

Mapping Opportunities for Cocoa Agroforestry in Côte d'Ivoire

Assessing its potential to contribute to national forest cover restoration targets, and ecosystem services co-benefits



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Key messages

Transforming existing cocoa landscapes through agroforestry practices can support national and sub-national forest restoration targets now and under future climate change and provide multiple benefits through improved ecosystem service provisioning and biodiversity conservation.

Agroforestry is seen as a solution for the long-term sustainability of the cocoa sector and national efforts to restore forest cover in Côte d'Ivoire in highly degraded classified forests and in the rural domain. By increasing tree cover it supports net zero deforestation, carbon sequestration, resilience to climate change and improved farmer livelihoods.

Within the rural domain, 1.8 million hectare of full sun cocoa could potentially be transformed into partial shade (around 30% canopy cover) agroforestry systems, which exceeds the 1 million hectare target set in the National REDD+ Strategy.

This study did not find enough highly degraded classified forest land under cocoa to meet the 1 million hectares cocoa agroforestry policy target in classified forests, though other degraded lands in these forests would be suitable for cocoa (or other agroforestry crops) to help meet this target.

The increase in tree cover achieved through the implementation of agroforestry in the rural domain and highly degraded classified forests does not strictly meet Côte d'Ivoire's definition of Forest as set out in the 2019 Forest Code. However, national policies referring to 20% forest cover as an objective do consider the contribution of agroforestry and forest plantations to an increase in tree cover ("couvert arboré" in French).

Cocoa growing areas classed as full sun systems were more likely to be under less favourable climates in the future. Full sun systems are more vulnerable to climate change. It is thus important to consider whether agroforestry could support adaptation in these areas or whether they may need to transition to more drought tolerant (tree) crops.

The largest potential gains in ecosystem services, such as carbon storage can be achieved from implementing (partial shade) agroforestry in the rural domain, where the largest area of full sun/low shade is available.

Potential carbon stock gains across all targeted areas were estimated at 120Mt carbon or 440 MtCO₂e, which could generate significant income through the sale of carbon credits.

Areas close to existing intact forests and settlements should be prioritised for transformation to agroforestry systems, as doing so would provide greater benefits to biodiversity conservation (buffering) and people (services provision).

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Introduction

Background

Cocoa and forests in Côte d'Ivoire

Forests in Côte d'Ivoire have experienced severe degradation in recent decades. According to a recent study, more than 60% of forest cover disappeared between 1986 and 2019, with only 3.05 million hectares remaining in 2019, or less than 9% of the national territory, compared to 15% in 1986 (SEP-REDD+ and FAO, 2017; VividEconomics, 2020). This decline is largely due to the expansion of cash crops, notably cocoa, but also rubber, coffee, cashew and palm oil plantations (VividEconomics, 2020; see also Barima *et al.*, 2020; Abu *et al.*, 2021).

Awareness is increasing of the connection between global demand for cocoa and deforestation and efforts aiming to combat deforestation and ensure the production of commodities, such as cocoa, in a forest friendly way are increasing. Private sector cocoa players in West Africa including Barry Callebaut, Cargill, Olam, Nestle, Mars, Mondelez, Hershey's, Ferrero, Lindt and Sprungli have made commitments to improve sustainability in their supply chain and reduce deforestation to zero as a result of cocoa production (Ingram *et al.*, 2018; Abu *et al.*, 2021). Public-private zero-deforestation initiatives such as the Cocoa Forest Initiative (CFI) (RCI, 2018) but also by cocoa importing countries in Europe (EC, 2020) seek to align with national REDD+ strategies, as well as national policies on forest and biodiversity conservation (RCI, 2018).

Restoring forest cover, REDD+ and agro-forestry

The global initiative on REDD+¹ under the UN Framework Convention on Climate Change (UNFCCC), that Côte d'Ivoire committed to in 2011 by joining the UN-REDD Programme, represents an opportunity to address deforestation and restore forest cover while supporting the transition towards a more sustainable, low-carbon development pathway. The National REDD+ Strategy, which was endorsed by the Government in 2017, provides a strategic direction to this opportunity within the broader context of Côte d'Ivoire's national development objectives and goals (*Plan National de Développement 2016-2020*).

The National REDD+ Strategy is a public policy instrument aiming at addressing the main direct and indirect drivers of deforestation and degradation of forests in Côte d'Ivoire. Acknowledging the close linkages between deforestation and cocoa expansion in recent decades, the National REDD+ Strategy places a strong emphasis in moving towards a zero-deforestation agriculture, in partnership with supply chain organisations and the private sector. In the case of cocoa, this includes reducing cocoa-driven deforestation by at least 80% by 2030 and contributing to the national objective of restoring forest cover to 20% of land area. It is worth noting that the 20% forest cover target consists of both forests as per the Forest Code definition (RCI, 2019) as well as agro-forests and forest plantations in heavily degraded classified forests and the rural domain.

Agro-forestry, a type of land management in which agriculture and trees interact, including through the agricultural use of trees for multiple purposes², has been identified as a solution to effectively contribute to the long-term sustainability of the cocoa sector and the national effort to restore Ivorian forest cover. In fact, agro-forestry is at the heart of all forest restoration policies in Côte d'Ivoire³.

Agro-forestry is to be implemented to gradually restore the most degraded state-owned classified forests, by transitioning from agricultural systems to agro-forestry systems and then to forest plantations (Figure 1). Due to the long history of agricultural use, the costs of rehabilitation and risk of social conflict if people are evicted are high. Therefore, in classified forests that are more than 75% degraded, government aims to stabilise existing agricultural areas and extend lease contracts for their sustainable commercial exploitation for tree crops through an agreement with the Forest Development Corporation (SODEFOR). The National REDD+ Strategy plans to rehabilitate 1 million hectares of cocoa plantations in classified forests through this system by 2030.

¹ "Reduced Emissions from Deforestation, forest Degradation, and the role of conservation, sustainable management of forests and enhancement of forests carbon stocks in developing countries"

² <https://www.worldagroforestry.org/about/agroforestry>

³ Initiative Cacao et Forêts, Stratégie Nationale REDD+, Stratégie Nationale de préservation, de réhabilitation et d'extension des forêts, Dialogue UE et Côte d'Ivoire sur le cacao durable

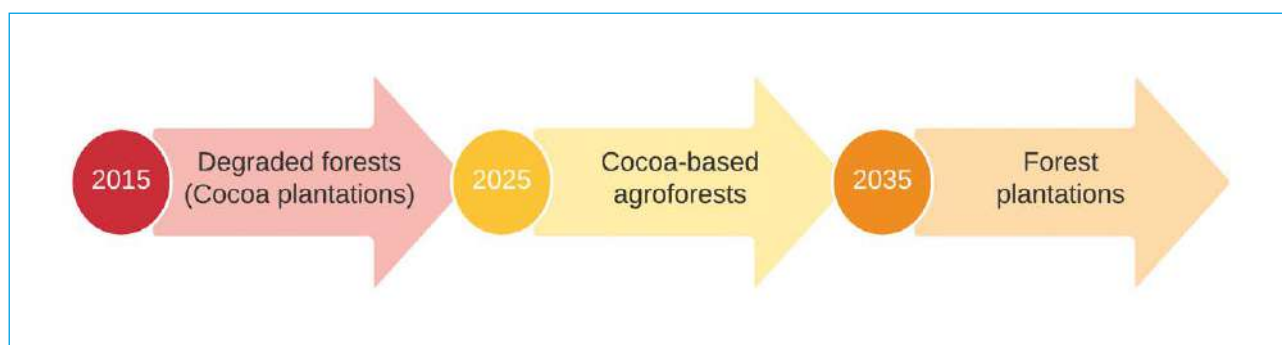


Figure 1. Planned transition from cocoa plantation to forest plantation in classified forests through the use of agroforestry. Source: Côte d'Ivoire's National REDD+ Strategy.

In addition to this, Côte d'Ivoire aims to promote agro-forestry in smallholder cash-crop plantations (cocoa, rubber and oil palm) in the south of the country. Increasing tree cover in cocoa and other commodity producing rural areas is part of a strategy to compensate for (uncontrolled) residual deforestation and attain net zero deforestation, support carbon sequestration, enhance resilience to climate change and improve local ecosystem services. In the case of cocoa plantations, the objective is to increase tree density to at least 50 trees/hectare to secure timber and fuelwood supply while ensuring food security by increasing the number of native and/or fruit trees in agro-forestry systems (National REDD+ Strategy). Promoting agro-forestry also aims to help to diversify farmers' incomes, making cocoa plantations more sustainable in the long-term and, in this way, reduce cocoa-driven deforestation by 2030.

Cocoa agro-forestry trends

In cocoa agro-forestry systems, cocoa is cultivated under shade or within a tree-shaded environment (Somarriba, 1992). Agro-forestry is the traditional method of growing cocoa, resulting from thinning the original canopy cover, planting cocoa and useful fruit and timber species whilst retaining a diversity of forest trees. According to Ruf (2011) a 'complex agro-forest' is a cocoa with "more than 15 mature timber trees per hectare (and possibly as many as 60–80), usually giant trees more than 15 m

tall, which are native to the natural tropical forest. A 'simple agro-forest' has a light shade and may include up to 5-6 trees per hectare emerging above the cocoa whilst a 'full-sun' system has only one level of canopy storage: cocoa trees (Figure 2). However definitions and designs vary: from traditional, diverse and multi-strata systems to simpler integration of cocoa and useful shade trees, to edge planting of non-cocoa trees (Figure 2). There is no single model for how cocoa agro-forests should be implemented and designed (Thomson *et al.*, 2019). However, according to the Conseil du Café-Cacao, cocoa agro-forests in Côte d'Ivoire must maintain at least 800 cocoa trees/hectares and 30-50% shade (Conseil du Café-Cacao, 2019).

Historically, there has been an increasing move towards low or no-shade cocoa practices in West Africa to maximise production and meet growing global demand (Ruf, 2011; Vaast and Somarriba, 2014). Removing shade from plantations can increase cocoa yields in the short to medium term through reducing competition with cocoa trees (Blaser *et al.*, 2018). This was supported by the introduction of new more productive hybrids that perform well without the need for shade (Ruf, 2011) and by encouraging farmers to remove trees seen as potentially incompatible with cocoa, though sometimes with little scientific evidence (Dumont *et al.*, 2014).



Figure 2. Different types of agroforestry systems: from traditional multistrata to mixed with forest remnants and fruit trees and cocoa and more simple edge-planting systems (graphic M Sassen)

However, most studies find that shade is unlikely to compromise productivity at levels up to around 40% (Blaser *et al.*, 2018), and linkages between shade tree canopy and cocoa productivity are still poorly understood. Wade *et al.* (2010) demonstrated that plots with a higher cocoa yield had lower carbon storage, indicating that intensification of cocoa by removing shade trees results in a loss of carbon from farms. N'Gbala *et al.* (2017) estimated that secondary forests' conversion into full-sun cocoa plantations resulted in an 89% decrease in total carbon stock in Centre-West Côte d'Ivoire. From a biodiversity conservation perspective, cocoa plantations with diverse shade canopies provide and connect habitat, which may be vital in stemming the loss of wild species in Côte d'Ivoire (Rice and Greenberg, 2000; Clough *et al.* 2009). Transforming full sun or low shade cocoa systems can help restore biodiversity intactness in cocoa landscapes (Maney *et al.*, 2021).

Moreover, associated trees in cocoa plots have been linked to reducing household vulnerability to climatic stress, pests and diseases, cocoa price fluctuations and food insecurity (Tscharntke *et al.*, 2011; Dumont *et al.*, 2014; Sonwa *et al.*, 2014; Niether *et al.*, 2020). Studies have shown that farmers highly value shade trees for 'bringing the rain', increasing soil moisture and reducing soil erosion (Dumont *et al.*, 2014).

Cocoa agro-forestry is therefore increasingly seen as a system that may help achieve multiple objectives at once: restore tree cover in degraded forests and agricultural landscapes to support climate mitigation objectives whilst also meeting biodiversity conservation and socio-economic objectives (Middendorp *et al.*, 2018; Niether *et al.*, 2020).

Objectives

UNEP-WCMC in collaboration with UNEP, the Secrétariat Exécutif Permanent REDD+ (SEP-REDD) of Côte d'Ivoire and Centre Suisse de Recherches Scientifiques en Côte d'Ivoire previously developed spatial analyses to identify areas where forest conservation and restoration could provide benefits such as biodiversity conservation and climate change mitigation (Maukonen *et al.*, 2017). The work described here builds on this work by exploring the potential contribution of cocoa agro-forestry to forest restoration objectives and for what benefits.

In support of the different national level policies and strategies on forest conservation and restoration that look to agro-forestry, there is a need to understand where and how far agro-forestry can contribute to achieving national forest restoration and other relevant targets. Moreover, to prioritise areas for intervention, it is important to determine where cocoa agro-forestry could achieve carbon and non-carbon benefits simultaneously. This means considering which areas are most suitable for cocoa production, their current tree cover status and options for increasing or restoring tree cover, and how they may be affected by climate change.

To support the country's restoration objectives this study therefore seeks to identify priority areas in existing cocoa landscapes where tree cover could be increased to meet agro-forestry definitions, and where to prioritise actions based on potential for multiple benefits such as carbon sequestration and biodiversity conservation. It will also assess the potential for cocoa agro-forestry to contribute to the country's target of restoring forest cover to 20% of land area by 2030, in accordance with current national policies and action plans.

This document presents the methodology, the results of preliminary supporting activities to guide the methodology, and the results of its application to identify and prioritise those areas.

This is a spatial prioritisation exercise to identify the potential to achieve environmental objectives and does not, at this stage, include socio-economic considerations. Such considerations, including gender related dimensions, should be part of any subsequent step towards implementation of agro-forestry in the priority areas identified through this study.

Preliminary Steps



After a review of key national policies and potential methodological approaches and available data, the basic approach was presented to national stakeholders in early 2021. The methodology was then further refined based on their review and feedback and through the identification of additional data sets to support the objective of the work.

Stakeholder consultation

A workshop with stakeholders (25% women participants) from the public and private sectors and from civil society took place on January 21st, 2021. The workshop aimed to inform stakeholders about the project and gather feedback to validate the criteria for defining cocoa agroforestry in Côte d'Ivoire, identify additional co-benefits to consider in the analysis, review the proposed method and data sources and further identify government and private sector efforts that the analysis can or should inform. The workshop outlined the main aims of the project, the methodology and data sources proposed. The workshop was interactive, using Miro boards which allowed participants to contribute their thoughts and provide feedback on questions.

Feedback was consolidated and helped to define shade canopy criteria, confirm important co-benefits of agroforestry to include in the analysis, and identify potential sources of data as well as additional policies or projects that the proposed method and analysis could inform. It also highlighted some of the practical challenges in implementation of agroforestry at scale in the country (including availability and distribution of shade tree seedlings). Further details can be found in the workshop report⁴.

Definitions

Definition of agroforestry: Agroforestry is a heterogeneous habitat where a range of canopy cover (shade) levels can be applied, and associated tree species differ for different purposes (e.g. timber or fruit production). These can influence the ecosystem services they provide, e.g. carbon stock, habitat for wildlife, food, income. Agroforestry can range from *partial-shade*, where these services are considerable benefits compared to full-sun systems (e.g. increased carbon stock), but where cocoa production is still the focus, to high-shaded systems where other ecosystem services are at least as or even more important than cocoa production.

Shade trees can fall into several classes: edible, medicinal, timber and others (Sonwa *et al.*, 2007, 2017a). The more non-wood forest products and timber a system contains as shade plants, the larger the aboveground biomass and associated carbon stock (Sonwa, 2017b).

In order to identify priority areas where tree cover could be increased to meet agroforestry criteria in Côte d'Ivoire, these must be well understood. Different studies and documents suggest a range of potential definitions, these include:

- Gockowski and Sonwa (2010) reported 6 to 56 shade trees per hectare in cocoa agroforestry systems in Côte d'Ivoire.
- When integrating agroforestry for climate change mitigation and adaption in Côte d'Ivoire, Bunn *et al.* (2019) recommended at least 18 shade trees per hectare with a canopy coverage between 30 and 40%.
- The National REDD+ strategy used tree density to determine classification as cocoa agroforestry – “50 trees for each hectare of cocoa. At least 30 trees, mainly local fruit species, can be introduced for shade and fuelwood. Timber trees will be used for the delimitation of plots [...]”⁵.
- For cocoa agroforestry systems in Côte d'Ivoire, the number of cocoa trees is not less than 800 trees/hectares and shade after the plantation is established is 30-50% canopy cover by forest trees. Tree species must be compatible with cocoa production and farmers must decide which species are selected for the system (Conseil du Café-Cacao, 2019⁶).

Definitions using either canopy cover (%) or shade tree density make comparisons difficult. It is impossible to accurately translate shade tree density to shade canopy cover (and vice versa) as tree crown area varies with tree diameter and species (Asare and Ræbild, 2016; Isaac *et al.*, 2007). However, shade tree density could not be mapped using available remotely sensed products, and therefore for this analysis, a canopy cover-based definition for cocoa agroforestry was needed. Furthermore, the optimal shade canopy coverage may vary due to region-specific climatic conditions, site-specific microclimates and the age and quality of the cocoa trees (Thomson *et al.*, 2019).

⁴ <https://cocoasoils.org/wp-content/uploads/2021/12/Rapport-atelier-UNEPWCMC-cacao-AF-21-Janvier-2021.pdf>

⁵ SEPREDD, 2017. Stratégie Nationale REDD+ de la Côte d'Ivoire

⁶ CCC, N. Ref. 019/2019.

During the stakeholder workshop, most participants proposed a criterion of 30% canopy cover for agroforestry systems in Côte d'Ivoire. For this analysis, **cocoa agroforestry was considered across two classes, partial (around 30% shade cover) and high shade**. Partial shade agroforestry was assumed to have slightly lower shade canopy coverage than full-shade, but still represent a more diverse habitat than full-sun cocoa plantations (typically less than 10% canopy cover).

Definition of full-sun cocoa: Full-sun, or monoculture, cocoa systems range from monoculture to very low-shaded systems. Shade canopy coverage is typically below 10% canopy cover.

Definition of forest: Minimum area of 0.1 hectare with a tree canopy coverage of at least 30%, reaching maturity at a minimum height of 5m, forming dynamic and heterogeneous environment with direct and indirect effects on soil, climate and water regulation (RCI, 2017; RCI, 2019).

Definition of Agro-forest: the new 2019 Forest code provides for the definition of agro-forests as areas defined and delimited as such, by a reglementary text, situated in the private forest domain of the State (Classified Forests) and in which agricultural plantations and forest trees coexist (RCI, 2019).

Identifying policy related targets and constraints

A preliminary review of key national policies helped determine the criteria and constraints for the mapping potential of cocoa agroforestry implementation. The list below includes key national policy objectives that look to cocoa agroforestry and whose implementation this analysis aims to inform, where in scope:

1. Primary target

Restoring forest cover to 20% of the land area by 2030 (Côte d'Ivoire's Vision for REDD+, National REDD+ Strategy and National Forest Rehabilitation, Conservation and Expansion Strategy).

2. Secondary targets (contribute to the primary target)

A. Restoration of degraded classified forests: Gradually restore classified forests over 75% degraded by transitioning from open agricultural systems to agroforestry systems and then to forest plantations (PM 5 under Strategic Option 1 in the Agricultural Sector, National REDD+ Strategy and The National Forest Rehabilitation, Conservation and Expansion Strategy).

B. Related to the above, to transform 1 million hectares of cocoa plantations in classified forests to agroforestry systems by 2030: through the introduction of shade trees in full-sun cocoa plantations, payments to farmers to adopt these techniques and the abandonment of the crop at the end of the cultivation (PM 3 under Strategic Option 3, National REDD+ Strategy and the Quantitie, Quality, and Croissance (2QC) programme (Conseil du Café-Cacao, 2014)).



C. To restore 3.2 million hectares of degraded lands in the rural domain: including through the promotion of agroforestry in 1 million hectares of cocoa, rubber and oil palm crops by 2030. In the case of cocoa plantations, the goal is to introduce at least 50 shade trees per hectare (PM 3 under Strategic Option 4, National REDD+ Strategy).

For target C, only the promotion of cocoa agroforestry in current cocoa growing areas is assessed (so the promotion of agroforestry in rubber and oil palm crops is not included in the analysis). Furthermore, we were not able to implement tree density in the methodological approach but use canopy cover to meet agroforestry definitions instead.

3. Constraints

The following constraints based on the various relevant policies will be taken into account to identify opportunity areas to achieve the policy targets described above.

- Protect all remaining primary and secondary forests, including classified forests whose degradation is less than 75%.
- Natural ecosystems should be favoured over cocoa agroforestry. Natural non-forest ecosystems, such as wetlands or natural grasslands, should not be converted to cocoa agroforestry plantations.
- In principle, cocoa agroforestry should be implemented in current cocoa plantations only, except in classified forests that are more than 75% degraded, where it can be implemented in agricultural lands.
- Areas where conversion to cocoa agroforestry could reduce carbon stocks, in both biomass and soil, should be avoided.

Setting the criteria

The following criteria were considered to identify where within the opportunity areas would be most suitable for cocoa agroforestry.

- Areas where cocoa is currently grown (VividEconomics, 2020) were target areas for conversion to cocoa agroforestry (Figure 4).
- Climatic suitability: to refine the current cocoa growing data, we used the Cocoa Climate Suitability in West Africa (Schroth *et al.*, 2016) dataset to determine areas that are climatically suitable for cocoa. We reviewed other biophysical variables such as elevation and soil suitability for inclusion in the analysis,

we did not find a soil suitability dataset that could be implemented for the purposes of this study. Therefore, we assumed that areas being used for cocoa growing currently would meet soil requirements. We use a minimum threshold of 20% for suitability for cocoa growing (Schroth *et al.*, 2016) (Figure 7).

- Areas which will most likely be climatically suitable for cocoa under climate change (Schroth *et al.*, 2016) (Figure 7).

Defining priority areas and co-benefits

Identifying potential areas for the promotion of cocoa agroforestry

Considering the identified policy targets, constraints and suitability criteria, this analysis seeks to identify potential areas for the promotion of cocoa agroforestry in current cocoa growing areas in the rural domain and opportunities for implementing cocoa agroforestry as a means of restoring forest cover in highly degraded classified forests. The work will assess the potential in terms of achieving the following policy targets:

1. Transform 1 million hectares of existing cocoa plantations in the rural domain into agroforestry systems by 2030 through the introduction of shade trees.
2. Restore areas within classified forests that are degraded over 75% through agroforestry (in first instance before transitioning to forest plantations – which are not covered in this study), including 1 million hectares of cocoa plantations⁷.
3. Based on 1. and 2.: Assess the potential for cocoa agroforestry to contribute to the country's target of restoring forest cover to 20% of land area by 2030, in accordance with current national policies and action plans.

Multiple benefits of promoting cocoa agroforestry

Implementing agroforestry can support multiple benefits such as carbon sequestration, biodiversity conservation and other ecosystem services. Assessing the potential for such co-benefits spatially, can help to identify the most adequate areas for the provision of specific co-benefits, given that some are highly location specific. Furthermore, such targeted benefit maps, in combination with other relevant types of information would allow decision makers to better balance the trade-offs between different potential benefits.

⁷ Art 1. Loi. No 2019-675 du 23 juillet 2019: <http://www.droit-afrique.com/uploads/RCI-Code-2019-forestier.pdf>.

Carbon stocks and sequestration were the most important co-benefits identified by the stakeholder workshop participants, followed by adaptation to climate change, income diversification for farmers and habitat connectivity.

In terms of carbon benefits, the study seeks to assess the potential benefits achieved if areas identified for cocoa agroforestry based on the identified criteria and constraints were converted to agro-forests. This would therefore be the maximum benefit, in terms of carbon, that could be achieved should all areas identified as suitable be converted. The potential for agroforestry to support adaptation of cocoa to climate change depends on many factors that cannot be quantified at this level. Though climate risk for growing cocoa can and is incorporated.

The potential for income diversification cannot be assessed at the scale of this study, though agroforestry development close to human settlements may increase local ecosystem services such as timber and fuelwood provision or enhance food security (through fruit trees). This would also inform the selection of the most adequate shade tree species in each location.

In relation to habitat connectivity, agroforestry implementation in potential ecological corridors can help increase habitat connectivity between primary forests, whilst in agricultural areas around remaining forests it can help buffer impact of human activities on local biodiversity. The National REDD+ Strategy also assumes that agroforestry can help reduce pressure on remaining forests by increasing productivity of existing cocoa land (cocoa and other products).



A photograph of the back of a blue truck, its bed filled with a large quantity of harvested cacao pods. The pods are in various stages of ripeness, showing shades of green, yellow, and orange. A large, dark, round object, possibly a coconut, is visible among the pods. The truck's metal frame and a side mirror are visible in the background. The word "Methodology" is written in a large, white, sans-serif font across the middle of the image. On the left side, there is a decorative pattern of orange and white dots. The background shows lush green foliage.

Methodology

The process of mapping cocoa agroforestry potential and priority areas for implementation consists of the following steps:

1. Identify suitable areas to promote cocoa agroforestry, based on the criteria and constraints defined in the prior section.
2. Assess the potential co-benefits from promoting cocoa agroforestry within the areas identified in step 1.

Different datasets were combined to refine the identification of potentially suitable priority areas for cocoa agroforestry implementation (Figure 3) and assessing co-benefits.

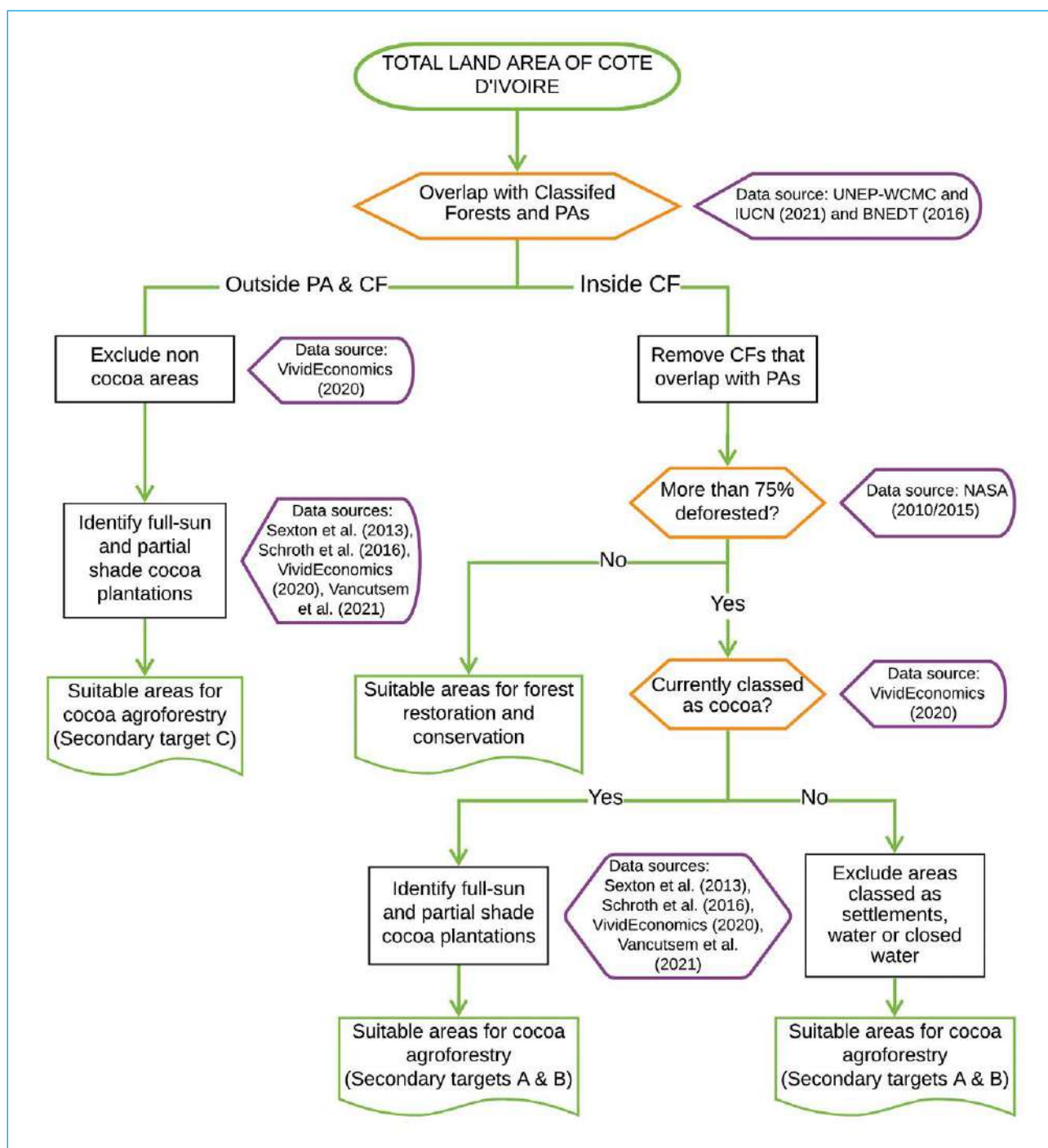


Figure 3. Decision tree to identify potentially suitable priority areas to implement cocoa agroforestry. PA = Protected Areas and CF = Classified Forests.

Identifying areas to promote cocoa agroforestry

This section describes the stepwise approach and datasets (Table 1) used to identify those areas that are suitable for cocoa production, their current tree cover status (i.e. level of shading in cocoa) and options for increasing or restoring tree cover, and how they may be affected by climate change.

Analysis was conducted first at the national level, within existing cocoa growing areas (as per VividEconomics, 2020), excluding areas on the basis of tree canopy cover, forest disturbance and climatic suitability. Analysis was further refined to look at potential cocoa growing areas climatically suitable for cocoa within classified forests (BNEDT/ SEP-REDD, 2016) and in the rural domain (outside of designated protected areas and classified forests). Within classified forests, this included areas currently identified as cocoa and areas not currently under cocoa cultivation, but where the land is considered highly degraded (<25% canopy cover). Classified forests were identified from boundary data provided by BNEDT (2016), any classified forests overlapping with designated protected areas (IUCN

and UNEP-WCMC, 2021) were removed (Figure 4), as designated protected areas (national parks etc.) are not considered for restoration through agroforestry but through natural or assisted ecological restoration (National REDD+ Strategy and CFI Implementation Plan).

All spatial analysis was carried out in Python Jupyter Notebook, using the geemap package (Wu, 2020) to access both local datasets and those available on Google Earth Engine. Maps were produced using QGIS version 3.18.1.

Assessing shade levels in cocoa growing areas

To assess the potential for increasing shade tree cover in existing cocoa landscapes to meet cocoa agroforestry criteria (i.e. approximately 30% shade cover), data on current levels of shade cover is required. However, spatial data on levels of shading in cocoa growing areas is not available and constrained by the technical difficulty of distinguishing cocoa from and under a canopy of other trees. We therefore combined datasets on current cocoa growing areas, forest canopy cover, temporal forest dynamics and climatic suitability (Table 1) to identify plausible levels of shading in cocoa growing areas in Côte d'Ivoire in a stepwise approach, clarifying assumptions at each step.

Table 1. Datasets used in analysis. All datasets were rescaled to a 30m resolution in Google Earth Engine.

Dataset	Reference	Description	Temporal resolution (Year(s))	Spatial Resolution	Link (if publicly available)
VividEconomics Land Cover	VividEconomics (2020)	Land cover of Côte d'Ivoire	2019	20m	NA
JRC Tropical Moist Forests	Vancutsem <i>et al.</i> (2021)	Long-term monitoring of tropical moist forest dynamics	1990-2019	30m	Yes
NASA Forest Canopy Cover	Sexton <i>et al.</i> (2013)	Forest canopy cover (%) where trees are greater than 5m in height.	2010 and 2015	30m	Yes
GLAD Forest Height Dataset	Potapov <i>et al.</i> (2020)	Height of forests (m)	2019	30m	Yes
Cocoa Climate Suitability in West Africa	Schroth <i>et al.</i> (2016)	Suitability for cocoa based on climate. Both current and projected (2050)	Current and 2050 climate	1km	NA
WDPA Protected Areas	UNEP-WCMC and IUCN (2021)	Protected areas globally	2021	NA	Yes
Classified Forests	BNEDT (2016)	Classified Forests within Côte d'Ivoire	2016	NA	NA

Land cover data

Vivid Economics 2019 land cover map of Côte d'Ivoire (10m spatial resolution) was used to identify areas currently classed as cocoa plantations (VividEconomics, 2020) (Figure 4). This dataset does not distinguish full-sun or agroforestry cocoa specifically, and there is likely to be a combination of both. Studies have found that on average 35% of

cocoa grown in Côte d'Ivoire is thought to be full-sun and around 50% under partial shade (<30%) cocoa agroforestry (WWF, 2006). Furthermore, most of the cocoa is grown on smallholdings (less than 10 hectares) which can increase the challenges in identifying these areas. Therefore, other datasets were used to establish where existing cocoa plantations are likely under full sun, partial or high shade systems (Table 1).

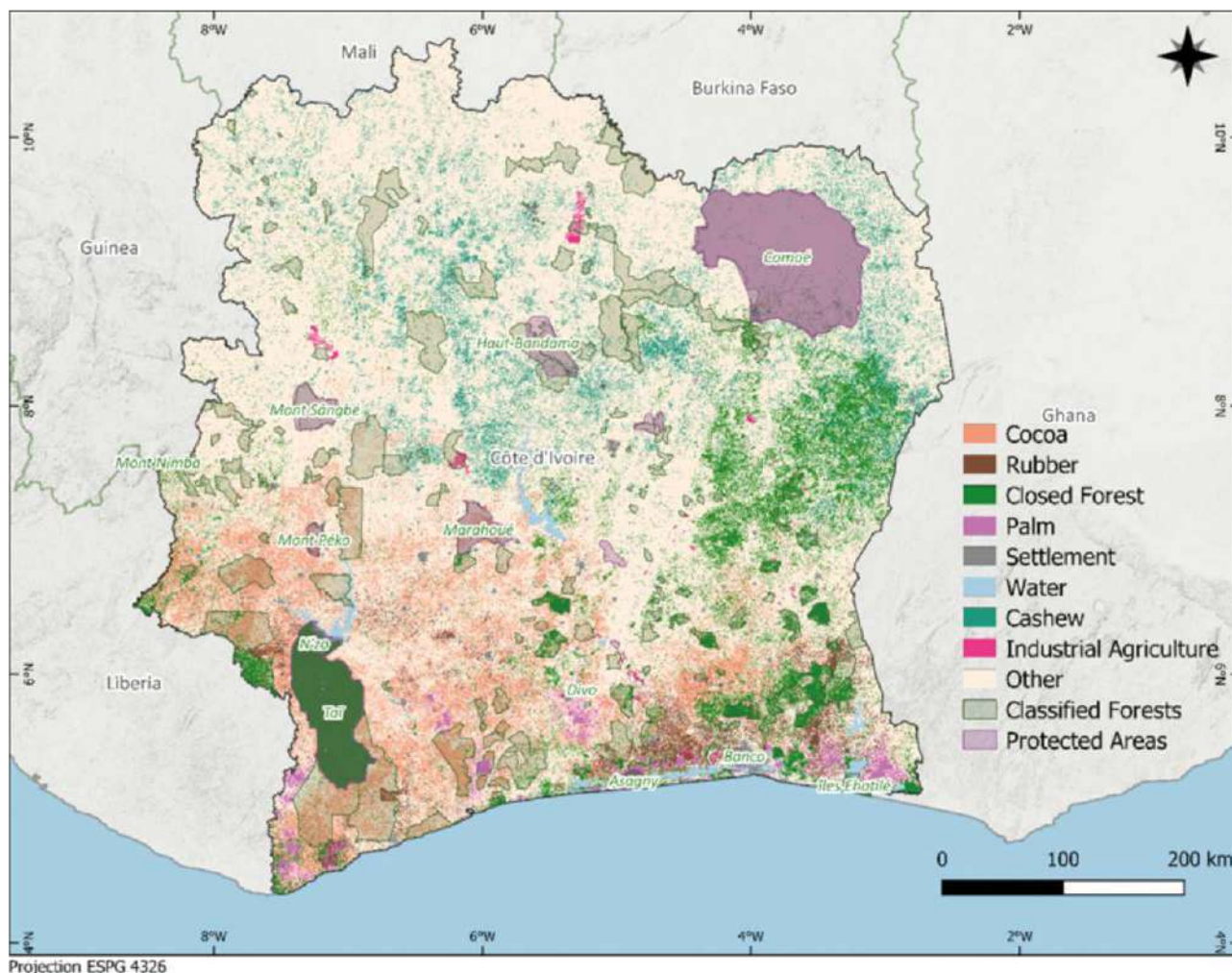


Figure 4. Land cover of Côte d'Ivoire in 2019 overlaid with classified forests, including those which are protected areas (BNEDT, 2016; Vivid Economics, 2020; UNEP-WCMC and IUCN, 2021). Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Tree canopy cover

NASA tree canopy cover datasets (Sexton *et al.*, 2013) were used to determine the potential canopy cover in cells classed as cocoa by VividEconomics (2020). The 2015 dataset had missing data values, possibly due to satellite scan lines and cloud cover. Therefore, the missing values in the 2015 dataset

were filled with values from the 2010 dataset where possible. Where there was also no value present in the 2010 dataset, the value of the cell was assumed to be 0 assuming that no trees over 5m in height were present). Although this approach helped fill some data gaps in the 2015 dataset, we assume that cells with null values in 2015 and data present in 2010 may have been deforested (Figure 5).

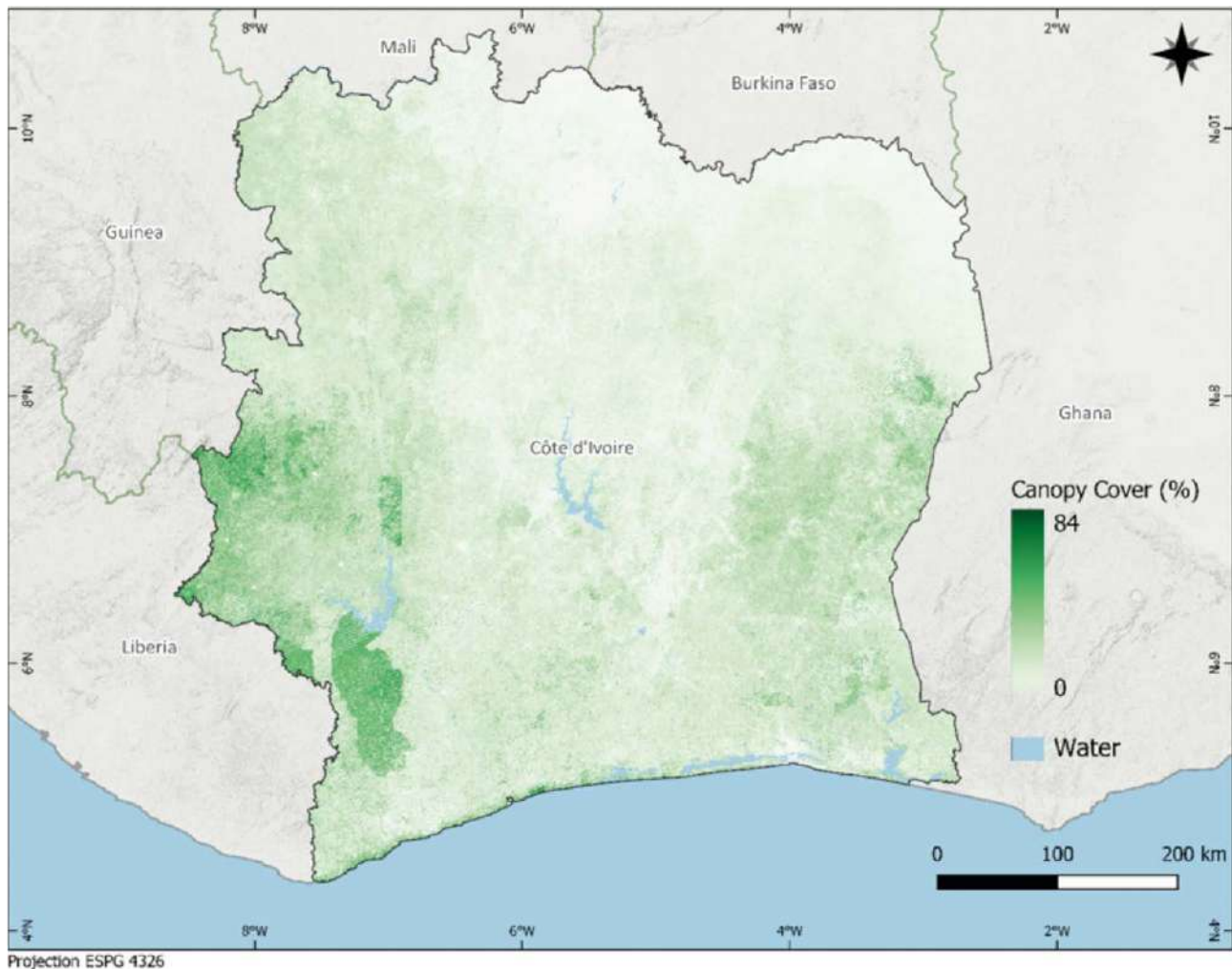


Figure 5. Percent (%) canopy coverage in Côte d'Ivoire where trees are above a height of 5m (NASA). Some missing values exist due to scan lines, cloud cover etc. Gaps in the 2015 dataset were filled with data from 2010 where available. Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

The NASA forest canopy cover datasets identify tree cover where trees are above 5m in height. Cocoa trees in Côte d'Ivoire are 4.5-6m tall (Rainforest Alliance, 2016). Therefore, monoculture cocoa plantations may be identified as forest cover by satellite remote sensed tree cover datasets. The GLAD Tree Canopy Height in the 2019 dataset (Potapov *et al.*, 2020) detects canopy height above three meters at 30m resolution. However, cells with a canopy height greater than 5m may still represent cocoa monocultures and full-sun cocoa does typically contain some trees, and excluding cells from the class on the basis of tree canopy height within the cells may misrepresent cells under full-sun management. We therefore do not use tree canopy height as a criterion to classify plausible shade levels. Instead, the mean tree canopy height in each cocoa management class was calculated to sense-check final results.

In order to determine the relationship between actual shade canopy cover as measured from the ground and the canopy cover as detected through remote sensing, samples from the [CocoaSoils](#) project, where shade canopy coverage in cocoa plantations was assessed from the ground, were compared to the combined NASA datasets (Sexton *et al.*, 2013). Using this data, it was shown that most actual 'full-sun' cocoa plots (up to about 10% canopy cover) could show a detected canopy cover of up to at least 30%, with some points reaching up to 50% canopy cover (Figure 6). Therefore, any cocoa cells with canopy coverage (according to Sexton *et al.* (2013) for years 2010 and 2015) below 30% were assumed to potentially be full-sun cocoa plantations.

In the case of degraded non-cocoa areas in classified forests, which are a target for agroforestry,

areas were considered highly degraded where canopy coverage was below 25% as detected by Sexton *et al.* (2013). This value was chosen to align with the national description of highly degraded classified forests.

Temporal forest dynamics

The cells likely to represent 'full-sun' were then further refined using the Tropical Moist Forest dataset (Vancutsem *et al.*, 2021), a long-term (1990 – 2019) dataset identifying cells where forest has been converted to other land uses, degraded, or dating when and where afforestation has occurred. Cocoa in Côte d'Ivoire has been driving deforestation and degradation, particularly since 2010 (VividEconomics, 2020). Therefore, cells identified as cocoa by VividEconomics and which overlap with cells classed as deforested, degraded, or 'Other land use (including agriculture)' in the Tropical Moist Forest dataset are likely to be cocoa plantations. It was assumed that cells classed as 'Other land use (including agriculture)' or as deforested were likely to be full-sun cocoa plantations. Cells classed as 'Degraded' were assumed to represent partial-shade plantations (at least 30% canopy cover). Those which were classed as intact or recently afforested in the Tropical Moist Forest dataset and with at least 30% canopy cover were classed as high-shade cocoa agro-forests (Table 2).

Where tree canopy cover (%) in cocoa areas was classed as over 30%, but deforestation had occurred since 2016 according to Vancutsem *et al.* (2021), cells were classed as full-sun plantations.

If deforestation occurred before 2016 and tree canopy cover was estimated as being $\geq 30\%$, the cell was classed as partial-shade agroforestry.

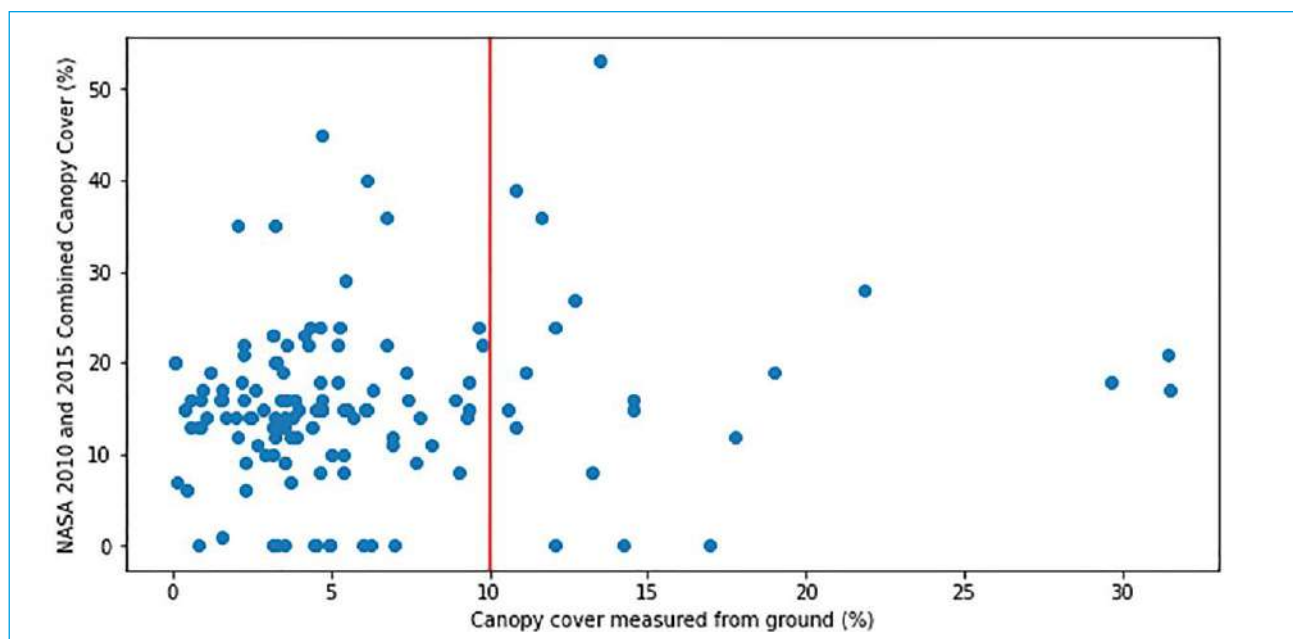


Figure 6. Canopy cover measurements taken from CocoaSoils plots vs remotely sensed from the NASA 2010 layer (30m resolution). Canopy cover of less than 10% measured on the ground is considered full sun.

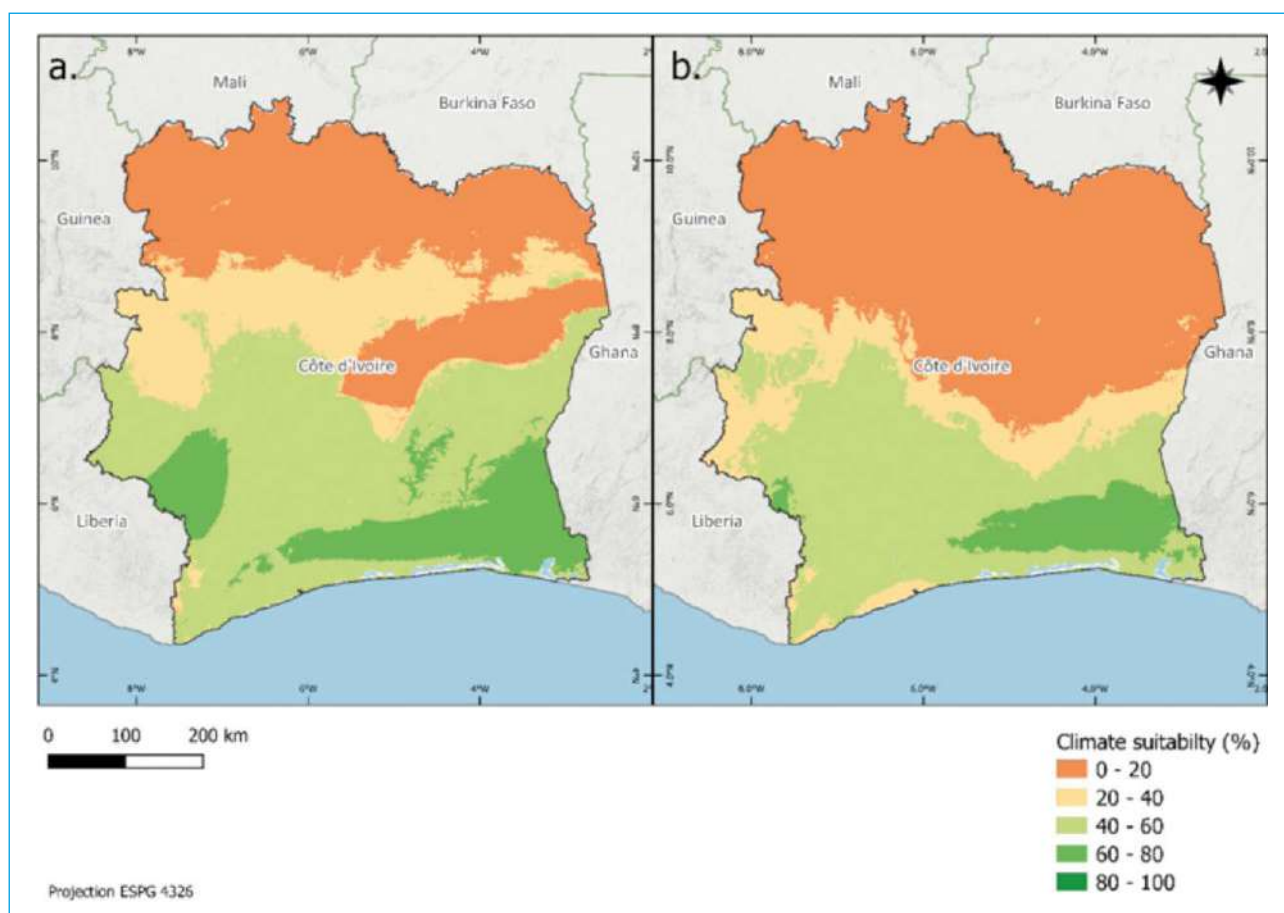


Figure 7. Cocoa climate suitability under a). current climatic conditions and b) projected climatic conditions in 2050 (Shroth *et al.*, 2016). Areas below 20% suitability are considered unsuitable for cocoa growing. Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations

Climatic suitability

Finally, two datasets were created using the cells identified as potential areas for the promotion of cocoa agroforestry in the previous steps. Firstly, those which are suitable for cocoa cultivation under the current climate and those suitable for cocoa under a projected climate for 2050 from Schroth *et al.* (2016). Cocoa cells were classed as climatically suitable where suitability was at least 20% under either scenario (Figure 7). We assume here that areas suitable for cocoa growing are similarly suitable for cocoa agroforestry as agroforestry-specific suitability data is not available and there are indications that shade trees in agroforestry systems can support adaption to climate change by buffering temperature extremes (Neither *et al.*, 2020).

Summary: assessing shade levels in cocoa growing areas

Land cover, tree canopy cover, forest disturbance, climatic suitability data were combined to distinguish areas under different cocoa management practices (full-sun, partial-shade and high-shade agroforestry)

(Table 2). These were then used to identify areas suitable for agroforestry promotion in cocoa growing areas in the rural domain and in classified forests.

Where cocoa was mapped by VividEconomics (2020) and had a canopy cover below 30% (Sexton *et al.* (2013) years 2010 and 2015), it was assumed that the cell represents full-sun cocoa plantations. The Tropical Moist Forest dataset (Vancutsem *et al.*, 2021) was then used to distinguish between cocoa cells with canopy cover above 30% which were potentially under a partial or high shade agroforestry system. Where canopy cover is greater than 30% on 'other land use without afforestation', classed as deforested before 2016, degraded or disturbed by Vancutsem *et al.* (2021) they are classed as partial-shade agroforestry. Cocoa cells were classed as a high shade agroforestry system where they were classed as 'Undisturbed Tropical Moist Forest', 'Forest regrowth', young and old afforestation in the Vancutsem *et al.* (2021) dataset and had a canopy coverage of $\geq 30\%$ in 2015 (or 2010 if no cell value was present in 2015).

Cells identified as cocoa in the VividEconomics (2020) dataset but classed as plantation regrowing, conversion to tree plantation, water converted to forest regrowth, undisturbed mangrove, other mangrove classes by Vancutsem *et al.* (2021) were excluded from the analysis. 'Plantations' were defined as being mainly oil palm and rubber (see Appendix 2). Similarly, any cells with climatic suitability (current or projected 2050 climate) below 20% were excluded.

Identifying suitable non-cocoa growing areas in degraded classified forests

Non-cocoa growing areas were only considered within highly degraded classified forests, defined as forests that are more than 75% degraded in the CFI implementation plan. We therefore included areas where canopy coverage (Sexton *et al.*, 2013) was below 25%. Areas which were classed as settlements, closed forest and water by VividEconomics (2020) were excluded by the analysis as these were not deemed suitable for establishing cocoa agro-forests.

Table 2. Criteria used to identify areas suitable for agroforestry promotion based on available datasets and cocoa management descriptions.

Class	Land cover (VividEconomics, 2020)	Tree canopy coverage (2010/2015) NASA (%)	Tropical Moist Forest Classes (Vancutsem <i>et al.</i> 2021)	Suitability (current or 2050) (Schroth <i>et al.</i> , 2016).
Full-sun	Cocoa	<30%	Other land use without afforestation, deforestation	>=20%
Full-sun	Cocoa	>=30%	Deforestation (2016 onwards)	>=20%
Full-sun	Cocoa	<30%	Degraded forest (short, long, 2/3 term disturbance), degradation started in 2019	>=20%
Full-sun	Cocoa	<30%	Undisturbed Tropical Moist Forest, Forest regrowth, young and old afforestation	>=20%
Partial-shade agroforestry	Cocoa	>=30	Other land use without afforestation (includes agricultural land), deforestation (before 2016)	>=20%
Partial-shade agroforestry	Cocoa	>=30	Degraded forest (short, long, 2/3 term disturbance), degradation started in 2019	>=20%
High-shade Agroforestry	Cocoa	>=30%	Undisturbed Tropical Moist Forest, Forest regrowth, young and old afforestation	>=20%
Non-cocoa (inside classified forests only)	Rubber, palm, cashew, Industrial agriculture, Other	<25%	Not included	>=20%
Excluded	Cocoa	>=30%	Plantation regrowing, conversion to tree plantation, water converted to forest regrowth, undisturbed mangrove, other mangrove classes	>=20%
Excluded	Cocoa	<30%	Plantation regrowing, conversion to tree plantation, water converted to forest regrowth, undisturbed mangrove, other mangrove classes	>=20%
Excluded	Cocoa	<30%	Plantation regrowing, conversion to tree plantation, water converted to forest regrowth, undisturbed mangrove, other mangrove classes	<20%
Excluded	Cocoa	NA	Cocoa classes above (full-sun, partial and agroforestry) but unsuitable climate	<20%
Excluded	Settlements, Closed Forest, Water	NA	Not included	NA
Excluded	Rubber, palm, cashew, Industrial agriculture, Other	>25%	Not included	<20%

Co-benefits

Carbon stock values by cocoa management

Carbon storage by cocoa agroforestry systems is partially a function of their management (Nadege *et al.*, 2018). Therefore, carbon values for different cocoa management scenarios were applied from the literature. Some examples of recent studies are shown Appendix 1. Carbon stock values under each cocoa management class (full-sun, partial-shade and high-shade) were identified through literature review. The review focussed initially on studies in Côte d'Ivoire, however results were expanded to nearby West African countries (E.g. Ghana and Cameroon) due to lack of data. The most complete data to estimate total carbon stock values for each class, was found in Sonwa *et al.* (2017b). This study estimated a total carbon stock (above and belowground biomass of cocoa and shade trees, soil and litter) of 60 tC.ha⁻¹ in full-sun plantations, 81 tC.ha⁻¹ in partial-shade systems and 201 tC.ha⁻¹ in high-shade agroforestry systems.

Other ecosystem services and biodiversity conservation

Due to the lack of studies quantitatively comparing impacts on non-carbon ecosystem services and biodiversity between agro-forests, plantations with partial shade and full-sun monocultures (see also Neither *et al.*, 2020), these impacts could not be mapped. Instead, we used proximity to forests and settlements as proxies for the potential importance of cocoa agroforestry for biodiversity conservation and ecosystem service provisioning respectively (Figure 8).

Areas near settlements are often of greater importance for ecosystem service provisioning, such as timber and non-timber products. Proximity to closed forests was used as a proxy to estimate importance for biodiversity conservation, cocoa agroforestry areas nearest closed forests are assumed to be of greater importance for biodiversity conservation as they may increase the availability and quality of habitat, whilst improving connection to existing habitats for wildlife.

Proximity to settlements and closed forests (as defined by VividEconomics, 2020) was estimated using the Proximity (Raster Distance) tool in QGIS (version 3.18). Values were normalised by scaling between 0-1 using the Raster Calculator.

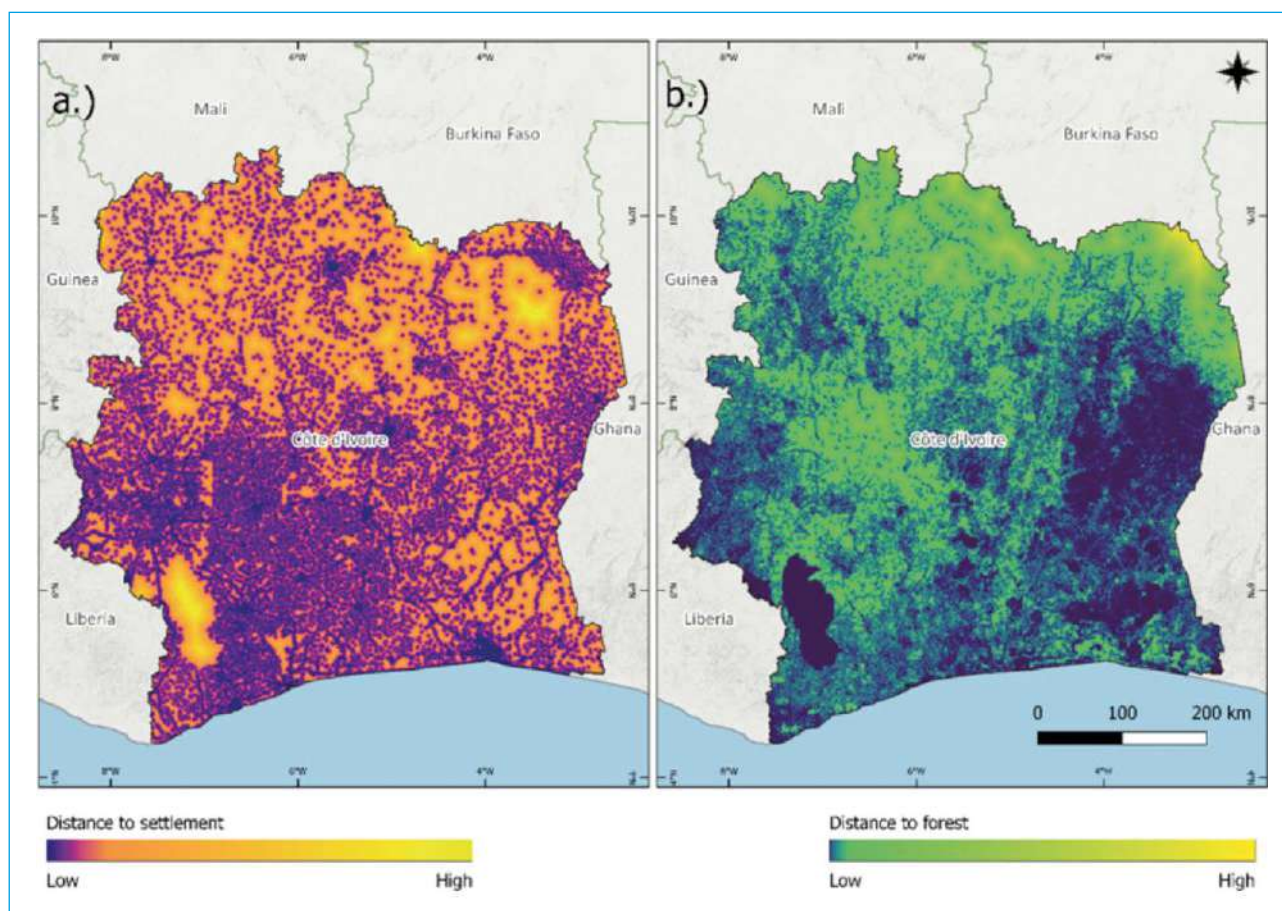


Figure 8. Distance to settlements and to closed forests. Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Results

Areas to promote cocoa agroforestry in existing cocoa landscapes

Within cells classed as cocoa by VividEconomics, the average canopy coverage in 2010 was 22.64%, falling to 19.3% in 2015 (min = 0, max = 85), according to the most recent NASA forest canopy cover datasets.

To check for consistency, we compared the final classification resulting from the methodology with the tree height dataset (Potapov *et al.*, 2020) across all cocoa growing areas. We found that the average tree canopy height within the full-sun cocoa class was 6.84m, whilst the average height was greater in both agroforestry management classes: 8.95m and 11.78m in partial-shade and high-shade agroforests respectively. This gives an indication that the classification is consistent with expected patterns in canopy height difference between the classes.

In classified forests

Based on VividEconomics (2020) land cover data, cocoa plantations are thought to represent 625,332 hectares of the land cover within classified forests which do not overlap with protected areas (BNEDT, 2016; UNEP-WCMC and IUCN, 2021) (Table 3).

Within classified forests (which don't overlap with designated protected areas), the assessment focused on existing cocoa landscapes and other degraded non-cocoa lands (excluding settlements, closed forests, and water).

Area with potential for promotion of cocoa agroforestry

Within all Classified Forests which do not overlap with protected areas (BNEDT, 2016) and under current climate suitability for growing cocoa, 508,342 hectares or 83% of cocoa cells are assumed to be under full-sun management, followed by partial-shade agroforestry (86,807 hectares or 14%) and 15,718 hectares of high-shade agroforestry (2.6%). Under the projected 2050 climate (Schroth *et al.*, 2016), classes remain largely unaffected, with negligible decreases in all classes (Table 4).

When looking at other degraded lands (non-cocoa areas with less than 75% canopy cover) within classified forests, 1,368,969 hectares was found to be within current climatically suitable areas for cocoa growing. When limiting areas using climate suitability in 2050, the area of degraded non-cocoa lands which could be used to promote cocoa agroforestry within Classified Forests decreases to 966,586 hectares. This represents a reduction of approximately 30% of potentially suitable land due to climate change.

Priority areas for increasing tree cover through cocoa agroforestry in highly degraded classified forests, are mainly in the West and South-west of the country (Figure 9). The northern degraded classified forests are at the lower end of current suitability (20-40%) as defined by Schroth *et al.* (2016) and likely unsuitable in 2050 (Figure 11), which means that they should only be targeted for cocoa agroforestry promotion as an adaptation strategy in existing cocoa plantations. If there is no cocoa currently, then they should most likely not be targeted for restoration through cocoa agroforestry but through other more adapted agroforestry crops or forest plantations.

Table 3. Land cover within classified forests (BNEDT, 2016) based on VividEconomics (2020) land cover. Classified forests overlapping with protected areas (UNEP-WCMC and IUCN, 2021) were excluded.

Land class	Area (ha)	Proportion (%)
Cocoa	625,332	17.9
Rubber	35,887	1
Closed Forest	519,670	14.8
Palm	15,387	0.4
Settlement	18,690	0.5
Water	15,073	0.4
Cashew	48,111	1.4
Industrial Agriculture	12,963	0.4
Other	2,209,659	63.11
Total	3,500,772	100

Table 4. Cocoa categorised into full-sun cocoa, partial and high-shade agroforestry and degraded non-cocoa land within Classified Forests. Classified forests overlapping with protected areas (UNEP-WCMC and IUCN, 2021) were removed.

Class	Current Climate Suitability (ha)	2050 Climate Suitability (ha)
Full-sun	508,342	507,847
Partial-shade agroforestry	86,807	86,800
High-shade agroforestry	15,718	15,716
Degraded non-cocoa land	1,368,969	966,586
Total potential cocoa growing areas	1,979,836	1,576,949

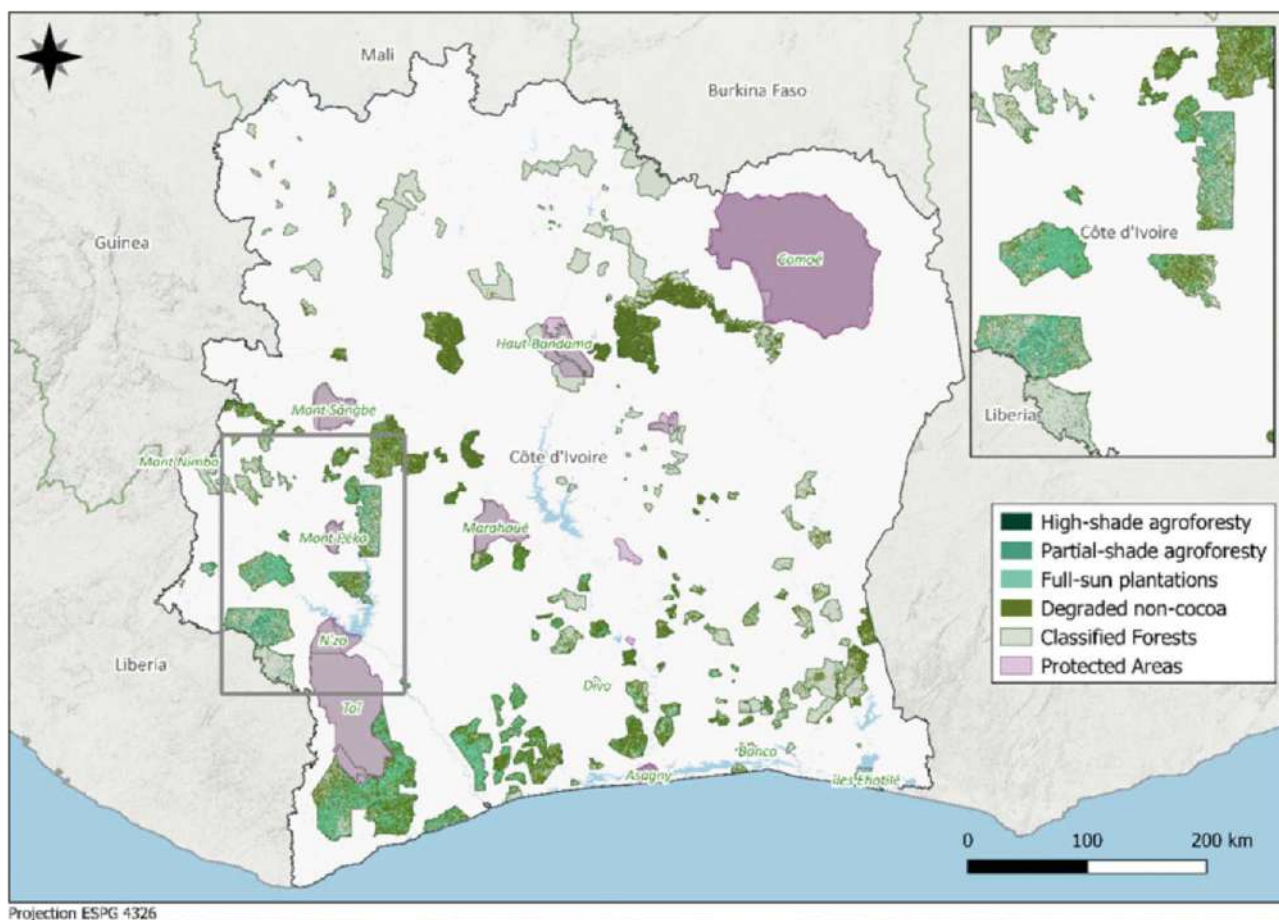


Figure 9. Classification of estimated shade levels in existing cocoa growing areas and degraded non-cocoa areas which are climatically suitable under the current climate within classified forest. Classified forests which are also protected areas are not considered (BNEDT, 2016; UNEP-WCMC and IUCN, 2021).

In the rural domain

Within the rural domain (protected areas and classified forests excluded), an area of over 2 million hectares was identified as being potentially under cocoa cultivation. Of this, 89% were assumed to be under full-sun management, which represents a significant opportunity for increasing carbon stocks and other ecosystem services. This was followed by partial-shade agroforestry (9.3%) and high-shade agroforestry (2%) (Table 5).

Similar to trends seen in classified forests, most areas currently identified as being cocoa growing remain suitable under future climate projections (Schroth *et al.*, 2016). Cells in the full-sun class are the most affected, decreasing by 10,885 hectares (0.6%), whereas changes to areas identified as partial and high-shade are negligible.

Table 5 Cocoa categorised into full-sun cocoa, partial and high-shade agroforestry within the rural domain. Excluding designated protected areas and classified forests (UNEP-WCMC and IUCN, 2021).

Class	Current Climate Suitability (ha)	2050 Climate Suitability (ha)
Full-sun	1,808,860	1,797,975
Partial-shade agroforestry	191,498	190,434
High-shade agroforestry	41,764	41,673
Total potential cocoa growing areas	2,042,122	2,030,082

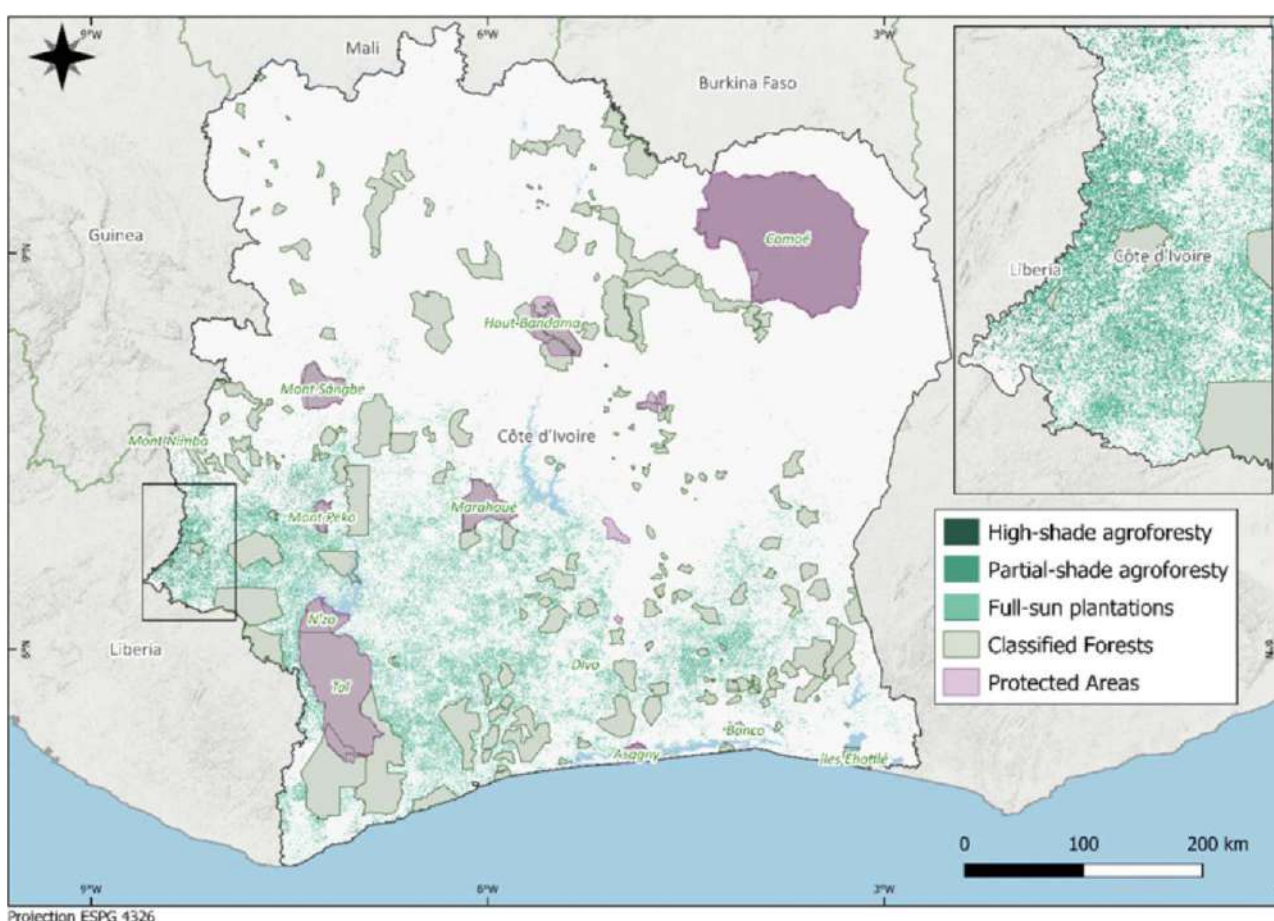


Figure 10. Classification of estimated shade levels in existing cocoa growing areas which are climatically suitable for cocoa growing under the current climate within the rural domain, excluding designated protected areas and classified forests (BNEDT, 2016; UNEP-WCMC and IUCN, 2021).

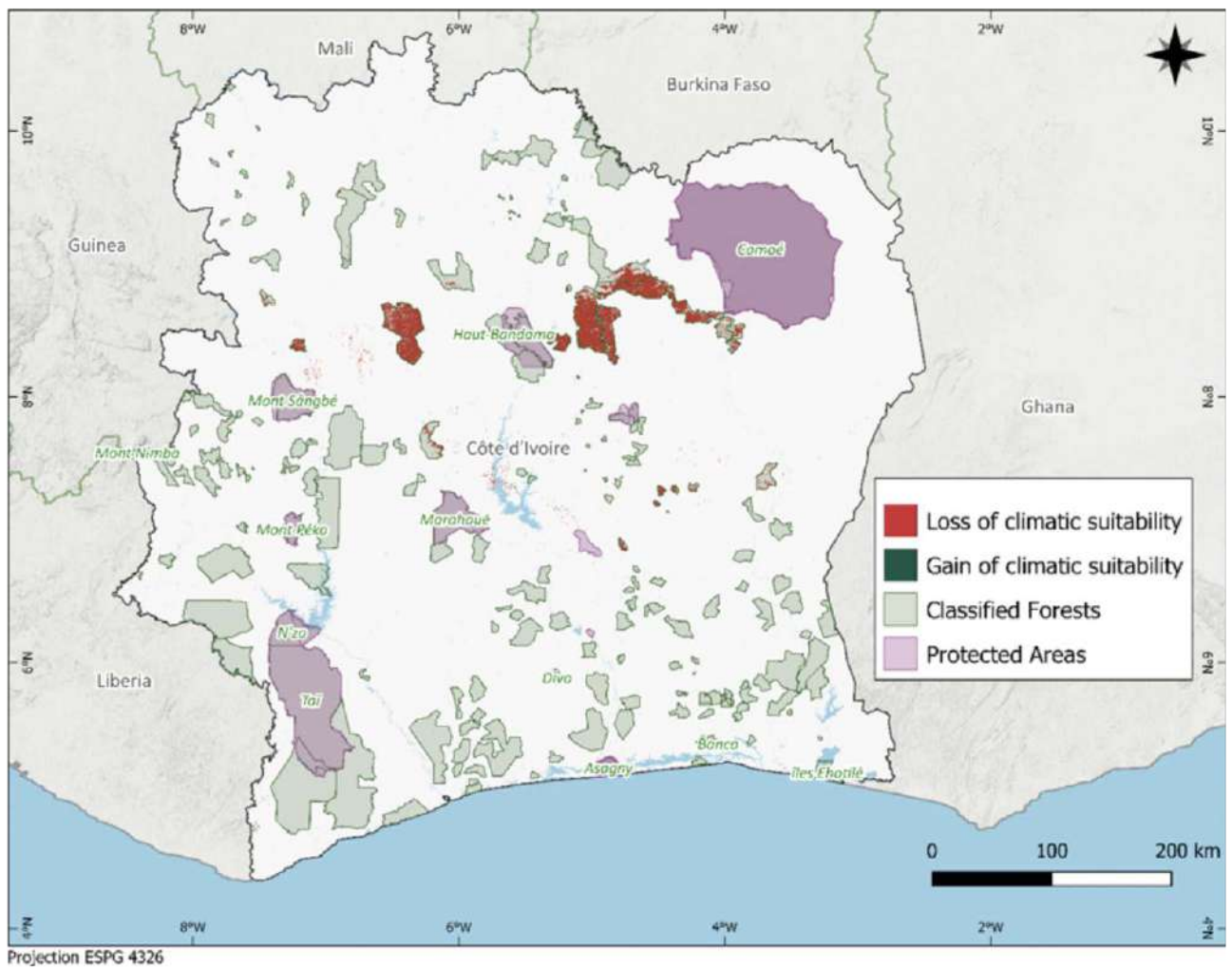


Figure 11. Potential cocoa growing areas within classified forests and the rural domain which become climatically unsuitable (<20% suitability) and climatically suitable ($\geq 20\%$ suitability) under a projected 2050 climate. This includes areas that are either currently under cocoa or degraded non-cocoa areas in classified forests which may be targeted for restoration through cocoa agroforestry. Classified forests which are also protected areas are not considered (BNEDT, 2016; UNEP-WCMC and IUCN, 2021). Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Co-benefits

Carbon co-benefits

More than 2.6 million hectares of cocoa growing areas suitable under the current climate were identified within classified forests and in the rural domain. Under their current management practices, it was estimated that these store 173 million tonnes of carbon. If high shade agroforestry were to be implemented in all full-sun and partial-shade areas, the total carbon stock stored within cocoa landscapes would increase to more than 533 million tonnes of carbon (Table 6) (Figure 12).

However, in the rural domain, we assumed it to be unlikely that high-shade agroforestry will be

widely implemented (by 2030) due to practical considerations and potential trade-offs with cocoa yields. We therefore consider a differentiated scenario: **transformation to partial shade in full sun cocoa in the rural domain, and transformation to high shade in classified forests**, supported by restoration programmes under the CFI. The potential carbon stock gains for a transition from full sun to partial-shade agroforestry in the rural domain (1.8 million hectares) would represent an increase in carbon stock of almost 38 million tonnes in areas currently climatically suitable for cocoa (Table 6). In classified forests (approx. 595,000 hectares), transformation to high-shade cocoa would yield an increase of 82 million tonnes of carbon (Table 6), for a total of 293 million tonnes (classified forests and rural domain).

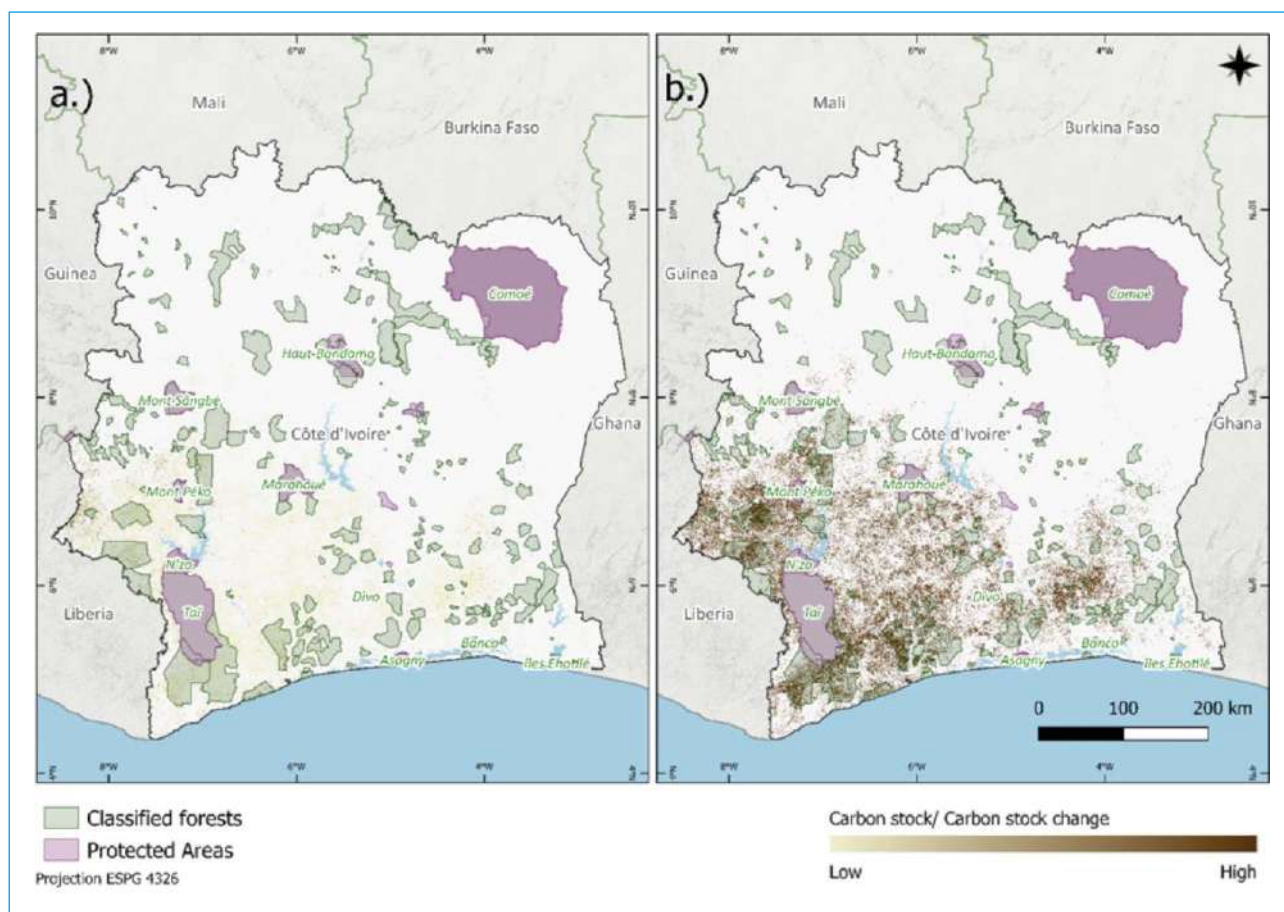


Figure 12. a.) estimated carbon stocks in current cocoa growing areas in both classified forests and the rural domain and b.) change in carbon stocks after transition to high-shade agroforestry. Current cocoa growing areas are restricted to areas currently climatically suitable for cocoa. Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Table 6 Cocoa carbon stocks (AGB, BGB, litter and soil) within classified forests and the rural domain under the current and agroforestry implementation scenario when climatic suitability under the current climate is considered. Non-cocoa lands are excluded. Most plausible scenarios shaded.

Area	Class	Current Climate Suitability (ha)	Current carbon stocks (tC)	Partial-shade agroforestry scenario carbon stocks (tC)	High-shade agroforestry scenario carbon stocks (tC)
Classified Forests	Full-sun	508,342	30,499,193		102,172,299
	Partial-shade agroforestry	86,807	7,047,046		17,487,114
	High-shade agroforestry	15,718	3,110,133		3,110,133
	Sub-total	601,867	40,656,372		122,769,546
Rural Domain	Full-sun	1,808,860	108,510,587	146,489,293	363,510,468
	Partial-shade agroforestry	191,498	15,572,344	15,572,344	38,642,483
	High-shade agroforestry	41,764	8,264,168	8,264,168	8,264,168
	Sub-total	2,042,122	132,347,099	170,325,805	410,417,119
Total Area	Full-sun	2,317,202	139,009,780		465,682,767
	Partial-shade agroforestry	278,305	22,619,390		56,129,597
	High-shade agroforestry	57,482	11,374,301		11,374,301
	Total	2,643,989	173,003,471		533,186,665

Under a 2050 climate, around 3,000 hectares of land currently used for cocoa will become less than 20% suitable for cocoa. Under current management practices, an estimated 172 million tonnes of carbon are stored in the remaining areas. Under the high-shade agroforestry implementation scenario, this

increases to more than 530 million tonnes (Table 7). Under the differentiated 'rural domain to partial shade- classified forests to high-shade' scenario, an estimated total carbon stock of **292 million tonnes** could be obtained.

Table 7 Cocoa carbon stocks (AGB, BGB, litter and soil) within classified forests and the rural domain under the current and agroforestry implementation scenario when climatic suitability under the future climate is considered. Non-cocoa lands are excluded. Most plausible scenarios shaded.

Area	Class	Current Climate Suitability (ha)	Current carbon stocks (tC)	Partial-shade agroforestry scenario carbon stocks (tC)	High-shade agroforestry scenario carbon stocks (tC)
Classified Forests	Full-sun	507,847	30,469,482		102,072,766
	Partial-shade agroforestry	86,800	7,046,473		17,485,692
	High-shade agroforestry	15,716	3,109,900		3,109,900
	Sub-total	610,363	40,625,855		122,668,358
Rural Domain	Full-sun	1,797,975	107,856,124	145,605,768	361,318,017
	Partial-shade agroforestry	190,434	15,485,969	15,485,969	38,428,145
	High-shade agroforestry	41,673	8,245,090	8,245,090	8,245,090
	Sub-total	2,030,082	131,587,183	169,336,827	407,991,252
Total Area	Full-sun	2,305,822	138,325,606		463,390,783
	Partial-shade agroforestry	277,234	22,532,442		55,913,837
	High-shade agroforestry	57,389	11,354,990		11,354,990
	Total	2,641,185	172,213,038		530,659,610

The potential increase in carbon stock as a result of implementing cocoa agroforestry on lands which were not previously cocoa plantations cannot currently be calculated.

This is due to a lack of specificity of some of these land cover classes (e.g "other", grouping annual crops and grasslands) and data on carbon stocks for each land cover class.

Prioritising areas for restoration through cocoa agroforestry

When combining potential for increasing carbon stocks with proximity to settlements and to closed forests, priority areas are located in the West and Southwest, near and in degraded classified forests and other protected areas (e.g. Tai forest) (Figure

13). The areas highlighted in the South West and East of the country are priority regions for the CFI start-up phase in Côte d'Ivoire, which includes forest protection and restoration as well as agroforestry promotion activities. In the south West this corresponds to areas of high potential benefits from implementing agroforestry as identified in this study; whilst in the East this study draws attention to an area slightly more to the West (Figure 13).

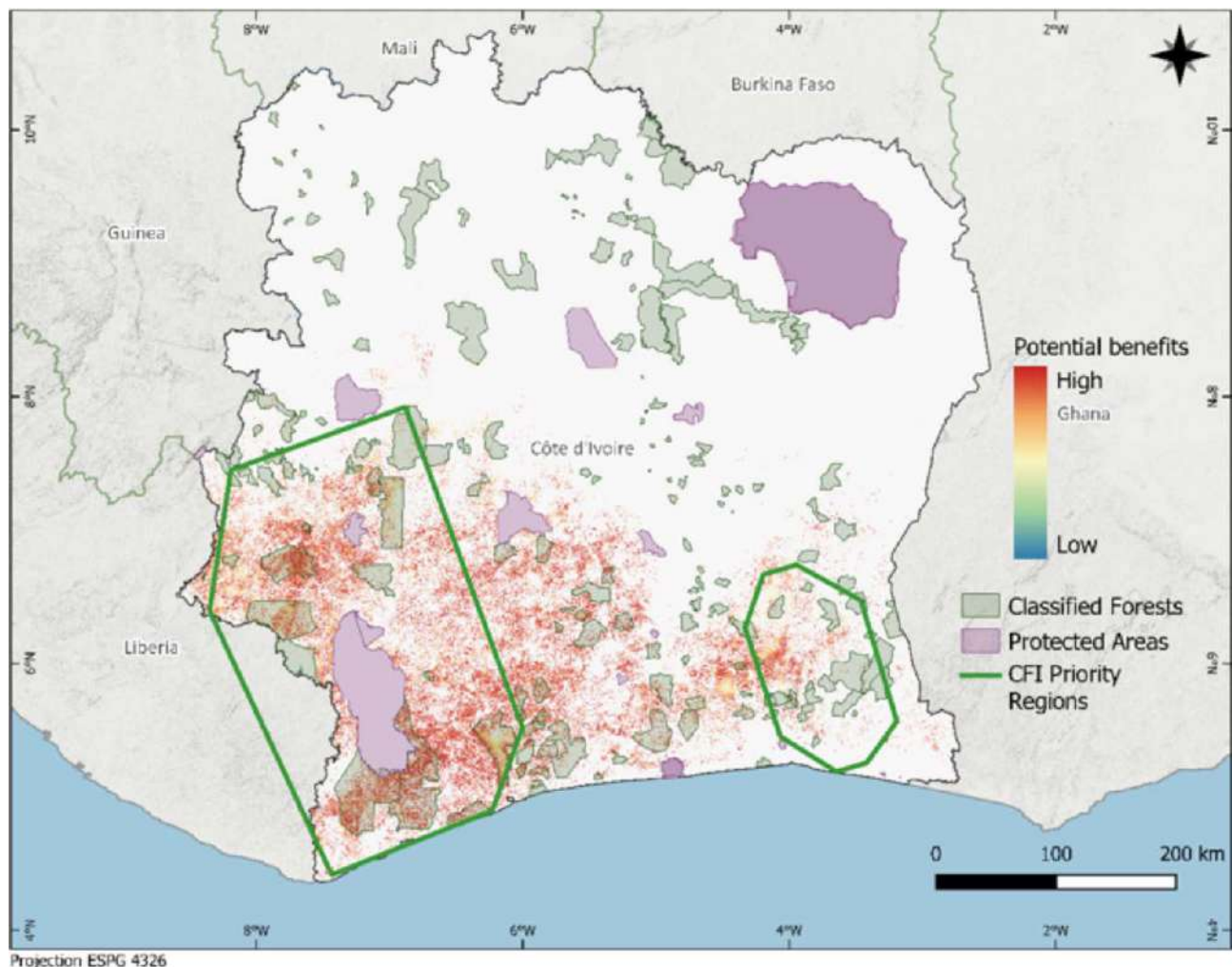


Figure 13. Combined priorities for increasing carbon stock, proximity to forest and proximity to settlements within cocoa growing areas identified as full-sun or partial-agroforestry. Current cocoa growing areas are restricted to those suitable under the current climate. Green circles indicate priority regions for the Cocoa and Forests Initiative start-up phase. Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

A photograph of a young tree with a slender trunk and a dense canopy of green leaves, standing in a field of low-lying green vegetation. The background shows more trees and a clear sky. In the top left corner, there is a decorative graphic consisting of a grid of dots in shades of orange and light beige.

Discussion

Below we first discuss methodological considerations and study limitations and how they may have affected the study results. We then assess the results considering the primary and secondary policy targets that this work aimed to inform as well as some further implications.

Data and methodological considerations

The methodology draws on several different datasets to identify suitable cocoa growing areas and distinguish between different cocoa management practices. There are some general limitations with this approach, such as a lack of consistent temporal timescales and spatial resolution between datasets. Where possible, data was selected which aligned temporally with the landcover dataset and data was resampled to a 30m resolution.

Landcover data

The VividEconomics (2020) dataset makes it possible to identify where cocoa may be growing at the national scale. However, the dataset is still limited, in that the type of cocoa management cannot be identified. Compared with other datasets, the VividEconomics dataset estimates a much smaller coverage of cocoa in Côte d'Ivoire: approximately 2.8 million hectares in 2019, whereas the Ministry of Environment and Sustainable Development (MINEDD) estimated 3.5 million hectares (MINEDD, 2014 cited in National REDD+ Strategy), the FAO (2018) estimates that cocoa plantations cover approximately 4 million hectares, and Abu *et al.* (2021) estimate a total coverage of 3.69 million hectares in 2019. Therefore, this study may underestimate the cocoa lands available for restoration. The underestimation of area under cocoa may be widespread due to the difficulties in detecting it remotely, with young cocoa plantations often established under existing tree canopies which may not be distinguishable from satellite imagery. This may also limit the detection of cocoa encroachment into protected areas and dense forests. Estimations by MINEDD and FAO are most likely based on reported harvested areas, not on actual measurements.

The vast majority of the cocoa cells detected by VividEconomics (2020) were classed as likely full-sun plantations through our method factoring in forest disturbance and tree canopy cover. This was significantly greater than the proportion of cocoa farms thought to be full sun, on average 35% is thought to be full-sun and around 50% under partial shade (<30%) cocoa agroforestry (WWE, 2006). This difference may be due to agroforestry plantations being more difficult to distinguish remotely due to cocoa being under canopy cover. Likely for similar

reasons, in classified forests, we found less cocoa area available and suitable for transformation to agroforestry than the 1 million hectares target. No ground data was available to verify our classifications. However, this study aimed to identify cocoa growing areas to prioritise for agroforestry implementation, and the less shaded areas are the most important in that regard.

Infrastructure was not included as a land cover class in the land cover dataset. Infrastructure could limit available land for cocoa agroforestry or be a driver of degradation of intact areas through improved accessibility.

The VividEconomics (2020) land cover dataset was limited in its use to identify grassland and wetland areas. Therefore, when assessing non-cocoa areas with potential for restoration through cocoa agroforestry in classified forests, it was not possible to ensure that natural non-forest ecosystems, such as wetlands or natural grasslands, were excluded. Therefore, areas identified as being potentially suitable will need to be further refined through ground-truthing or improved datasets.

Tree density vs Canopy cover

It is not yet possible to map tree density at large spatial scales using remotely sensed products. Therefore, for this analysis, canopy cover was used. Limitations of this approach include the fact that cocoa trees, where their height reaches above 5m, may be detected as part of the canopy cover by earth observation sensors. Yet, canopy cover definitions in agro-forests often refer to that of the shade trees rather than the overall canopy cover of the agro-forest. Canopy cover (from shade trees or overall) is also an important variable to measure in the context of benefits from agroforestry systems since shading affects production and is often used to assess trade-offs with cocoa yield. The approach based on tree canopy cover data may therefore have been limited in its ability to accurately distinguish different cocoa management approaches within cocoa plantations. Although spatial canopy cover data is more readily available than tree density data, there were limitations with the data used. Large gaps in the data were evident even in areas known to be highly forested (e.g. Taï National Park). This is likely due to image scan line and cloud cover issues. Where possible, they were filled using data from an earlier point in time, however gaps still remained and these were assumed to represent cells with 0% canopy cover (see Figure 5).

Climatic suitability

In this study we considered suitability as a homogenous variable (i.e. suitable or not suitable). Yet, climatic suitability is assessed on a gradient and the impacts of future climate change vary in space as do potential adaptation strategies (Bunn *et al.*, 2019). Further analyses should assess how this influences the potential for implementing agroforestry throughout the country.

Defining cocoa management types

Descriptions of management types varied: according to information sources some use shade tree density, others canopy or qualitative descriptions or terms such as 'Innovative' cocoa management vs 'traditional'. Studies also vary in the number of classes used. For example, some studies split cocoa plantations into two classes, full-sun and traditional agroforestry, whereas others may distinguish cocoa into further classes such as 'innovative cocoa' and partial-shade systems. Where studies refer to similar types of cocoa systems (e.g. high shade/traditional), their descriptions were inconsistent. For example, Dawoe *et al.* (2016) describe 'traditional' cocoa systems as having a shade canopy cover of above 25%, whereas Wade *et al.* (2010) describe 'high-shade' agroforestry systems as having a shade canopy cover of above 15%. Variations in the description and classification of these systems increase the difficulty in accurately applying ecosystem service values to understand the impact of a shift to agroforestry systems. There is a need to improve cocoa management descriptions and data collection within Côte d'Ivoire and other West African countries to understand the benefits and limitations of cocoa agroforestry for cocoa production, carbon storage and other ecosystem services (timber products, soil erosion, nutrient cycling, local climate, water purification, biodiversity etc.).

Estimating carbon stocks and carbon stock changes

There is a lack of consistent data in the literature on carbon stock density in cocoa management types, within and outside of Côte d'Ivoire. The values for carbon stocks differed considerably between studies, though this was also due to the lack of consistent definitions of low/high shade between studies. Studies included different carbon pools, including aboveground biomass, belowground, soil, deadwood and litter. Some studies report carbon stocks in terms of the shade trees only, others both shade and cocoa. Tools that allow assessment of carbon stocks based on relative tree cover, such as Co\$ting Nature, restrict the analysis to coarser resolution (100m or 1km) and use remotely sensed canopy cover products, which may misrepresent the shade tree canopy on cocoa plantations. Therefore, it was considered more appropriate to identify cocoa plantations under different shade management systems by combining datasets on forest canopy cover, forest disturbance and climatic suitability.

Other ecosystem services and biodiversity

Many studies describe ecosystem service and biodiversity conservation benefits of cocoa management systems in qualitative terms, but the quantitative benefits and drawbacks of cocoa agroforestry in direct comparison to full-sun systems is lacking (Niether *et al.*, 2020). De Beenhouwer

et al. (2013) compared studies on cocoa and coffee agroforestry systems with natural forest and plantations with sparse trees, but not full-sun monocultures, whereas Niether *et al.* (2020) compared agro-forests to full-sun monocultures but not plantations with sparse trees. They also found few studies investigating the impacts on ecosystem services.

In this study, we therefore use a simple approach to assess a limited set of potential co-benefits from implementing agroforestry in cocoa, based on available data and time. There is a need for more studies to fully understand the range of ecosystem service and biodiversity impacts of cocoa management systems (within Côte d'Ivoire and elsewhere) and to quantify the differences in ecosystem service provisioning by cocoa management type. This analysis could be broadened to cover services such as timber and non-timber forest products, soil nutrients, moisture and retention as well as microclimatic outcomes.

Contribution to restoration targets

This section describes how the results contribute to addressing the policy related targets set in the introduction, starting with the secondary targets.

1. Secondary targets (contribute to the primary target)

A. Restoration of degraded classified forests: Gradually restore classified forests over 75% degraded by transitioning from open agricultural systems to agroforestry systems and then to forest plantations (PM 5 under Strategy Strategic Option 1 in the Agricultural Sector, National REDD+ Strategy).

B. Related to the above, to transform 1 million hectares of cocoa plantations in classified forests to agroforestry systems by 2030: through the introduction of shade trees in full-sun cocoa plantations, payments to farmers to adopt these techniques and the abandonment of the crop at the end of the cultivation (PM 3 under Strategic Option 3, National REDD+ Strategy).

An estimated total **1.96 million hectares** of highly degraded classified forest meets the restoration criteria of being either under full-sun or partial shade cocoa or open-land that is currently climatically suitable for cocoa. Of this almost 600,000 hectares (approx. 30%) are existing cocoa growing areas. The remaining 1.36 million hectares include currently degraded/open land agriculture areas characterised by low canopy coverage (excluding settlements and areas covered with water).

Based on VividEconomics (2020) data, existing cocoa plantations were identified in only 625,332 hectares (Table 3) of classified forests. However, due to the small size of cocoa plantations and difficulties in distinguishing cocoa plantations underneath shade canopies, the total area available may be higher.

Of all areas identified as cocoa in the classified forests, more than 500,000 hectares are most likely full sun plantations and almost 87,000 hectares partial-shade agroforestry. Transforming them to high shade agroforestry systems (based on current climate suitability for cocoa) would help meet almost 60% of the 1 million hectares objective for cocoa agroforestry (Target B). This means that in classified forests, not quite 1 million hectares of cocoa are available for transformation into high shade agroforestry.

Including open non-cocoa in classified forests land would support the 1 million hectares objective and exceed it by 964 thousand hectares under current climate suitability for cocoa. Implementing cocoa agroforestry in these areas would require assessing the relative benefits of transforming non-cocoa open systems to cocoa agroforestry in classified forests compared to other options and depend on local biophysical and socio-economic context. The final area of non-cocoa land available for restoration through cocoa agroforestry will also need to be further constrained to avoid natural habitats, such as grasslands and wetlands, which may have lower carbon stocks but are of national and international importance.

When considering climatic suitability for cocoa under future climate projections, the total area potentially available in classified forests decreases to 1.56 million hectares. In some areas identified as currently degraded non-cocoa open land systems in classified forests, the climate is expected to become unsuitable or cocoa growing in 2050 (Table 4, Figure 11). These tend to be areas on the lower end of the current suitability range as well and are not also considered in existing spatially explicit recommendation domains for adaptation through climate smart cocoa systems (Schroth *et al.*, 2016; Bunn *et al.*, 2019). This is the case, for example, of classified forests in the north. Such areas should not be targeted for restoration via cocoa agroforestry. Rather they should be restored using a crop more adapted for a potential future climate, or by restoring natural vegetation cover.

C. To restore 3.2 million hectares of degraded lands in the rural domain: including through the promotion of agroforestry in 1 million hectares of cocoa, rubber and oil palm crops by 2030. In the case of cocoa plantations, the goal is to introduce at least 50 shade trees per hectare (PM 3 under Strategic Option 4, National REDD+ Strategy). In this analysis only the promotion of cocoa agroforestry in current cocoa growing areas is assessed.

Within the rural domain, more than 1.8 million hectares of cocoa was estimated to be under full-sun management and suitable for potential implementation of partial shade or high shade agroforestry systems, which exceeds the 1 million-hectare target (which includes oil palm and rubber). These areas would represent the largest potential gains in ecosystem services from cocoa, such as carbon sequestration and storage.

2. Primary target

Restore forest cover to 20% of the land area by 2030 (Côte d'Ivoire's Vision for REDD+, National REDD+ Strategy) and National Forest Rehabilitation Conservation and Expansion Strategy.

According to the Forest Resources Assessment Report (FAO, 2020), forests covered less than 9% of land in Côte d'Ivoire (2,836,710 hectares) in 2020 (see also VividEconomics, 2020). Cocoa plantations identified as full-sun or partial shade within the rural domain and potentially available land in classified forests (both cocoa and other degraded areas), total more than 3.96 million hectares available for cocoa agroforestry promotion (within areas which are currently climatically suitable). This represents 12.5% of land nationally, and when combined with existing forest cover in Côte d'Ivoire, 21.4% of forest cover could be achieved. If considering only areas which will be suitable for cocoa under a future climate projection, this may decrease to 3.55 million hectares, or 11.1% of land cover, achieving a total of 20% forest cover in Côte d'Ivoire.

These estimates are based only on areas that may be available through establishing cocoa agroforestry both in existing plantations and on other degraded lands in classified forests. On the latter category of lands, any restoration strategy that achieves canopy cover equivalent to that of highly shaded cocoa may help achieve the same objective, but with different co-benefits than cocoa production. Forest cover could also be increased through other afforestation and forest restoration initiatives, as well as implementing agroforestry practices on other agricultural lands, such as cashew nut, rubber and/or oil palm.

It has to be noted that the forest cover achieved through the implementation of agroforestry in the rural domain and highly degraded (more than 75%) classified forests does not strictly meet all elements of the definition of forests in Cote d'Ivoire as set out in the Forest Code (RCI, 2019). Therefore, rather than an increase in the area of forest, cocoa agroforestry can support an increase in tree cover ("couvert arboré" in French), though this is generally referred to as forest cover, as set out in the reviewed policy documents. Forest plantations are seen to contribute in a similar manner.

Future climatic conditions seem to affect areas with full sun systems the most in our analysis

(Table 4 and Table 5). The reasons why full sun systems seem more prevalent in areas that are more vulnerable to potential climate change needs to be further investigated. However, full sun systems are especially vulnerable to climate change impacts, such as drought and temperature stress, and it is important to consider whether these are areas where agroforestry can support an adaptation strategy or whether these are areas more likely to transition to more drought tolerant (tree) crops (see also Bunn *et al.*, 2019).

Combining the potential for these co-benefits shows that some areas, particularly those close to existing closed forests and settlements should be prioritised for transformation to (high shade) agroforestry systems, as this combines benefits for people and can support biodiversity conservation. It also shows which areas with high potential that are not covered in the start-up phase of the CFI could be targeted in the next phase (Figure 13).

Further considerations

This study provides a spatially explicit assessment of potential priority areas for increasing tree cover in cocoa growing areas to meet cocoa agroforestry definitions, considering specific policy objectives. It does not aim to be prescriptive in those areas, as other factors than the level of current shading will impact where cocoa agroforestry can or should be best implemented and what system designs are most appropriate. Particularly in the rural domain, land ownership and future land use planning, such as settlements and infrastructure development, must be taken into consideration.

Cocoa management must meet a variety of needs for farmers, local people, and wildlife. Therefore, there are several trade-offs which must be considered in establishing the most appropriate management system for a given area. This level of detail was not possible in this analysis and should be implemented on a case-by-case basis with multiple stakeholder views taken into consideration.

Cocoa agro-forest shade trees can consist of a variety of species, each with different purposes. For example, farmers may wish to include shade trees which can be harvested for timber or fruit. The choice of shade tree species (alongside canopy density) can influence the ecosystem services provided by them (including carbon storage and sequestration, pest and disease control and habitat for biodiversity). The choice of shade trees also needs to take agroclimatic factors into consideration: not all trees can grow everywhere, and some tree species may compete with cocoa over resources, such as water, especially in drier areas.

The success of implementing cocoa agroforestry will depend on capacity building, such as training in Good Agricultural Practices in soil and pest and disease management to improve cocoa productivity, improving knowledge of shade management and which associated tree species to use. Appropriate species and management are key to maximising the synergies between productivity and ecosystem service outcomes. Farmers should be consulted when selecting the choice of tree species to be planted, e.g. nitrogen fixers, timber or fruit species or multi-purpose species (Atangana *et al.* 2021). See also Thomson *et al.* (2019) for practical guidance on implementing cocoa agroforestry in Ghana and Cote d'Ivoire.

Finally, agroforestry implementation needs to bring tangible benefits to cocoa farmers. In a meta-analysis, Niether *et al.* (2020) found that when considering all crops harvested (e.g. timber and non-timber forest products) agroforestry system (cocoa and other products) yields were approximately 10 times higher than full-sun monocultures (only cocoa). However, returns from cocoa agroforestry were highly variable and on average lower, which they attributed to the fact that not all economic benefits from agroforestry are easily assessed and to the lack of markets for non-cocoa products. The access to markets for crops other than cocoa from agroforestry systems is crucial for the success of implementing agroforestry promotion programmes. Furthermore, as carbon markets continue to emerge, there may be opportunities for farmers to gain income through the sale of carbon credits as they transition to cocoa agro-forests and re-establish forests. Potential total carbon stock gains in the differentiated scenario (transformation of full sun to partial shade cocoa in the rural domain, and all suitable degraded areas to high shade in classified forests) were estimated at 120Mt carbon or 440 MtCO₂e (Table 6). Assuming a payment of \$10 per tonne of CO₂e (LEAF coalition), this could generate a total of \$ 4.4 Billion in potential income through carbon credits. However, uncertainty and buffer deductions, as well as transaction costs, will reduce this. Further studies are needed to understand the opportunities available to farmers and the impact these markets may have on the diversification of their income.

Conclusions

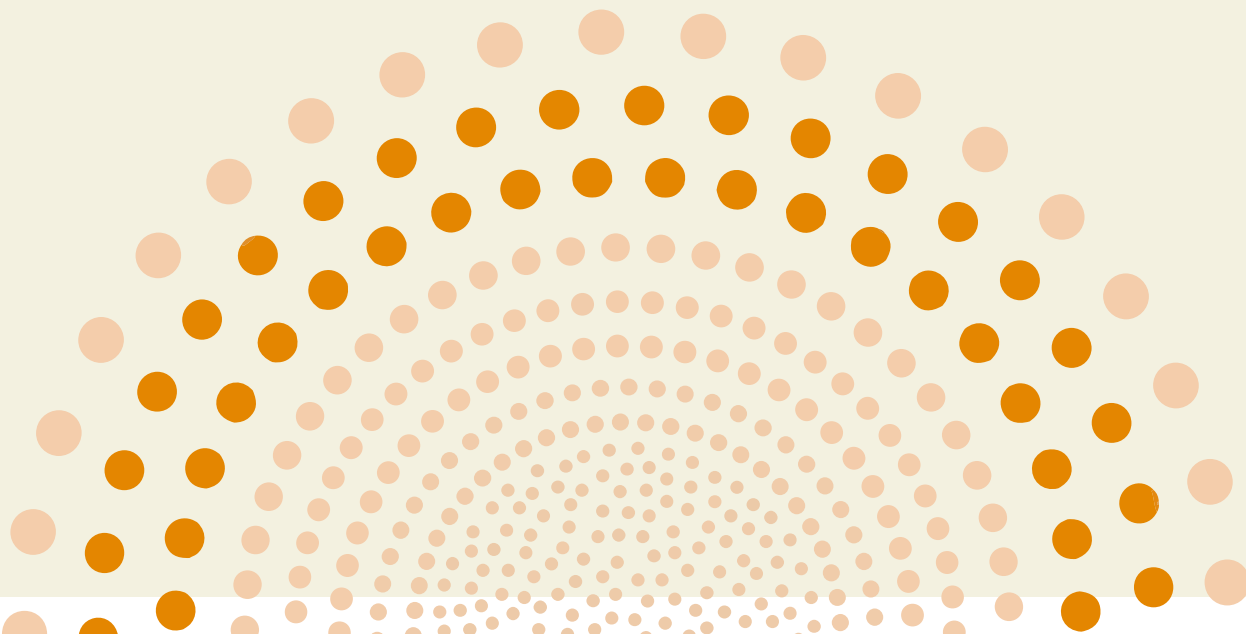
Conclusions

Transforming existing cocoa landscapes to agroforestry practices by increasing tree cover in or around cocoa plantations can support national and sub-national forest cover restoration objectives as set out in national policies, even when considering the impact of climate change on suitability for cocoa growing.

Under these policies, large areas of highly degraded forests in Classified Forests will be restored towards productive uses (agroforestry and forest plantations) that generally have lower biodiversity and carbon values than natural forests. It is therefore important to ensure the restoration or regeneration of less degraded areas within Classified Forests to natural forests, considering the limited coverage of natural forest in Côte d'Ivoire.

More studies are required to understand how a changing climate will impact adaptation efforts through cocoa agroforestry and how agroforestry systems should be implemented to maximise the benefits for farmers, local communities, carbon sequestration and biodiversity conservation.

Finally, the conditions and incentives for cocoa farmers to adopt agroforestry practices need to be improved for large scale implementation programmes to be successful.





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Appendix

Appendix 1 – Cocoa carbon stock values

Example characteristics of cocoa agroforestry management types described in literature, including carbon stock, basal area and tree density. Highlighted entries were used in this study.

Study	Country	Management type (description)	Shade canopy coverage (%)	Total C Stock (tonnes C ha ⁻¹)
Namirembe <i>et al.</i> (2015)	Ghana	Full-sun	<=30%	61 (biomass and soil carbon stocks)
Namirembe <i>et al.</i> (2015)	Ghana	Moderate to high shade	>30%	80 (biomass and soil carbon stocks)
N'gbala <i>et al.</i> 2017	Côte d'Ivoire (Centre-West region)	Unshaded	Not measured but plots described as 'monoculture'	Total biomass = 45.4 +/- 3.5 and litter biomass = 9.3 +/- 1.1
Nadege <i>et al.</i> 2018	Cameroun	Innovative		46.9
Nadege <i>et al.</i> 2018	Cameroun	Traditional		136.1
Sonwa <i>et al.</i> 2018	Cameroun	Cocoa agro-forest with high levels of Musa spp. And oil palm plants. Medium shade density (52% of the carbon pool)	Not specified	95 (Cocoa, shade trees, Litter, belowground, soil)
Sonwa <i>et al.</i> 2018	Cameroun	Agroforêt de cacao à densité élevée de cacao Densité moyenne d'ombrage (48% de la réserve de carbone)	Non spécifié	81 (cacao, arbres d'ombrage, détritux, sous-sol, sol)
Sonwa <i>et al.</i> 2018	Cameroun	Cocoa agro-forest with high density of timber and non-timber tree species High shade density (73% of the carbon pool)	Not specified	201 (Cocoa, shade trees, Litter, belowground, soil)
Sonwa <i>et al.</i> 2018	Cameroun	Unshaded cocoa orchard	Unshaded	60 (Cocoa, shade trees, Litter, belowground, soil)
Wade <i>et al.</i> 2010	Ghana	Intensive cocoa (< 25% shade)	<25%	39 (AGB, BGB and Soil)
Wade <i>et al.</i> 2010	Ghana	Traditional cocoa (> 25% shade)	>25%	131 (AGB, BGB and Soil)
Dawoe <i>et al.</i> 2016	Ghana	No-shade	0	15 (AGB)
Dawoe <i>et al.</i> 2016	Ghana	Low-shade	5.8-8	10.9-13.2 (AGB)
Dawoe <i>et al.</i> 2016	Ghana	Medium-shade	8.1-14.9	15.4-17.9 (AGB)
Dawoe <i>et al.</i> 2016	Ghana	High-shade	>15	18.5-23.5 (AGB)

Appendix 2 – Land cover and forest disturbance classes

JRC Tropical Moist forest dataset

Class descriptions

1 – undisturbed moist forests (class 1) as tropical moist (evergreen or semi-evergreen) forest coverage without any disturbance (degradation or deforestation) observed over the Landsat historical record.

1a – bamboo-dominated forest

1b – undisturbed mangrove

2 – Deforested lands. All disturbance events for which the impacts were observed over more than 2.5 years (900 days) were considered as deforestation processes, with 86% of such deforestation events observed over more than five years. When a deforestation process is not followed by a regrowth period at least over the last 3 years, it is considered as a Deforested land. Deforested land is also characterized by the recurrence of disruptions, i.e. the ratio between the number of years with at least one disruption observed and the total number of years between the first and last disruption observations. This information allowed to discriminate deforestation without prior degradation from deforestation occurring after degradation, the latter also having a lower recurrence due to the period without any disruption between the degradation and deforestation phases.

2a – TMF to tree plantations - mainly oil palm and rubber.

2b – water surface (discriminating permanent and seasonal water)- mainly due to new dams.

2c – other land cover - agriculture, infrastructures, etc.

3 – Degradation

3a – degradation with short-duration impacts (observed within a 1-year maximum duration), which includes the majority of logging activities, natural events and light fires.

3b – degradation with long-duration impacts (between one and 2.5 years) which mainly corresponds to strong fires (burned forests).

4 – recent degradation and deforestation. Initiated in the last three years (after year 2016) and that cannot yet be attributed to a long-term conversion to a non-forest cover, owing to the limited historical period of observation.

4a – duration of minimum 366 days for the years 2017-2018 and a threshold of 10 disruptions for the last year (2019) to consider a deforested land.

4b – The temporal thresholds used to define short-duration degradation, long-duration degradation (at 1 and 2.5 years, respectively).

5 – Forest regrowth. A two-phase transition from moist forest to (i) deforested land and then (ii) vegetative regrowth. A minimum 3-years duration of permanent moist forest cover presence is needed to classify a pixel as forest regrowth (to avoid confusion with agriculture).

6 – Other land cover. Includes savannah, deciduous forest, agriculture, evergreen shrubland and non-vegetated cover.

7 – Vegetation regrowth. Consists of a transition from other land cover to vegetation regrowth and includes two sub-classes of vegetation regrowth according to the age of regrowth (between 3 and 10 years, and between 10 and 20 years) and a transition class from water to vegetation regrowth.

VividEconomics Land Cover Classes

1 = Cocoa

3 = rubber

5 = closed forests

6 = palm

7 = settlement

10 = water

19 = cashew

20 = industrial agriculture

99 = other

