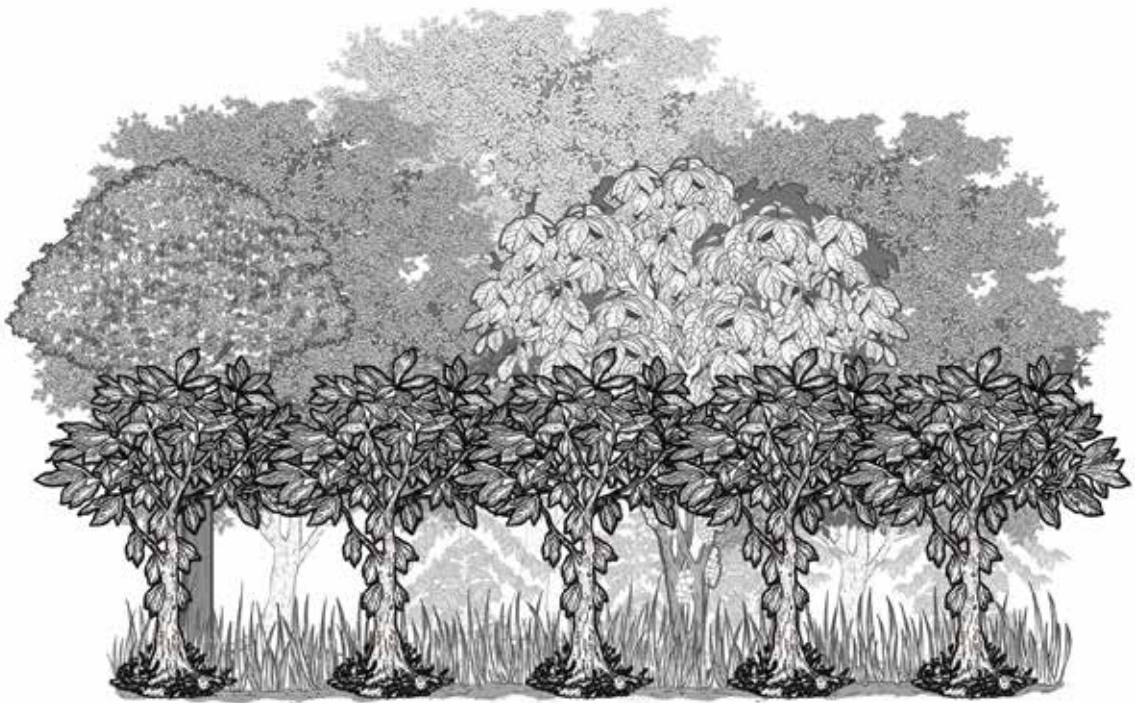
2. Microclimate regulation: Tree canopies in agroforestry systems help to create a more stable microclimate by reducing temperature extremes and protecting cocoa plants from direct sunlight and heavy rainfall.

3. Water circulation: Agroforestry systems are circular agricultural systems that mimic the natural water flows of forest ecosystems. Trees pull up water from soil layers that the cocoa cannot reach, and some of this water is then released into the air through transpiration, keeping the cocoa layer more moist and humid than in a full-sun system [8].

However, to leverage the physiological and ecological processes to ensure that cocoa grown in agroforestry systems can exhibit greater resistance and resilience to climate variability, the right species and management practices for the system have to be selected. Shade levels have to be carefully planned, monitored and managed over the lifetime of a shade cocoa system: inappropriate shade levels have dramatic effects. Under-shaded trees will show stunting, signs of water stress, scalded leaves and stems, flower cushions damaged by scalding, fewer leaves and low yield. Over-shaded trees will also show stunted growth, together with elongated stems and leaves, low flowering rates, fewer pods, higher incidence of disease (including Phytophthora, cherelle rot, pod rot and swollen shoot virus), and higher incidence of pests such as pod borers [8].

Optimising the design of cocoa agroforestry systems to maximise the synergy between the components is a skill that requires training and a detailed knowledge of the physiology and phenology of each species – that is, about the timing of leaf loss, production of new leaves and shoots, flowering and fruiting [35], [8].

Multistrata systems, such as shaded cocoa, take advantage of species' differing needs for water, light and nutrients; they



Modelling agroforestry system with cocoa

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are also the most complex of all kinds of agroforestry. They must be designed so that the components work together in a complementary way, which is referred to as 'synergy'. To achieve synergy, trees, crops and sometimes livestock are arranged to make the best use of nutrients, water and energy (light) within systems, while managing competition for these resources. Full synergy is achieved when the productivity of an agroforestry system is greater than it would be if the components were established in separate monocultures.

Multistrata agroforestry systems are 'greater than the sum of their parts'. Competition is controlled by carefully selecting species that support each other. For example, in cocoa agroforestry, cocoa is grown as an understorey of the canopy and emergent layers. In a well-managed system, ground-cover crops such as forage legumes and grasses can also be grown beneath the cocoa. The layers optimize the use of light, water, nutrients and space. The emergent and canopy layers maximize light utilisation and provide shade to the cocoa trees, which absorb both direct and diffused light. Below ground, the range in root depth allows the system to exploit more water and nutrients, and protects the soil against erosion and landslides. Deep-rooted trees bring up nutrients such as nitrate, phosphate and organic acids from deep in the soil, and make these available to shallow-rooted trees, including cocoa, through their litter. Self-shading in cocoa trees occurs when upper leaves and neighbouring trees shade lower leaves, impacting the need for additional shade. Factors such as plant age, pruning intensity, grafting and spacing influence self-shading levels. Higher self-shading reduces the need for overstorey shade but limits additional produce and services in the cocoa plot [8].

Agroforestry systems not only regulate microclimatic conditions but also mitigate climate-related production risks by cultivating more than one cash crop on the

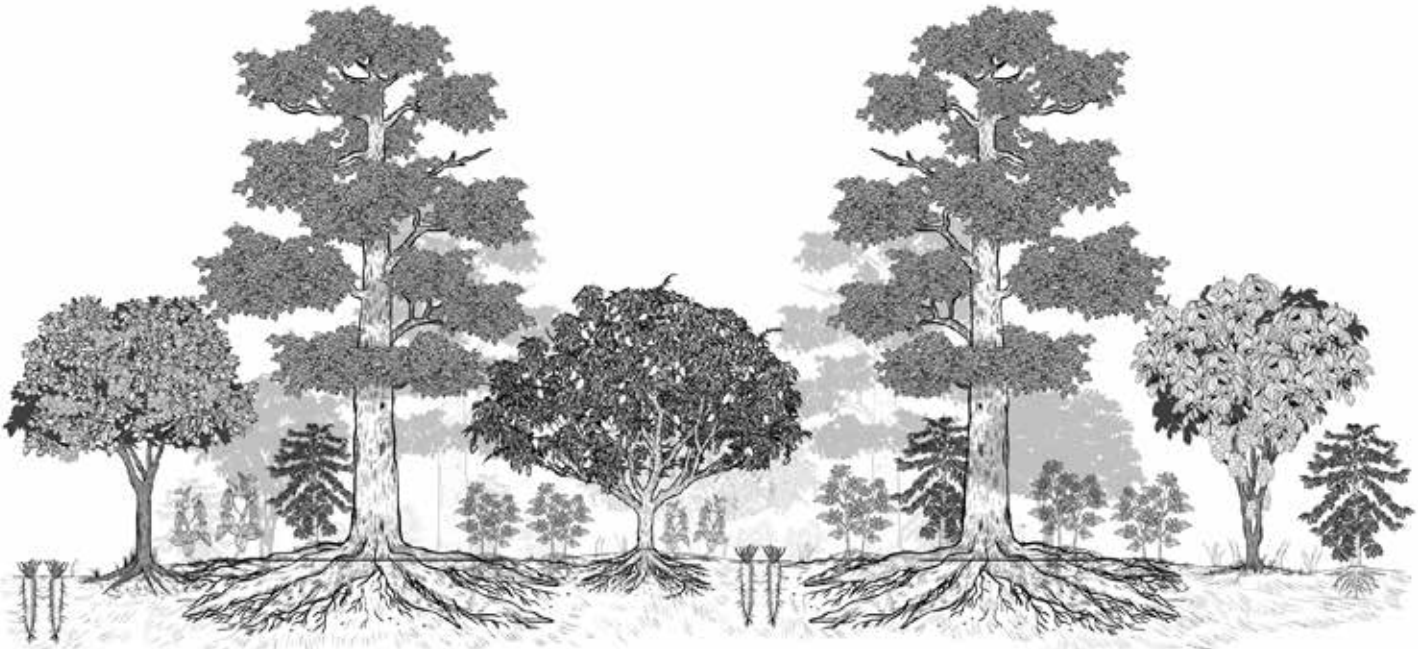

Illustration of multistrata systems

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same farm. An example is the cocoa-oil palm agroforestry systems in Brazil, which were co-designed by a consortium of research organisations, a global cosmetics group and local farmers. In these systems, palm oil and cocoa trees are intercropped, with the palm oil trees serving as the upper shade layer for the cocoa plants. The management of the individual cash crops can be adjusted to favour the production of one commodity over the other, depending on market prices.

Data and scientific information in the public domain on cocoa agroforestry systems

In arguing for the need to establish a selection programme for cocoa genotypes within the framework of agroforestry management [9], the authors point out the lack of agronomic performance data on cocoa varieties under shade, since a large

share of the existing information on yield, pest and disease resistance, and fertiliser response derives from cocoa genetic trials conducted in full sun.. To assess if the situation has changed, we conducted a literature review using two search strings on the Web of Science. The first string used was TS = (("cacao" OR "Theobroma cacao") AND ("agricultural management" OR "genotype" OR "planting distance" OR "fertilization" OR "yield") AND ("full sun" OR "shaded" OR "shade management")), the second TS = (("cocoa" OR "cacao" OR "Theobroma cacao") AND ("agronom*") AND ("agricultural management" OR "genotype" OR "planting distance" OR "fertilization" OR "fertilisation" OR "yield" OR "full sun" OR "shad*" OR "shade management" OR "agrofor*")).

The initial string yielded 52 papers on the Web of Science, of which 44 contained relevant agronomic data. The second string resulted in 90 papers, with 56 having pertinent agronomic data. The scientific literature can be divided into two broad categories: breeding and genetic improvement (38 per cent) and agroforestry (47 per cent). Research that focuses on the interaction of both, i.e. the effects of shade on performance traits of different cocoa genotypes, is very rare [34], [36]. Often these studies are field trials, with data being very specific to the specific field conditions. In our sample only 22 papers included agronomic data on shaded cocoa at landscape and agroecological system levels (Table 2). Existing research primarily investigates

Agronomic data on cocoa production in the public domain

	Farm/soil level	Agroecological system	Country
Fertiliser	6% References A	3% References B	Costa Rica, Malaysia, Ghana, Côte d'Ivoire, Global, Latin America and the Caribbean
Genotype	20% References C	18% References D	Costa Rica, Indonesia, Brazil, Ghana, Bolivia, Colombia, Côte d'Ivoire, Global, Trinidad and Tobago, Ecuador
Planting distance	6% References E	3% References F	Costa Rica, Bolivia, Cameroon, Ghana, Latin America and the Caribbean
Shade cover	34% References G	13% References H	Peru, Indonesia, Mexico, Brazil, Ghana, Nigeria, Ecuador, Cameroon, Honduras, Costa Rica, Colombia, Bolivia, Latin America and the Caribbean, Argentina, Guinea, Mexico, Togo
Shaded tree species	16% References I	7% References J	Costa Rica, Indonesia, Malaysia, Bolivia, Ghana, Cameroon, Honduras, Colombia, Latin America and the Caribbean, Peru, Argentina, Guinea

= 0 to 10% of the reviewed papers; = 10 to 30% of the reviewed papers;
= > 30% of the reviewed papers

Table 2: Agronomic data on cocoa production in the public domain – by topic, scale and country.

planting methods based on local conditions and ecological benefits of sun- vs. shade-grown cocoa, highlighting the lack of systematic agronomic data on shaded cocoa systems. Daymond et al. (2022) [20] underscore the limited understanding of successful cocoa farming models as a barrier to adopting innovative practices, and emphasize the diverse range of agroforestry practices in current literature.

> **A limited understanding of successful cocoa farming models is a barrier to adopting innovative practices.**

In Table 2 below, we share the results of our literature review in terms of topics covered (fertiliser, genotype, planting distance, shade cover and shaded tree species), scale of investigation (farm/soil level or agroecological system-wide), and country of research.

The need for investments towards a new golden standard

Climate change is leading to variation in rainfall and temperature patterns in all major cocoa growing regions, with profound effects on cocoa yields.

The benefits of integrating trees within cocoa fields, plantations and landscapes are widely understood, both in terms of environmental and social benefits. Agroforestry is recommended as one of the regenerative practices by the Science Based Targets initiative (SBTi) and included in their guidelines for land-inten-

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sive sectors to transform to a low-carbon economy through setting science-based targets [37]. All major certification standards have recommendations for integrating trees, and over the last 10 years the industry has embraced trees in its plantations and invested significantly in working with producers to see a higher uptake of agroforestry within its value chains.

However, there is surprisingly little accessible research in the public domain focusing on new agronomic technology packages to adjust cocoa production to contemporary climatic conditions. Systematic studies that evaluate the combinations of cocoa varieties with shade trees under changing temperature and rainfall conditions at landscape scale are almost absent. At the same time, it is very well understood by agroforestry practitioners and researchers that the full benefits of growing cocoa with trees can only be achieved if the right tree species are planted with the right cocoa varieties, and shade is properly managed.

Overall, there is a clear mismatch between the demand and need for innovative, climate-resilient cocoa systems, including agroforestry, and the current research priorities of public research institutions.

Given the importance of cocoa, as a global traded commodity and – especially – for millions of people's economic prosperity in both producing and processing countries, a Green Revolution approach is now needed for cocoa agroforestry systems. Public-private partnerships will be crucial, with governments and development banks funding research and infrastructure, such as investments into seed and seedling systems for shade trees, while producer companies invest in long-term trials to select the best varieties for different shade regimes under future climate scenarios.

It will take a concerted effort from all actors to fill the current knowledge gap and allow for the emergence of a cocoa "gold standard" – a benchmark for excellence that the industry can use to ensure the highest levels of quality, sustainability and compliance, supported by scientific and evidence-based criteria that are translated into transparent and measurable performance indicators. Only if we are able to close the current knowledge gap can we move from planting trees for compliance towards planting them to effectively mitigate production risks and increase profitability.

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There is a clear mismatch between the demand and requirement for innovative, climate resilient cocoa systems

In essence, the technical parameters for optimal cocoa agroforestry are still missing – but with a converted effort, a new "gold standard" can be established to fill this gap.

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Agronomic data on cocoa production in the public domain

(All literature study web sources last accessed on June 25, 2025)

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