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Simulating cocoa production: A review of modelling approaches and gaps



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HIGHLIGHTS

GRAPHICAL ABSTRACT

- Cocoa modelling can aid improving cocoa production but it has received little attention.
- We reviewed existing cocoa models and highlighted the main knowledge gaps in cocoa modelling.
- Substantial gaps remain in the representation of cocoa physiological processes, 3D structure and decision support systems.
- Data availability is the main bottleneck for future model development.
- A coordinated effort of the cocoa research community is needed to close those knowledge gaps.

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ABSTRACT

CONTEXT: Cocoa is an important commodity crop and source of income for millions of small-holder farmers. Nonetheless, questions on cocoa tree functioning, best management practices and climate change responses remain. Modelling is a powerful tool to address these questions, complementing experimental work that is expensive and time consuming due to the long productive cycle of the cocoa system. However, compared to other crops, cocoa modelling has not received as much attention. OBJECTIVE: We reviewed existing cocoa models and identified the main gaps in the literature and possible strategies to advance models of cocoa production.

METHODS: We first classified relevant research questions in cocoa production along three main axes (fundamental-applied, spatial organization, prediction horizon) and aligned modelling approaches along these. We then reviewed six published cocoa models using these axes as framework. This comparison revealed several modelling gaps for which we provide an overview of data availability for future model development.

RESULTS: (i) Several plant processes (i.e., water stress responses, respiration, climate change responses, nutrient effects and phenology) are either missing from existing cocoa models or are simulated based on general plant physiological knowledge rather than cocoa-specific knowledge. (ii) The only currently existing 3D model of cocoa architecture has very limited scope and does not include physiological processes. (iii) There are no model-based decision support tools available for supporting the main management practices such as irrigation, fertilization and pruning. (iv) Data for model calibration and validation are often scarce.

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Review

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CONCLUSIONS: We conclude that data availability for model design, calibration and validation is currently the main bottleneck for further development of cocoa models. Extensive cooperation within the cocoa research community and a large network of long-term experiments under different climatic and management conditions are required to close the identified modelling gaps.

1. Introduction

Cocoa (*Theobroma cacao* L.) is one of the most important agricultural commodity crops globally, produced by five to six million mostly smallscale farmers (World Cocoa Foundation, 2014), contributing to the livelihood of millions. In 2018-2019 global production was approximately 4.8 million tons (ICCO, 2021) most of which is produced in the humid tropics across West and Central Africa, Latin America and South East Asia (ICCO, 2021) in a variety of cropping systems that range from monocultural systems to highly diverse agroforestry systems.

Increases in cocoa production over the past decades were mostly driven by expansion of cropped land, often at the expense of natural ecosystems and other crops (Ajagun et al., 2022), rather than increases in yield per unit land area (van Vliet and Giller, 2017). Cocoa cultivation is predominantly extensive and rainfed (Lahive et al., 2019) with average yields per hectare around 440–550 kg ha⁻¹ of fermented dry beans across production regions (FAOSTAT, 2021). However, highyielding farms in Ghana for example, may achieve yields up to 2125 kg ha⁻¹ depending on climatic conditions (Abdulai et al., 2020). Reducing this yield gap could help improving the livelihoods of cocoa small-holder farmers (van Vliet et al., 2021) though the effect of increased cocoa supply on prices would need to be considered. At the same time, projected shifts in climate suitability for cocoa producing regions (Bunn et al., 2018; Läderach et al., 2013; Schroth et al., 2016), increase land use for food production and growing attention for deforestation-free certified cocoa (Cocoa and Forest linitiative, 2021) call for substantial improvement in per hectare yields.

Multiple factors contribute to high yield gaps such as erratic precipitation patterns (Abdulai et al., 2020); limited availability of improved planting material from national breeding programs (Edwin and Masters, 2005), untreated pests and diseases (Asante et al., 2022; Opoku et al., 2000), low soil fertility and fertilizer input (Ali et al., 2018), low plant density (Asante et al., 2022), inadequate shading levels (Asare et al., 2017) and plantation ageing (Lachenaud and Montagnon, 2002; Mahrizal Nalley et al., 2014). With changing climate, predicted higher maximum temperatures and reduced water availability in dry seasons are also expected to become limiting for cocoa production in West Africa (Schroth et al., 2016), and most areas will be able to sustain production only if adaptation strategies are implemented (Bunn et al., 2018).

Designing strategies to reduce the current yield gaps and designing effective adaptation strategies to sustain future production require a quantification of the relative contributions of yield-limiting factors and a solid understanding of how cocoa responds to environmental conditions and management practices.

Several steps have been taken in the quantification of the contribution of yield limiting factors, using yield gap analysis (Abdulai et al., 2020; Asante et al., 2022) and regression analysis (Asante et al., 2021). Yet, how cocoa trees respond to management practices and how best practices should be adapted to different climatic conditions and different cropping systems, remains largely unknown. For instance, cocoa nutrient requirements are still unclear and fertilizer recommendations vary greatly among producing countries (van Vliet and Giller, 2017). Reported pruning effects on cocoa yield are inconsistent and pruning recommendations are not tailored to different cocoa systems (Tosto et al., 2022).

How cocoa responds to changing climatic conditions remains uncertain. Black et al. (2020) suggested that the negative impact of higher temperature is (partly) compensated by the positive effects of higher atmospheric carbon dioxide concentration ($[CO_2]$) on photosynthesis. However, the long-term impact of elevated atmospheric $[CO_2]$ and temperature on cocoa photosynthesis, transpiration and respiration, are not well understood. Nor is much known about how assimilate allocation may change under adverse conditions and how cocoa responses to various changing environmental factors will interact (Lahive et al., 2019). Finally, the genotypic potential of cocoa adaptation to climate change conditions is still largely unexplored (Lahive et al., 2021).

Cocoa agroforestry is considered a promising adaptation strategy to changing climatic conditions and a means to reduce the negative socioenvironmental impact of cocoa production (Niether et al., 2020). However, contrasting effects of shade on cocoa yield are reported in literature (Abdulai et al., 2017; Asare et al., 2018; Asare et al., 2017) and these effects can also vary with agroclimatic conditions (Asare et al., 2017; Clough et al., 2011). Such complexities hamper the formulation of recommendations on cocoa production within agroforestry systems. For instance, recommendations on managing the shade canopy, both in terms of planting design and pruning, are lacking. Finally, it is still uncertain how cocoa viability and productivity is affected by climate extremes in agroforestry systems (Abdulai et al., 2017).

Addressing those knowledge gap in cocoa production is challenging, as cocoa is a woody perennial with a multi-decade production cycle which means experiments for agronomic improvement or breeding are slow and expensive. Addressing these gaps for cocoa agroforestry systems presents even bigger challenges, due to their structural heterogeneity and large number ecological interactions within the system. This calls for the use of cocoa simulation models to complement and inform experimental and on-farm research. Cocoa simulation models can combine agro-ecological, physiological, and farming system knowledge with experimental and observational data to estimate cocoa yields, resource-use efficiency and ecosystem services such as carbon sequestration. They can be used as a virtual breeding tool, to develop hypotheses, to predict yields under current and future climate scenarios, to investigate spatio-temporal patterns of production at landscape to global level, or as decision-support tools for advising agronomic practices and aid the design of cocoa cropping systems. Despite this potential, modelling of cocoa growth and production has received less attention than other crops, including similar tropical perennials such as coffee.

With this review we aim to: 1) explore how simulation models can aid in addressing some of the most important problems in cocoa production.2) provide an overview of the state of the art of existing cocoa models; and 3) identify the main knowledge gaps and technical bottlenecks that limit the further development of cocoa models.

The focus of the review is on abiotic stresses (present and future climate condition) and associated management practices (planting design, nutrient management, irrigation and pruning). We do not address issues related to pest and disease management, even though they play a crucial role in cocoa production (Wessel and Quist-wessel, 2015) as the topic is too broad to be included in the present review.

2. Model approaches for key questions in cocoa production

Open questions and issues in the cocoa sectors can be classified along various dimensional axes: (i) a "fundamental vs applied" axis that goes from more fundamental questions of cocoa tree functioning to problems connected to cocoa field management and investment choices; (ii) a spatial scale axis, that refers to the level at which a problem needs to be analyzed and that goes from single trees to regional/global level; and (iii) a prediction horizon axis, that takes into consideration the temporal scale at which predictions need to be made, from daily predictions to predictions encompassing the whole life cycle of a plantation, or even multiple generations, as in breeding programs or studies on climate-change effects (Fig. 1).

Along these axes, the best suited modelling approach to address a given problem will change with the level of detail, complexity, biological understanding and predictive power that the problem requires, and it can include both explanatory and descriptive components (see Box 1), depending on the model purpose and available knowledge (Fig. 2). In this section we link these axis to the suggested model approaches expanding on Jones et al. (2016) to include organ-level and plant models (Louarn and Song, 2020; Medlyn, 2004) in order to set the criteria to evaluate the existing cocoa models, for which the description is given in Section 3.

2.1. The fundamental vs applied axis

Fundamental questions (Fig. 1), are related to underlying processes driving cocoa phenology or responses of cocoa trees to management or climate. Addressing these questions requires an explanatory modelling approach, with an emphasis on the interpretability and understanding of the relevant physiological mechanisms.

More applied problems regarding strategic decisions on investments or management options, spanning from the application of pruning, fertilizer use and irrigation to system design, require the development of decision support systems (DSS). Large networks of experiments are needed to build robust empirical relations that describe crop responses to management practices. Alternatively, simplified expressions can be derived using metamodels of well-validated explanatory models.

2.2. The spatial scale axis

At the lower end of the spatial scale axis (Fig. 1) are questions related to environmental conditions and resource availability that are heterogeneously distributed within plants and their environment. To simulate environmental heterogeneity, a 3D modelling approach of organs or plants is needed. Functional-structural plant (FSP) modelling can be used to address problems that require an explicit representation of tree structure at organ level and an accurate representation of the environment within the canopy (Vos et al., 2010) as is the case for questions related to microclimate or pruning. Those models though also require detailed architectural data that are time consuming to obtain and generally scarce (Louarn and Song, 2020).

When detailed architectural data is not available, simpler plant-level models may be more useful to address questions such as the interaction between shade and cocoa trees in agroforestry systems. However, modelling heterogeneous light availability for understory crops is challenging and typically leads to overestimating photosynthesis (Rosati et al., 2020). Furthermore, for both organ and plant level models, improper scaling of photosynthesis from the leaf to canopy level and improper diurnal integration, can lead to an overestimation of carbon assimilation and light-use efficiency, due to the non-linear relationship between photosynthesis and environmental factors.

If horizontal uniformity of key resources such as light, water, or nutrient availability, can be assumed at the stand level and the dynamic structure of the stand can be described in simple terms, 1D classical crop growth models that focus on physiological processes could be used. When linked to spatial climate and soil data, such crop models can be employed to generate regional or national yield maps under present and future climate scenarios serving as a starting point for yield gap analysis (van Ittersum et al., 2013) and to inform decisions on investment and adaptation strategies to climate change.

2.3. The prediction horizon axis

At the lower end of the prediction horizontal axis in Fig. 1, management decisions taken at daily or seasonal time scales (e.g., irrigation, fertilization) are included. To support such decisions a DSS able to capture the intra-annual pattern of growth and production should be used. On the contrary, problems that require predictions at a coarser temporal scale such as yield responses to climate change scenarios in near and far future require less accurate short-term predictions and



Fig. 1. Main questions in cocoa production along the fundamental vs applied axes and the spatial scale axis. Classification along the prediction horizon axis is color coded.

Box 1

a glossary of modelling approaches.

Explanatory (sub)models: An output of the model is calculated as a function of underlying processes, such that it becomes an emerging pattern of the simulation (van Ittersum et al., 2003). These models allow making predictions across a wide range of conditions, as long as they include the causal links between the different processes and the environment (Yin and van Laar, 2005).

Descriptive or empirical (sub)models: An output of the model is described as a function of environment and crop traits by data-driven functions or metamodels (van Ittersum et al., 2003). Their applicability is limited to the set of conditions used to calibrate the model given the lack of causal relationships (Jones et al., 2016).

Interpretability: Interpretability of a model output refers to the extent that models can be understood and their output explained. Parameter interpretability refers to the extent to which a parameter has a clear meaning in a certain domain (e.g., biology, physics, etc.).

Decision support system (DSS): A model of the system built with the purpose of supporting decision making at the tactical and strategic level by the different stakeholders. The model should include the outputs and management practices of interest and have well-calibrated predictions at a local level (Jones et al., 2016). Optimal decision making also requires the DSS to provide uncertainty of predictions (Keith and Ahner, 2021). The development of DSSs should be driven by user needs and the interface design should be user friendly (Antle et al., 2017).

Metamodels: Data-driven approximations to explanatory models consisting of multiple regressions or other algorithms linking input variables (e.g., climate) to model output.

Models can be classified in terms of the level at which a system is represented:

Organ-level models: Models that simulate plant structure at a sub-plant level (i.e., organ, axis, growth unit) specifying how different organs are positioned and oriented in space (plant architecture), how they are connected (topology), and, when included, how their emergence and expansion is coordinated over time (development). This is typically done in functional-structural plant (FSP) models. Thus, processes at the plant and plot levels are emergent properties of the interactions among individual sub-plant level entities (Louarn and Song, 2020).

Plant-level models: Individual plants are simulated explicitly and represented by coarse geometries such as simplified crown shapes (e.g., ellipsoids, cones) or collections of voxels (le Roux et al., 2001). Within each crown, profiles of leaf area density, nitrogen concentration and leaf orientation are used to describe vertical pattern of within crown variability. Processes at the plot level are emergent properties of the interactions among individual plants.

Crop-stand level models: These models do not represent individual plants or organs and most processes are either described at the stand level, or they are scaled from the organ to the stand-level using profiles and simplifying assumptions about structure (van Ittersum et al., 2003). These models are also known as process-based models or crop models and for simplicity we use the latter term hereafter.



Fig. 2. Visualization of how existing cocoa models can be placed within the axes frameworks. Relevant example for other systems are given. The left vertical axes refer to the level at which the models make predictions, which coincides with the level at which questions can be addressed with those models. The right vertical axis refers instead to the level at which processes are described within the models. The prediction horizon axis is not added as model outcomes can be relevant at various time scale.

Agricultural Systems 206 (2023) 103614

allow for a higher level of abstraction. At the upper end of the prediction horizon axis, are decisions that need to be made during the establishment phase of a cocoa field (e.g., planting density and design, formation pruning). To assess the impact of those early decisions, it is necessary to simulate the system over multiple years. However, most models of perennial systems do not simulate early phases of tree development since it is difficult to accurately capture the rapid changes in tree characteristics that occur during the juvenile stage.

3. An overview of existing cocoa models

In this section we present the existing models of cocoa systems that comply with our selection criteria as described below, highlighting which questions those models can address and their main limitations. An overview is given in.

Table 1. We gathered published cocoa models in the Web of Science by searching with the keyword combination ((cacao OR cocoa OR Theobroma) AND model*). Where the asterisk (*) extends the search to words derived from "model" (e.g. models or modelling). We then

Table 1

Overview of existing cocoa models.

selected only models that focus on cocoa structure, biomass production and yield, thus excluding models that focus on ecosystem services (for example Middendorp et al., 2018). We also only focused on abiotic environmental factors such as climate, water and nutrients, while models focusing on the effects of pests and diseases were not taken into account. Finally, we did not take models into consideration that simulate only part of the crop (e.g., pod development models, ten Hoopen et al., 2012), and prediction models mostly used for economic analyses based on time series of national or regional average yield (Ajetomobi and Olaleye, 2019) that do not include any underlying biological processes.

3.1. A rubber-cocoa bioeconomic model

A first attempt to model a cocoa system was published by Wojtkowski et al. (1991) who developed a DSS for a rubber-cocoa intercropping system to support management decisions (planting density, thinning and fertilization) for a mature system (no early development), that would result in the highest profitability over the production cycle. Yield is estimated empirically as a function of shade, tree age, planting

	Model description	Output type	Spatial scale	Time scale	Main applications and limitations	Reference
Cocoa-rubber agroforestry system	Descriptive bioeconomic model of cocoa and rubber production, based on empirical equations that relate cocoa (and rubber) yield to fertilizer input and tree age.	Attainable yield /profit	Crop level	Annual	Applications: assess fertilizer application and thinning impact on system profitability. Limitations: rubber-cocca system only, application to other locations require full recalibration. Applications: Explore design of agroforestry	Wojtkowski et al. (1991)
WaNuLCAS	Stand-level model of tree-soil–crop interactions. It uses a radiation use efficiency approach and requires input from specific crop models. It allows for water, nitrogen and potassium stress simulation.	Attainable yield	Crop level	Daily	systems, investigate role of (belowground) interactions, estimate yield (for calibrated crops and trees). Limitation: Not fully calibrated for cocoa, so not suitable for quantitative estimation. Some parameters are difficult to estimate (RUE, lag time of recovery after disturbances).	Khasanah et al. (2020); van Noordwijk et al. (2011)
Coconut-cocoa agroforestry mock up	3D static model of a coconut-cocoa agroforestry system. It estimates light interception by the coconut and cocoa canopy.	Light interception	Organ level	Hourly	Applications: explore planting designs of coconut-cocoa agroforestry systems, assess the role of architectural traits in light interception. Limitations: cocoa juvenile stage only, does not simulate any physiological processes, representation of shade layer too complex to be adapted to multispecies systems. Applications: drivers of cocoa yield and	Mialet-Serra et al. (2001)
CASE2	Process-based crop model that simulates cocoa yield responses to climatic factors (temperature, rainfall, radiation) assuming a homogeneous shade canopy.	Potential and water limited yield	Plot level	Daily	reparticular infector of concernment relative importance, compute potential and water-limited yields for different environments, effect of shade on cocoa production. Limitations: nutrient dynamics not included, homogeneous shade and cocoa canopy, some processes are based on general physiological knowledge and are not cocoa specific.	Zuidema et al. (2005)
DDE-Cocoa	Delayed Differential Equation model of cocoa yield, modelling cocoa flowering in relation to rainfall only and pod production as a constant fraction of flowering. Preliminary study.	Attainable yield	Crop level	Daily	Applications: provide insights into annual and inter-annual yield in relation to precipitation. Limitations: Precipitation is the only driver considered. Expansion of the model may be hampered by the difficulty of estimating flower production. Data demanding. Applications: investigated the potential	Wilson et al. (2019)
JULES (adapted for cocoa)	Process-based land-surface vegetation model calibrated to simulate instantaneous cocoa responses to high CO ₂	Water limited Net primary productivity	Landscape level	30 min	effects of climate change on cocoa primary productivity. Limitations: various assumptions on cocoa responses to climate change (no acclimation, same response in field conditions as in greenhouse), no yield simulation.	Black et al. (2020)

density and fertilizer availability, with calibration based on literature and expert knowledge. Due to its empirical nature, this model would need to be calibrated for each fertilizer and soil type, and for different water availability (Meyer et al., 2020) and varieties (Edwin and Masters, 2005).

3.2. WaNuLCAS

WaNuLCAS is a generic stand-level model of tree-soil–crop interactions that allows for the simulation of multiple species of trees and annual crops in a range of spatial configurations (van Noordwijk et al., 2011; van Noordwijk and Lusiana, 1999). The model includes the effects of water and nitrogen availability, via the application of stress factors on potential daily growth. Management options such as tree pruning can also be simulated. Several model parameters, such as radiation- and water-use efficiency and lag time of recovery after disturbances are difficult to estimate for tree species.

The model focuses mostly on below-ground interactions so it is less suitable to address detailed questions regarding light interception or canopy microclimate. WaNuLCAS has been applied to simulate an oil palm-cocoa-black pepper agroforestry system (Khasanah et al., 2020) but it focused on oil palm yield and cocoa trees were simulated using the generic routines for trees with minimal calibration. Using WaNuLCAS with cocoa as target species would therefore require further model development and calibration.

3.3. A 3D model of a coconut-cocoa agroforestry system

Mialet-Serra et al. (2001) developed an organ-level model of a coconut-cocoa agroforestry system with an emphasis on light distribution within the canopy. The individual trees are described based on detailed architectural descriptions of coconut and cocoa plants following the AMAP approach (de Reffye et al., 1995). The use of this model is limited by the fact that it only applies to juvenile cocoa trees, it does not include any physiological processes and it does not simulate growth. Also, as highlighted in Section 2.2, a plant-level model may be preferred if the intention is to simulate other shade tree species than coconut due to the general lack of detailed architectural data for tree species.

3.4. CASE2: A crop model for cocoa production

Zuidema et al. (2005) developed CASE2, a crop model based on the SUCROS2 model (Laar et al., 1997). It simulates cocoa growth and yield from processes including light interception, evapotranspiration, water uptake, photosynthesis, respiration and allocation of assimilates, and it captures the effect of climatic conditions such as solar radiation, temperature, humidity and precipitation. A shade canopy layer can be simulated which competes with the cocoa canopy for light but not for below-ground resources nor does it influence microclimate conditions. The study by Zuidema et al. (2005) provides examples of model applications to address questions related to drivers of cocoa yield and their relative importance, to compute potential and water-limited potential yields for different pedo-climatic conditions and to investigate the effect of shade on cocoa production.

The model has several limitations: (1) nutrient dynamics and effects on yield are not included; (2) the assumption of a uniform canopy prevents its application to juvenile stages as well as sparse or heterogeneous shade canopies of present in e.g. agroforestry systems; (3) some physiological processes are not based on cocoa-specific knowledge (see Section 4.1.1). The model has been applied to estimate potential and waterlimited yields in Malaysia (Zabawi and Gerritsma, 2009) and Ghana (Asante et al., 2022) and to estimate yield responses to shade (Clough et al., 2011). It has been widely cited in cocoa literature as it provides the only available general estimate of potential yield for cocoa and broad indications of cocoa yield drivers.

3.5. A delayed differential equation model of cocoa production

Wilson et al. (2019) developed a Delayed Differential Equation model (DDE) of cocoa production, linking flowering to interannual precipitation patterns and predicting pod production based on a fixed fruit-to-flower ratio, though this assumption may be too simplistic (see Section 4.1.4). The model is presented as a preliminary study providing a simple approach that could be expanded to add other environmental factors and management practices. The aim was to develop a tool that generates accurate inter-annual yield predictions and provides improved insights for on-farm management effects on annual yields.

3.6. Simulation of climate change on cocoa net primary productivity

Black et al. (2020) investigated the potential effects of climate change on cocoa primary productivity (but not yield) in West Africa, using a process-based land-surface model (JULES) driven by a climate model. The model was calibrated with leaf-level photosynthesis measurements on young cocoa plants in a greenhouse experiment emulating climate change conditions, whereas other processes relied on generic values from tropical broadleaf plants (Harper et al., 2016).

4. Gaps in cocoa modelling

Knowledge gaps in modelling cocoa systems are identified by comparing current published cocoa models (Section 3) against the framework of modelling concepts presented in Section 2. Gaps are presented according to whether they relate to physiological processes (Section 4.1), tree and stand structural characteristics (Section 4.2) or management (Section 4.3). When available, relevant modelling examples from similar systems such as coffee or mango that could potentially be adapted to cocoa are presented. We also provide indications of the availability of data for model development and calibration. A summary of our findings is presented in.

Table 2.

4.1. Gaps in modelling physiological processes

In this section we present the main gaps in how physiological processes are represented in current cocoa models, with emphasis on water relations, maintenance respiration, and climate change responses. Capturing the response of these physiological processes to the abiotic environment is needed e.g., to understand the main drivers of cocoa production, perform yield gap analyses and to address questions regarding future production of cocoa under changing climatic conditions. We also discuss how the effect of nutrients on cocoa physiology could be incorporated, as well as phenological processes such as flushing, flowering and pod abortion.

4.1.1. The effects of water stress

Water availability has been shown to be an important driver of cocoa yield (Abdulai et al., 2020) and severity of water deficit stress may increase with climate change (Läderach et al., 2013). Thus, to predict cocoa yields under current and future climate (Fig. 1), there is a need to accurately capture the physiological effects of water availability in cocoa models. Currently, in CASE2 water availability influences photosynthesis, assimilate allocation, and leaf senescence while in the JULES model water availability has an influence on photosynthesis only. In both models, net daily assimilation is multiplied by a water stress factor that depends on soil water content.

To capture the response of cocoa to simultaneous changes in temperature, evaporative demand and precipitation, a model should couple photosynthesis and stomatal conductance. In JULES, photosynthesis is coupled to a VPD-sensitive stomatal conductance model, but no coupling exists in CASE2. However, other factors are also known to influence stomatal conductance, such as radiation and CO₂ concentration

Table 2

Overview of main gaps in modelling cocoa. Details of how gaps were identified and how they relate to questions in cocoa production are given in sections 4.1, 4.2 and 4.3.

Gaps	Possible modelling approaches	Data required	Data availability for cocoa					
Sups	Dhusialasi	ol measure (Costion 4.1)						
Physiological processes (Section 4.1)								
Coupling of photosynthesis with stomatal conductance is missing in most models	Soil-plant atmosphere continuum models (Tuzet et al., 2003)	Stomatal conductance- photosynthesis relation	Acheampong et al. (2015, 2013); Araque et al. (2012); Ávila-Lovera et al. (2021, 2016); Baligar et al. (2008); Rada et al. (2005); Salazar et al. (2018); Suárez et al. (2021b): Tezara et al. (2020)					
		Leaf water potential-soil water potential	Jiménez-Pérez et al. (2019)					
Assimilate allocation in response to water stress missing or based on generic knowledge	Empirical allocation rules	Organ biomass under different stress levels	Moser et al. (2010); Schwendenmann et al. (2010)					
0 0	Allometric relation approach	Destructive measurement of	Borden et al. (2019) and ref. within					
	Functional equilibrium approach (Yin and van Laar, 2005)	organ biomass Cocoa-specific data not needed						
Leaf lifespan reduction under water stress based on hypothetical relation	Empirical function	Leaf lifespan under different water stress level	-					
		Litterfall dynamics	Mohammed et al. (2015); Moser et al. (2010); Schwendenmann et al. (2010)					
atmospheric [CO ₂] and high temperature		FACE and FACE-T experiments	-					
Acclimation of respiration to higher temperature not included	Modification to respiration- temperature response curve (Slot and Kitajima, 2015)	Temperature acclimation experimental data	-					
Nutrient responses are absent (CASE2 and JULES), too generic (WaNuLCAS), or too limited in scope (Wojtkowski et al., 1991)	Empirical nutrient availability- yield response curves-QUEFTS (Sattari et al., 2014)	Network of experiments with different levels of nutrient applications	van Vliet and Giller (2017b) and refs within, Cocoa soil project (CocoaSoils Workplan and Annual Report, 2019)					
	Application of stress factor to RUE, allocation, etc. LINTUL type models (Adiele et al., 2022) - CAF002 (van Oijen et al., 2010a) Mechanistic approach of nitrogen	nutrient-RUE responses, nutrient- allocation responses, etc. Nitrogen effect on several	On seedlings only: Acheampong et al. (2015); Anokye et al. (2021); Baligar and Fageria (2017); Costa et al. (2001); Djan et al. (2017); Ribeiro et al. (2008); Souza Júnior and					
	dynamics GECROS (Yin and van Laar, 2005)	plant processes	Carmello (2009)					
Leaf flushing is missing	drivers Leaf cycle linked to reserves (Taylor,	flushing cycle relation Reserve accumulation-	(1950); Sale (1968) Machado and Hardwick (1988); Taylor (1988)					
Flowering mostly not included	1988)	Data on fruit: flower ratio Pod abortion dynamics in	-					
Pod abortion dynamics are not simulated		relation to plant assimilate status	Valle et al. (1990); Waldburger et al. (2019)					
Structural characteristic (Section 4.2)								
A static FSP model for adult cocoa tree is missing	Static FSP models - VPalm (Perez et al., 2018)	Architectural measurement Terrestrial lidar scanning	-					
A dynamic FSP model of cocoa tree is missing	Dynamic FSP models - VMango (Boudon et al., 2020)	Time series of organ appearance and development	-					
Plant-level model of cocoa stand is missing	3D plant-level models - Coffee MAESTRA/MAESPA (Charbonnier et al., 2013; Vezy et al., 2018)	Measurement of stand LAI and canopy geometry	Daymond et al. (2002); Leiva-Rojas et al. (2019); Miyaji et al. (1997b); Moser et al. (2010)					
		Light availability under the canopy	Miyaji et al. (1997b); Tosto et al. (2022)					
		Microclimate	Abdulai et al. (2017); Acheampong et al. (2015); Jiménez-Pérez et al. (2019); Köhler et al. (2014); Suárez et al. (2021a)					
		Eddy covariance	Falk et al. (2005).					
Management practices (Section 4.3)								
A decision support system for cocoa that can simulate irrigation and fertilization practices is missing	Radiation use efficiency type crop- model	Direct and indirect measurement of radiation use efficiency, allometric relation	Borden et al. (2019) and ref. within; Regazzoni et al. (2015)					
	(drip irrigation- (Bonachela et al., 2001)	Cocoa specific data not needed						
	Irrigation/water availability effect on RUE	Water availability – RUE responses	On seedling only: Acheampong et al. (2019); da Silva Almeida et al. (2012); Posse et al. (2020)					

(continued on next page)

Table 2 (continued)

Gaps Poss	sible modelling approaches	Data required	Data availability for cocoa
Simu dyna 1998	ulation nutrient soil pools and amics – DAYCENT (Parton et al., 8)	Cocoa-specific data not needed	
A decision support system that can simulate pruning practices is missing Dyna	cic FSP models – QualiTree (courret et al., 2011) namic FSP models	Branching patterns Pruning responses (branching, leaf production)	-

(Hikosaka et al., 2016). Soil-plant-atmosphere continuum (SPAC) models integrate all of these factors and use the concept of leaf water potential to also couple water supply from roots to leaves with evaporative demand (Tuzet et al., 2003).

Developing a SPAC model for cocoa requires information on the relation between photosynthesis and stomatal conductance under a wide range of environmental conditions, as well as information on the relation between soil and leaf water potentials. Relationships between photosynthesis and stomatal conductance have been investigated under field and greenhouse conditions under different water availability levels (Araque et al., 2012; Ávila-Lovera et al., 2016; Rada et al., 2005; Tezara et al., 2020), shade levels (Ávila-Lovera et al., 2012; Salazar et al., 2018; Suárez et al., 2021b), a combination of the two (Acheampong et al., 2015; Acheampong et al., 2013) and in response to air evaporative demand (Baligar et al., 2008; Della Sala et al., 2021), while the relation between leaf and soil water potential has received substantially less attention (Jiménez-Pérez et al., 2019).

Water availability may also affect allocation of assimilates. This is captured only by CASE2 that increases allocation to fine roots as water availability decreases, though using a generic relation. In general, the mechanisms behind assimilate partitioning to various organs are poorly understood, preventing the development of explanatory models for these processes (Poorter et al., 2012). Empirical rules may be used, but this requires quantifying the dynamics of assimilate allocation under stress, yet relevant studies are rare for cocoa (Moser et al., 2010; Schwendenmann et al., 2010). Measuring root turnover in response to water limitation could also provide insights on changes in allocation to the root system, but dedicated studies in cocoa systems are lacking. Alternatively, some models (e.g., GECROS, Yin and van Laar, 2005), currently mainly used for annual crops, have successfully made use of the functional- equilibrium theory, stating that plants tune the relative allocation to root and shoot to maximize relative carbon gain and these models therefore do not require species-specific calibration (Charlesedwards, 1976; Yin and van Laar, 2005).

Finally, CASE2 also assumes a reduction in leaf lifespan with decreasing water availability but it relies on an untested linear relationship between the two. However, studies on the effect of water availability on leaf lifespan in cocoa are missing. This relation could potentially be derived from the analysis of litterfall dynamics in cocoa systems (Mohammed et al., 2015; Moser et al., 2010; Schwendenmann et al., 2010).

4.1.2. Climate change responses in the JULES model

Predicting future cocoa production (Fig. 1) requires a solid understanding of how cocoa physiological processes will be affected by changing climatic conditions. Cocoa responses to elevated atmospheric [CO₂] have been studied under greenhouse conditions in seedlings (Baligar et al., 2021; Black et al., 2020; Lahive et al., 2018) and juvenile plants (Lahive et al., 2021) but long-term free-air [CO₂] experiments on cocoa under field conditions are missing. Black et al. (2020) used the results from these greenhouse experiments to simulate cocoa biomass production under climate change. However, plants in free-air CO₂ enrichment (FACE) experiments have consistently shown lower photosynthetic stimulation under high CO₂ conditions than plants in greenhouse experiments (Long et al., 2006).

In the absence of long-term experiments some assumptions had to be made by Black et al. (2020). Long-term exposure to elevated [CO₂] was assumed not to result in photosynthetic down-regulation (i.e., the decline over time of the initial positive stimulation of photosynthetic activity, Dusenge et al., 2019) assuming the same response observed in coffee under a long-term FACE experiment (da Matta et al., 2019; Ghini et al., 2015). However, down-regulation of photosynthesis may increase with nutrient limitation (Dusenge et al., 2019), which is common in cocoa systems, especially in extensive small holder farms (van Vliet and Giller, 2017). More knowledge of the long-term effects of elevated [CO₂] on photosynthesis of cocoa under field conditions is thus needed.

Additionally, while many crop models, including CASE2 and JULES, assume an exponential increase in respiration with temperature, more or less doubling every 10 °C, extensive evidence shows that plants acclimate to higher temperature by downregulating respiratory processes. The degree of acclimation varies between species (Slot and Kitajima, 2015) and no information on this is currently available for cocoa.

Finally optimal temperature of photosynthesis under elevated atmospheric $[CO_2]$ was predicted to increase in the Black et al. (2020) study, partially offsetting the negative effect of projected higher temperature. This is a common property of models that make use of a Farquhar type model for photosynthesis (Collatz et al., 1991; Farquhar et al., 1980) and a response observed in many species (Dusenge et al., 2019). However, since the temperature range that cocoa can tolerate is not well known, and since it seems to vary among different genotypes (Lahive et al., 2019) the mitigating effect of increased optimal temperature may vary depending on the cocoa variety.

4.1.3. Modelling the effect of nutrient availability on cocoa functioning

The integration of nutrient responses in a cocoa model would allow to address practical questions on fertilizer requirements as well as more fundamental questions on how nutrient availability mediates the responses to other stress factors (Fig. 1). Currently, cocoa responses to nutrient availability are included in the work of Wojtkowski et al. (1991), but as previously stated, the purely empirical nature of this model limits a more general use. WaNuLCAS allows for the simulation of the effect of nitrogen availability, but the relevant equations are not calibrated for cocoa.

Modelling plant responses to nutrient availability is challenging due to the complex and simultaneous effects that nutrients have on several plant processes (Lambers et al., 2008). For this reason, crop models have relied on extensive experimental trials to determine empirical relations between nutrient availability, yield and plant functioning. The QUEFTS model, for example, simulates the simultaneous effect of the macronutrients nitrogen, phosphorus and potassium on crop yield (Sattari et al., 2014) and has been applied to assess nutrient demand for target yields of annual crops in tropical areas (e.g., Ezui et al., 2017; Shehu et al., 2019). Similar to WaNuLCAS, the CAF2007 model (van Oijen et al., 2010a) describes the effect of nitrogen limitation on coffee growth and production, using empirical relations.

The effect of nitrogen limitation on plant processes is far better understood than the effect of phosphorus and potassium and a more explanatory approach to model nitrogen-related processes is presented in the GECROS model (Yin and van Laar, 2005). However this model includes the prioritization of nitrogen partitioning toward reproductive organs, typically observed in annual crops (Sinclair and de Wit, 1975) for which GECROS was designed. This mechanism may not directly apply to shade-tolerant woody perennials, such as cocoa, that have probably been naturally selected to favour survival over reproductive effort, especially under stress conditions (Anten et al., 2003). Hence, increasing N availability may not necessarily have the same short-term stimulatory effects on yields as it does in many annual crops.

In cocoa, yield responses to fertilizer application are poorly understood and have been found to vary greatly between region, plots and even individual trees within a field (van Vliet and Giller, 2017). A promising development in this direction is the CocoaSoils project (report), a large-scale and long-term network of on-farm and on-station experiments of cocoa responses to fertilizer applications that have been set up in all major cocoa-producing regions.

Mechanisms behind cocoa responses to nutrients are also poorly understood. The effect of N availability on cocoa has been investigated in terms of growth (Souza Júnior and Carmello, 2009), relative growth rate (Baligar and Fageria, 2017), nitrogen-use efficiency (Ribeiro et al., 2008) and gas exchange (Acheampong et al., 2015; Costa et al., 2001) exclusively in potted seedling or juvenile plants. Fewer studies have investigated the effect of potassium availability on cocoa (Anokye et al., 2021; Djan et al., 2017), while studies on the effect of phosphorous availability are lacking.

4.1.4. Modelling cocoa phenology: Flushing, flowering and pod abortion

In order to understand how seasonal variability in climatic condition ultimately influences cocoa production and to enable short term intraannual yield prediction (Fig. 1), processes related to cocoa phenology, such as flushing, flowering and pod abortion, need to be modeled. Those processes though are largely missing in existing cocoa models.

As for flushing, all reviewed cocoa models assume a continuous production of vegetative biomass. However, in cocoa new leaves and branches are produced in rhythmic episodes, called flushes, followed by a dormant phase (Greathouse et al., 1971). Allocation to vegetative organs and internal competition for resources vary greatly between flushing and non-flushing periods. However, such fluctuations and their potential effect on pod abortion and development are not accounted for in current models. Including flushing in cocoa models would require an improved understanding of drivers of flushing activities. Several hypotheses have been proposed but no consensus has been reached so far, and the topic has attracted little to no attention in recent years. The proposed hypotheses span from endogenous hormonal regulation of flushing cycles (Orchard et al., 1980) also in combination with environmental cues (Greenwood and Posnette, 1950), to temperature and precipitation dependency (Almeida et al., 1987) and to cycles driven by accumulation of assimilate reserves (Machado and Hardwick, 1988; Taylor, 1988).

Whereas flowering is explicitly incorporated in the model by Wilson et al. (2019), estimating flower abundance is difficult and prone to have a large degree of uncertainty. Flowering in cocoa is in fact abundant (Niemenak et al., 2009), continuous (Waldburger et al., 2019) and flowers have a very short life span (Aneja et al., 1999). Some studies report on seasonal flower production on the trunk and on small sections of the canopy (Adjaloo et al., 2012; Omolaja et al., 2011; Tosto et al., 2022) but not for the entire tree. It is important to mention that the often-reported fruit:flower ratio of 0.5% to 5% (Aneja et al., 1999; Toxopeus, 1985) cannot be traced back to experimental results.

Pod abortion in cocoa (also referred to as cherelle wilting) is considered an important determinant of yield and regulates the tree sink demand in response to available assimilates (Valle et al., 1990). Developing pods can be aborted up to the moment they reach 10-15 cm in length and the number of aborted pods can be high, especially during a period of intense vegetative activity (Waldburger et al., 2019). This may result in a loss of assimilates and nutrients allocated to pods, which is not included in any of the current cocoa models.

Finally, it is worth mentioning that the CASE2 model simulates the seasonal fluctuation in pod production using a box cars approach. This part of the model, however, has not been validated.

4.2. Modelling tree and stand structural characteristics

Many questions regarding the design and management of a cocoa cropping systems (Fig. 1), especially in the case of systems with heterogenous shade canopy, like diverse agroforestry systems, require models at plant and organ levels (see Fig. 2 and Box 1). Those models in fact allow addressing questions at a higher spatial resolution, regarding the responses to environmental factors that may vary within a stand (e.g light, water availability, microclimate). Existing cocoa models are at present stage not sufficient. WaNuLCAS has the potential to address questions regarding belowground competition for resources, but it is less suitable to address issues on aboveground processes. The organ-level model of cocoa developed by Mialet-Serra et al. (2001) is very limited in its possible application and no plant-level model has been developed yet for cocoa. In this section we therefore explore how existing approaches to organ-level (FSP) and plant-level models could be applied to optimize cocoa architecture and improve the design and management of cocoa diverse cropping systems.

4.2.1. Modelling tree architectural development

There are at least two key issues FSP models of cocoa could address: 1) ideotyping cocoa architecture for different cropping systems to guide breeding programmes, and 2) understanding how tree structure and its management (e.g., pruning) influence tree performance and production (see also Section 4.3.3). No attempts have been done to develop and apply cocoa models in these directions, and to this end, the existing 3D cocoa model described earlier (Mialet-Serra et al., 2001) could be further extended.

The work of Perez et al. (2018, 2020) is an interesting example of using FSP models for ideotyping in oil palm. Using a previouslydeveloped static FSP model of oil palm, a set of oil palm ideotypes were presented based on a sensitivity analysis on palm leaf traits. Plastic responses of leaf traits in relation to density were also added to improve the model applicability to different planting designs. Density-dependent allometric relations for leaf geometry and biomass were based on data extracted from LIDAR scans, an approach that could drastically reduce the need for time-consuming manual architectural measurements. However, examples of LIDAR technology applications to cocoa are missing.

Understanding how tree structure and its management (e.g., pruning) influence tree performance and production requires a modelling approach that combines an explicit representation of cocoa architecture with the simulation of tree development and growth driven by environmental factors and resources. In contrast to annual crops (Gu et al., 2018), dynamic FSP models for tropical perennials are scarce. Recently, in mango trees, the complex interplay between the phenology of vegetative and reproductive branches was studied with V-Mango, a dynamic FSP model (Boudon et al., 2020). V-mango was based on extensive observations of mango organ sizes in well-defined developmental stages in vegetative and reproductive branches (Dambreville et al., 2015), and on time series of organ appearances (Dambreville et al., 2013). However, analogous studies on cocoa are missing.

4.2.2. Example of modelling stand structure

Plant-level models have been extensively used as a tool to investigate the contribution of stand structural characteristics (e.g., spacing, planting design, crown characteristics) on availability and utilization of resources such as light and water and on stand microclimate (le Roux et al., 2001; Medlyn, 2004; Pretzsch et al., 2015). We describe here the MAESTRA model, a widely used 3D plant model, and some of the models derived from it that have been applied in the context of coffee

agroforestry.

MAESTRA calculates the light interception of individual trees that are represented using geometric primitives (Medlyn, 2004) with speciesspecific values for the leaf area index (LAI), the leaf angle distribution and the leaf area density (LAD) profiles. Charbonnier et al. (2013) parameterized MAESTRA to represent a two-layer coffee agroforestry system able to analyze intra-plot light distribution.

Duursma and Medlyn (2012) developed MAESPA by integrating MAESTRA with a soil-plant-atmosphere continuum model to simulate the effect of water availability on transpiration and photosynthesis. MAESPA was further extended to calculate evapotranspiration, air temperature and vapour pressure for different canopy layers (Vezy et al., 2018) and used to simulate coffee agroforestry systems. However, MAESPA is computationally demanding. To reduce simulation time, Vezy et al. (2020) developed DynACof, a crop-level explanatory model of coffee agroforestry systems, integrating two existing crop-level coffee models (Rodríguez et al., 2011; van Oijen et al., 2010a) with metamodels derived from the MAESPA model to account for the spatial heterogeneity of the systems.

Similar approaches could be applied to model cocoa agroforestry systems. However there is limited data available to calibrate and validate MAESTRA or MAESPA for cocoa agroforests. For model calibration, we found various studies reporting LAIs of different cocoa systems (Daymond et al., 2002; Leiva-Rojas et al., 2019; Miyaji et al., 1997b; Moser et al., 2010), one study describing leaf area density profile (Miyaji et al., 1997a) but no studies assessing cocoa leaf angle distribution. Data on the characteristics of common shade trees in coffee agroforestry are reviewed by (van Oijen et al., 2010b) and several of those species are used also in cocoa agroforestry. However availability of shade tree data is overall scarce. For model validation we found a few studies reporting detailed measurement of light interception (Miyaji et al., 1997b; Tosto et al., 2022); several studies providing information on the effect of different shade levels and shade tree species on the microclimate of cocoa agroforestry systems (Abdulai et al., 2017; Acheampong et al., 2015; Jiménez-Pérez et al., 2019; Köhler et al., 2014; Suárez et al., 2021a) and one eddy-covariance study on a full-sun cocoa monoculture (Falk et al., 2005).

4.3. Gaps in modelling effects of crop agronomic practices

Decision support systems (DSSs) to guide common management practices such as fertilization, irrigation and pruning are missing for cocoa (Fig. 1 and 2). DSSs need to be applicable at the farm level and thus require site-specific calibration and validation. DSSs therefore tend to follow a more descriptive approach, and management responses are often captured in the model as empirical functions modifying traits such as the radiation-use efficiency (RUE) or allocation to leaf area of the crop. In DSSs, the use of RUE is an important simplifying step but has so far mostly been used in annual crops. In this section, the main limitations to the use of RUE in cocoa systems are presented, followed by a discussion on the implementation of the main cocoa agronomic maintenance practices such as irrigation, fertilization and pruning in future cocoa models.

4.3.1. Modelling radiation-use efficiency in tree crops

Radiation-use efficiency (RUE) is a widely used empirical parameter in crop and forest modelling, that linearly relates solar radiation to biomass production (Monteith, 1977). Unlike annual crops where the production cycle is constrained to less than a year, estimating RUE for trees and tree crops, like cocoa, is less straightforward and different methodologies have been suggested. RUE can be calculated via destructive harvesting, as in annual crops, but requires sampling over multiple years and is time consuming (Villalobos et al., 2006). Nondestructive techniques have also been suggested such as tree allometry, remote sensing, eddy covariance and hemispherical photographs but these different methods appear to be inconsistent in regard to their estimates of RUE (Krupková et al., 2017). Also, the latter three techniques are difficult to apply in cocoa agroforestry systems as the scale at which they measure often does not allow distinction between cocoa and shade trees.

RUE is known to vary with several factors, many of which are relevant to cocoa cultivation, such as proportion of diffuse light (Healey et al., 1998) and light intensity pattern (Rosati et al., 2020); water availability (Garbulsky et al., 2010); nutrient availability; and tree size (Collalti et al., 2020).

Only one estimate of RUE for cocoa has been published (Regazzoni et al., 2015) using destructive harvesting. As for non-destructive methods, some allometric models for aboveground and belowground biomass of cocoa have been developed (Borden et al., 2019) but their applicability may be limited only to systems with shade levels and management practices similar to the ones where the models have been developed. We are not aware of studies that have applied other non-destructive methods to follow cocoa biomass in the field over time. To develop a DSS for cocoa based on RUE with wide applicability, a network of on-farm experiments would be required encompassing a wide range of different tree sizes, levels and types of shade and climatic conditions.

4.3.2. Modelling irrigation and fertilization practices

To provide recommendations on irrigation and fertilization at farmlevel (Fig. 1), a cocoa DSS model needs to include cocoa responses to both water and nutrient availability as well as an accurate representation of the dynamics of the water and nutrient pools in the soil.

The development of empirical functions to simulate the effect of water shortage on cocoa RUE would require data from irrigation experiments. In the review by (Carr and Lockwood, 2011) various irrigation experiments with often inconclusive outcomes were reported, due to problems of experimental design. More recently, other studies investigated the impact of irrigation (also in combination with fertilization) on seedling growth (Acheampong et al., 2019; da Silva Almeida et al., 2012; Posse et al., 2020) and yield (da Silva Almeida et al., 2014; Meneses-Buitrago et al., 2019), but studies relating water availability to RUE in adult plants are missing. The development of empirical relations for nutrient availability is discussed in Section 4.1.3.

Regarding the soil component, a relevant and widely used example is given by the DAYCENT model (Parton et al., 1998) with a soil organic matter submodule that calculates the flow of C, N, P and S through plant litter and different inorganic and organic pools in the soils. Simulation of irrigation would require a soil module that allows for partial wetting of soil, especially in the case of drip irrigation, such as the model by Bonachela et al. (2001) that calculates soil evaporation on a partially wet soil, and the model by López-Bernal et al. (2018) that simulates a separate water balance for the irrigated and non-irrigated sections of the soil.

4.3.3. Modelling pruning practice

As discussed in Section 4.2.1, a dynamic FSP model could be used to analyze the effects of pruning on cocoa carbon dynamics and to optimize pruning practices (Fig. 1). FSP models have been applied to study the instantaneous effect that pruning has on plant functioning due to removal of leaf area, biomass and stored reserves in some horticultural crops. For example, Lescourret et al. (2011) developed QualiTree, a generic 3D fruit model that simulates the effect of branch removal and fruit thinning on fruit quality characteristics (fruit biomass, dry matter content, sugar concentration). A more recent example is given by the work of Bahr et al. (2021) that studied the effect of intensity and timing of leaf removal in grapevine cultivation.

To understand the long-term effect of pruning practices on plant structure and function, pruning induced changes in branching patterns would need to be included in a FSP model, but no published examples were found. Such a model would require a detailed account of pruning responses as done in the work by Fumey et al. (2011a, 2011b) that described changes in branching patterns in response to pruning in apple trees, or the work by Persello et al. (2019) that described the structural and temporal responses to different levels of pruning intensity in mango trees. Those studies however did not take the effect of heterogeneous light availability (that varies vertically through the canopy, and between shaded systems) on pruning induced branching into account. To model pruning in cocoa, detailed descriptions of pruning induced branching, both in young plants and in fully developed tree crowns are needed.

4.4. Considerations on availability of data

Availability of yield data is limited and subject to large degree of uncertainty. Yield data from experiments under close-to-optimal management conditions are rare (Appiah et al., 2000; Waldburger et al., 2019). On the contrary, farm yield data are more widely available but often subject to a large degree of uncertainty, caused by incorrect self-reporting, differences in water content of reported fermented bean weight, variable tree density within a farm and/or uncertainty regarding exact farm size (Asare et al., 2018; de Groote and Traoré, 2005; Desiere and Jolliffe, 2018). The large tree-to-tree variation in bean production (Wibaux et al., 2018) may also introduce errors in yield estimation especially in the case where yield per hectare is extrapolated from measurements of sub-plots of small size and where tree size distribution is not representive of the entire field (Tosto et al., 2022).

As we have shown throughout Section 4, availability of data on cocoa systems for model calibration and validation varies depending on the variables or processes considered. At present, calibrating and validating new model modules and new model types may require using data from several different sources. However, differences in environment, genotype and management between study sites may hamper the integration of data collected by different studies. Optimally all necessary measurements should be collected within the same plot, calling for experimental sites where a large number of measurements could be performed simultaneously.

5. Conclusions

Despite the importance of cocoa as a commodity crop and the advantages that modelling could bring to the understanding of cocoa systems, relatively few cocoa models have been developed. In addition, existing models have hardly been applied by the cocoa sector. We compared pertinent questions in the cocoa sector with existing cocoa models and their applications, therewith identifying various gaps in cocoa modelling. (i) Several physiological processes (e.g., water stress responses, respiration, climate changes responses) are simulated based on general plant physiological knowledge that is not cocoa-specific. (ii) Nutrient effects on cocoa functioning and production are missing in more explanatory models, while other models are either not calibrated for cocoa or too limited in scope. (iii) Phenological processes specific to cocoa, such as flushing and pod abortion are not represented in any of the existing models. (iv) Structural characteristics of the cocoa tree (3D organ-level models) are represented only in juvenile stages and models to simulate stand structural complexity especially in an agroforestry setting are missing (3D plant-level models). Finally (v) a decision support system including the main agronomical management practices in cocoa cultivation is missing.

Given the state of the art of existing cocoa models and the necessary steps that we identified to address some of the most pressing issues in cocoa production, we propose to focus future modelling efforts on developing: (i) cocoa management decision support systems, (ii) a more comprehensive plant ecophysiological model of cocoa and (iii) a 3D structural-functional cocoa model.

A cocoa management support system aims at supporting farmers in making decisions on management (e.g., irrigation and fertilization) as well as forecasting yields. Hence, the modelling strategy should focus on ease of calibration and high predictive power. This might require a significant simplification of process-based models such as CASE2 (Zuidema et al., 2005). A plant ecophysiological modelling approach of cocoa needs to focus on simulating the effects of climate, soil, water and nutrient availability on the growth and yield. Following the approach of MAESPA (Vezy et al., 2018), this model could also incorporate a simplified 3D structures of the system at plant level, thus allowing to address questions on the design of cocoa systems (including agroforestry systems) and evaluating the effect of heterogenous shade canopies on cocoa production. Lastly, the 3D structural-functional cocoa modelling approach needs to capture growth and development of cocoa trees at organ levels in order to address questions regarding the effect of microclimate on branching and pod production, pruning and shading.

Data availability in many cases hampers further development of cocoa modelling. To develop management decision support systems for cocoa cultivation, we need to understand how radiation-use efficiency varies under different environmental conditions and how cocoa trees respond to management practices. Methods of effectively obtaining reliable on-farm or at least within-region data also need to be improved. Further development of an ecophysiological model requires knowledge on long-term cocoa responses to climate change and on nutrient effects on tree processes, currently available only at seedling stage. Hence, detailed field experiments exploring Finally new model types, such as 3D organ-level and plant level models, require data on architectural and structural tree and stand characteristics, which is currently missing.

Obtaining knowledge of cocoa is challenging due to its perennial nature and the high variability of environmental conditions and cropping systems. Overcoming this challenge requires a concerted effort of the cocoa research community to develop networks of long-term experiments both under relatively controlled conditions at research stations (to develop and support explanatory models) and on-farm (to develop and support DSS). This requires collaboration across the sector, dedicated shared facilities (e.g. FACE experiment, well control experimental field) and long-term financial investments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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A. Tosto et al.

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Agricultural Systems 206 (2023) 103614

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A. Tosto et al.

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A. Tosto et al.

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