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RESEARCH ARTICLE

# Mapping climate change impacts on cocoa agroforestry systems in Cameroon to mitigate future deforestation

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**Abstract**

Climate change is projected to severely limit cocoa (*Theobroma cacao*) production, threatening livelihoods and increasing pressure on protected forests. To ensure resilient land-use planning, a nuanced understanding of climate change impacts on cocoa suitability—particularly within the context of diversified agroforestry systems and how they are embedded in protected forest areas—is crucial. To address this lack of knowledge, this study assesses the future viability of cocoa in Cameroon within a diversified agroforestry system, integrating high-value companion fruit trees such as safou (*Dacryodes edulis*) and mango (*Mangifera indica*), oil palm (*Elaeis guineensis*), and banana/plantains (*Musa* spp.). Unlike previous assessments, we are using long-term projection climate data until 2100, incorporate protected area constraints, and advance the EcoCrop model by integrating consecutive dry months. The results indicate a reduction in the suitable area for cocoa production in Cameroon from the current 64% of the total land area to 27% by 2090 under the high emission scenario SSP370. However, the suitable area for *Musa* spp. remains stable, while the suitable area for oil palm slightly increases. Regarding diversification, by 2090, only 8% of the national area is projected to remain suitable for a diversified system (including five species, such as cocoa), whereas 42% of the country is expected to be suitable for an oil palm-based system. Nevertheless, shading trees such as mango and safou remain suitable in up to 100% of the cocoa loss areas under SSP370, offering hope for mitigating the impact of climate change on cocoa production. Furthermore, diversified agroforestry enables year-round harvests, stabilizing farmers' incomes and enhancing food security. This study provides critical insights for stakeholders to develop climate-resilient cocoa agroforestry systems that sustain cash crop production, protect livelihoods, and reduce deforestation in Cameroon.

**Keywords** Cocoa · Agroforestry · Cameroon · Climate change · Land use planning · Protected forest area

## 1 Introduction

Globally, the livelihoods of approximately 40 to 50 million people depend on the cocoa value chain, with around 5 million being predominantly smallholder cocoa farmers (Tridge 2021). While the demand for cocoa is projected to increase in the next decades, many factors are threatening the stability of its production, particularly climate change (Beg et al. 2017; Läderach et al. 2013; Schroth et al. 2016). Cameroon is one of the major cocoa-producing countries in the world with a production level of about 300,000 metric tons in 2020/2021 (NCCB 2023). Cocoa is cultivated on an estimated total surface area of about 450,000 hectares (ha) by mostly smallholder farmers who usually cultivate 2.5 to 5 ha (Hütz-Adams et al. 2016). The cocoa sector plays a pivotal role in the nation's agricultural sector and economy at the national level but also at the local level, ensuring

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employment for rural communities (Amougou et al. 2013; Nkelle 2010). Cameroon's tropical climate and fertile soils create optimal conditions for cocoa cultivation; however, the average yields remain low because many trees are old and extensive cultivation methods are used (Läderach et al. 2013; Wessel and Quist-Wessel 2015). Despite this, national cocoa production and the cultivation area have increased over recent decades (FAO 2022) which is closely linked to ongoing deforestation as production increases are mostly reached through expansion of farmland (Wessel and Quist-Wessel 2015). Converting forest into agricultural land is one of the major reasons for the observable loss of forest cover in Cameroon, besides other factors such as demand for wood, settlement construction, or a combination of these aspects (Mukete 2018).

Several studies project that the suitability to cultivate cocoa might decrease in many areas in West Africa (Läderach et al. 2013; Schroth et al. 2016, 2017). However, climate impacts on cocoa cultivation show regional disparity: models predict limited suitability for current cocoa-producing areas in, for example, Côte d'Ivoire, while in other areas, the climatic suitability for growing cocoa might increase, for example, the Kwahu Plateau in Ghana (Läderach et al. 2013; Ofori-Boateng 2012). As cocoa has its origin as an understory tree in dense rainforest, increasing temperature and changes in rainfall patterns, such as prolonged drought periods, are identified as a major driver for suitability and yield decreases (Daymond and Hadley 2008; Schroth et al. 2016; Zuidema et al. 2005).

To combat these negative impacts, many national climate adaptation strategies mention agroforestry as a promising adaptation option to increase the resilience of ecosystems. Furthermore, the framework for deforestation-free cocoa production signed by the Cameroonian government, private sector, and civil society organizations and the research community has been established to promote cocoa agroforestry systems as an alternative to cocoa monoculture (without shading trees) (Republic of Cameroon 2021). Cocoa-based agroforestry systems, especially when integrating a high diversity of species, exhibit higher agroecosystem resilience compared to monocultures (Jacobi et al. 2013). Among the various co-benefits are improved pollination (De Beenhouwer et al. 2013), long-term stability of yields (Bisseleua et al. 2013), improved soil fertility and carbon sequestration through an amendment of soil organic matter (Jagoret et al. 2014a, b; Läderach et al. 2013; Mbow et al. 2014), contribution to afforestation (Jagoret et al. 2011), and regulation of the microclimate (temperature and moisture regimes) to mitigate negative effects of climate extremes on cocoa (Chemura et al. 2021; Mbow et al. 2014). Furthermore, agroforestry can be a strategy for ecological intensification of cocoa production by improving productivity while protecting the environment (Jagoret et al. 2014a, b); Smith et al. 2012; Tettey and Asare 2019).

In Cameroon, cocoa is traditionally associated with trees, either in (cleared or thinned) natural forests or in orchards with fruit such as safou (*Dacryodes edulis*), mango (*Mangifera indica)*, cola (*Cola nitida* Vent.), and oil palm (*Elaeis guineensis*) and medical or timber trees such as *Ceiba pentandra* L., *Erythrophleum ivorense* A. Chev., and *Milicia excelsa* Berg (see Fig. 1) (Gilbert Nicodeme et al. 2017; Michel et al. 2024; R. Asare 2005; Wessel and Quist-Wessel 2015). Safou, mango, and oil palm are among the most preferred companion trees in cocoa plantations (Asare 2005).

**Fig. 1** Cocoa-mango-based agroforestry system in Mbangassina (Centre), Cameroon. Photo credit: Mesmin Tchindjang.

These fruit trees have the potential to further income generation and improved food supply in contrast to cocoa monocultures (Pérez-Neira et al. 2023). Indigenous species such as the safou tree are particularly valued in Cameroon due to its nutritional benefits and cultural value (Ayuk et al. 1999; Kehlenbeck et al. 2013; Rimlinger et al. 2021). Oil palm, native to the coastal regions of West and Central Africa (Maley and Chepstow-Lusty 2001; Ngando-Ebongue et al. 2012), can enhance socioeconomic conditions through its high productivity, but expansion for oil palm cultivation poses threats to native ecosystems (Pashkevich et al. 2024). *Musa* spp. including sweet bananas (Musa acuminata) and plantains (*Musa* × *paradisiaca*), are especially in Africa an important source for food and income (Manzo-Sánchez et al. 2015), and thus often intercropped in cocoa agroforestry systems (Gockowski and Sonwa 2011; Michel et al. 2024). The fruits are highly valued for their nutritional benefits, medicinal properties, and commercial use in, e.g. the food and pharmaceutical industries (Basak et al. 2024). Although both sweet banana and plantain are cultivated, plantain has a higher importance in terms of cultivation area and production (MINADER 2022).

To address the impending challenges posed by climate change alongside evolving agricultural practices, there is a critical need to assess the future vulnerability of cocoa production. Recent research points out that adaptation towards climate-resilient cocoa production is crucial for viable production and that there is a need for comprehensive knowledge derived from scientific research and expertise to assist farmers and land use planners in navigating this multifaceted process (Somarriba et al. 2021).

Moreover, as cocoa is traditionally cultivated in association with shading trees, it is important for land use planning to assess not only cocoa suitability itself but to consider a system with companion trees (Singh et al. 2022). In addition, a more long-term assessment is needed as cocoa agroforestry systems, once planted, can remain productive for many decades (Jagoret et al. 2011). Our study is the first to explore the suitability assessment using EcoCrop for combining trees within an agroforestry system in Cameroon, with the further extension of including consecutive dry months, which is originally not part of the EcoCrop model, while considering also the barriers of protected forest areas. A novelty in our study is also the long-term perspective by using long-term projection climate data until 2100. Also, the existing studies regarding climate change impacts on cocoa mostly cover a broader spatial scale, such as the entire West Africa cocoa belt (Ariza-Salamanca et al. 2023; Schroth et al. 2016). However, there is also the need to derive country-specific information about potential impacts such as a shift in production areas that could put additional pressure on the remaining forest resources in Cameroon. While individual studies have assessed the land suitability of certain crops in parts of Cameroon (Kenzong et al. 2022; Olivier et al. 2023), to our knowledge, no country-specific assessment has comprehensively analyzed the future climatic suitability of a diverse cocoa-based system in Cameroon using local field data. This study fills that gap by integrating cocoa with multiple companion species (with a focus on fruit trees) into a unified framework for Cameroon. The objective is to derive information regarding potential losses and shifts in geographical areas for solely cocoa as well as for a diverse agroforestry system. Additionally, it evaluates the potential of the selected fruit trees to buffer future cocoa suitability loss areas and explores methods to enhance the resilience of cocoa production.

## 2 Material and methods

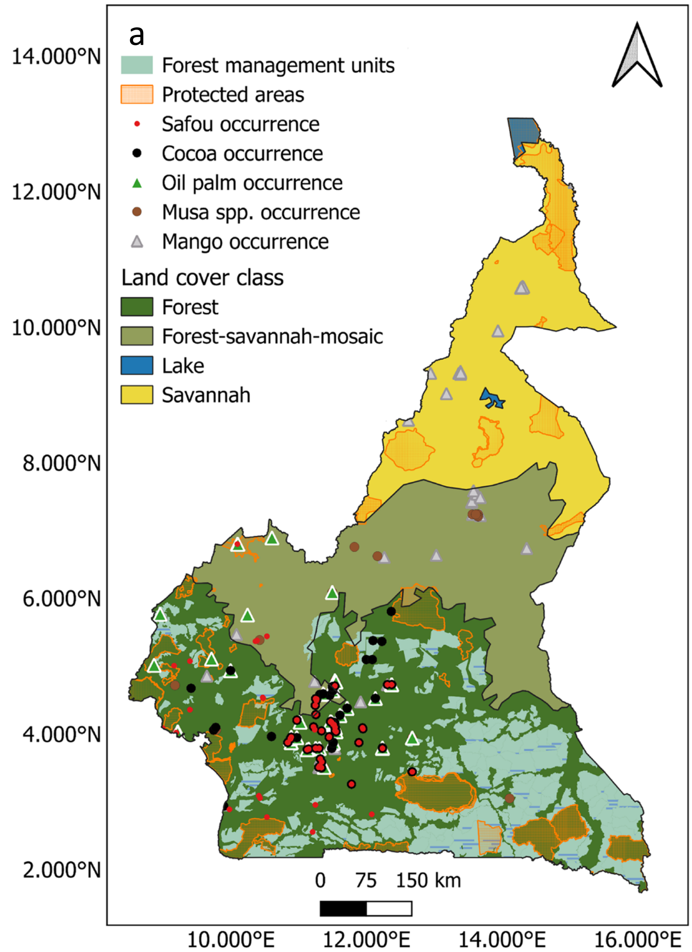
### 2.1 Study area

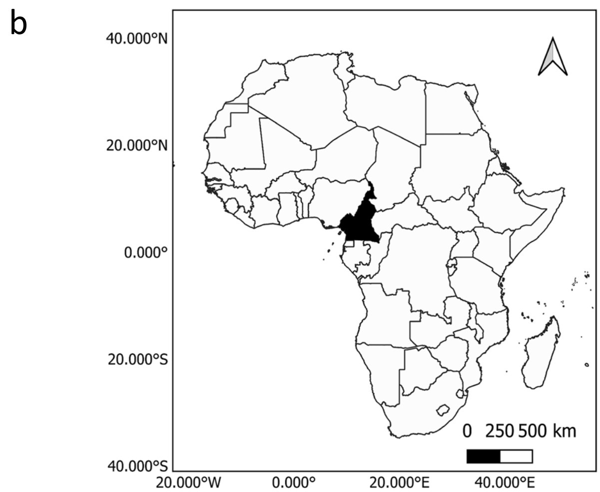
Located in Central Africa (Fig. 2b), the Republic of Cameroon has an estimated total land area of about 475,440 km$^2$, mainly covered by forests (42%) and agricultural land (21%), followed by other land uses such as grasslands and savannahs and built-up areas (CIA 2021). Nineteen percent of the national area is protected land, including several national parks and nature reserves across the country (Tchindjang et al. 2005). The climate of Cameroon is tropical, with mean annual temperatures between 22 and 29 °C, with the exception of cooler temperatures in the mountainous regions. Temperatures in the north are higher than in the south. While the inter-seasonal temperature differences are generally low, the north experiences some inter-seasonal fluctuations, with the hottest month being February or March. The mean annual precipitation sum ranges between 400 and 4000 mm per year, with a strong gradient from the dry north to the wet south. The rainfall regime is unimodal for most parts of the country. The rainy season in the most northern part is short, with rainfall occurring between June and September. The length of the rainy season increases steadily towards the south. In the most southern part of the country, December and January are the dominant dry season, and July has a shorter dry season.

### 2.2 Modelling approach

#### 2.2.1 Crop suitability in EcoCrop

Suitability models, such as the EcoCrop model, offer a systematic and data-driven approach to understand the changing dynamics of crop suitability under varying climatic conditions. Suitability models integrate climate data, soil characteristics, and crop-specific requirements to predict the suitability of crops, including cocoa and companion trees, in the target region. Suitability assessments for agroforestry




c

| Land cover class | % of protected area |
|---|---|
| Forest ((degraded) evergreen, dense humid, (degraded) semi-deciduous, montane forest) | 13.8 |
| Forest-savannah-mosaic (Herbal and wooden savannah, crop-savannah-mosaic, shrub savannah) | 1.7 |
| Savannah (herbal, wooden savannah, steppe, prairie) | 18.2 |
| Lake Chad | 92 |

**Fig. 2** **a** Map of Cameroon with simplified land cover classes, forest management units and protected areas with occurrence points for cocoa (black circle), mango (grey triangle) and safou (red circle), *Musa* spp. (including plantains, brown circle), and oil palm (green triangle); **b** location of Cameroon within the African continent; and **c** detailed land cover class descriptions linked to % of protected areas; the map is created based on different sources: UNEP-WCMC (2024), Guillaumet et al. (2009), MINFOF (2021).

systems consider, so far, soil characteristics, topography, and historical climate, e.g. (Chuma et al. 2021; Singh et al. 2022), and were recently advanced by integrating climate projections until 2050 (Ariza-Salamanca et al. 2023). Crop suitability assessments are based on the understanding that the biophysical parameters (e.g. soil pH) and climatic variables (e.g. total amount of precipitation received in the growing season) play an important role in determining crop production rates, which is true in many tropical areas where agriculture is mainly influenced by weather. This has been proven in previous studies, where the impact of climatic variables has been identified as much more relevant than that of edaphic variables (Ariza-Salamanca et al. 2023). A suitability model therefore uses these variables to create a score for each crop, each period, and each location depending on how the variables meet the crop requirements or conditions in known current production areas (Evangelista et al. 2013).

In this study, we use the mechanistic model EcoCrop (Hijmans et al. 2001) which was further developed by Ramirez-Villegas et al. (2013) and is based on the FAO-EcoCrop database (FAO 2000). The model analyzes the abiotic suitability of a specific area for a target crop considering crop-specific ecological ranges. In the past, the EcoCrop model had been widely used and produced robust results to define suitability for single crops and trees, e.g. sorghum on a global scale (Ramirez-Villegas et al. 2013); coconut, oil palm, and rubber in Southeast Asia (Appelt et al. 2023); maize and cassava in Angola (Hunter and Crespo 2019); root, tuber, banana, and further food crops in Sub-Saharan Africa (Chemura et al. 2024; Manners et al. 2021); and for soil fertility constraints assessment in Tanzania (Piikki et al. 2015). The EcoCrop model was selected because it has been shown to be effective in evaluating the suitability of many crops, using climatic and soil data. It can be set up for diverse crops with fewer crop-specific parameters, which is very attractive when dealing with less detailed eco-physiological information such as those in this study (Rippke et al. 2016). It also provides map outputs for spatialized impact and targeting and accommodates scenario-based simulation iterations to visualize and understand how target agricultural systems work or might be affected by changing biophysical and socioeconomic conditions. The EcoCrop model also requires relatively fewer input data to produce reliable results that are comparable with those models with a longer list of required input data. The model is designed to assess crop productivity (e.g. fruit yield), whereas timber trees are grown for wood volume, which depends on long-term ecological interactions, not just climate. The assessment of tree suitability follows the approach by Ramirez-Villegas et al. (2011) and calculates a suitability index from 0 (not at all suitable) to 1 (highly suitable). After assessing the individual tree suitability, we derived the potential for diversification following the approach of combining suitability for crops by Chemura et al. (2020): The individual rasters were stacked together and converted into a unique categorical raster using bitwise encoding. After obtaining the combined raster, we reclassify it into diversity classes. Finally, we assess if the defined cocoa loss areas could be covered by the fruit tree to derive information for potential future agroforestry implementation. The buffering potential describes the potential to grow mango or safou as a companion tree in areas where the suitability for cocoa decreases. Previous studies showed the effect of shading trees to mitigate climate impacts on understory plants through regulation of microclimate (Chemura et al. 2021; Mbow et al. 2014). However, EcoCrop does not account for interaction between individual tree and crop species. Thus, this study neither provides direct information about the yield effect on cocoa nor potential income effects of an implementation of such an agroforestry system.

#### 2.2.2 Occurrence data

Occurrence data points for cocoa (99), mango (58) and safou (85), palm oil (78), and *Musa* spp. (sweet banana and plantain) (71) were derived from the following three sources:

- Field data collection: Systematic field collection data was done using GPS to record occurrence and land cover data between April 2022 and June 2023 on the type of shade trees, especially fruit trees such as safou and mango, as well as intercropped crops such as plantains or sweet banana on cocoa farms. Data were collected in April–May 2022 in the Yoko subdivision (Centre Region) and between May and June 2023 in several further subdivisions and localities of the Centre Region, such as Mbangassina, Monatélé, Ngoumo Akono, and Nanga Eboko. The land cover classes recorded correspond to the presented map (Fig. 2a, c).
- Global Biodiversity Information Facility (GBIF 2023, www.gbif.org): The GBIF is an open access database containing primary biodiversity data based on community-driven and agreed standards and tools.
- Scientific publications: Further occurrence points were obtained from scientific publications that published presence points for safou in Cameroon (Leakey et al. 2003; Mpemboura Nsangou et al. 2021).

#### 2.2.3 Climate data

For the model calibration, we used present climate data derived from W5E5, a dataset based on a combination of simulations from global weather models, satellite data, and in situ observations (Cucchi et al. 2020; Lange et al. 2021). Variables include mean temperature and precipitation and allow us to calculate consecutive dry months. The data is provided at 0.5°×0.5° grid spacing (corresponding to approximately 55 km × 55 km in Cameroon) for each month of the year over the period 1995–2014, with 2004 as the baseline year.

Future climate projection data simulated by global climate models (GCMs) was obtained from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b; Lange 2019; Lange and Büchner 2021). The two emission scenarios SSP126 (based on RCP2.6, low radiative forcing) and SSP370 (based on RCP7.0, high radiative forcing) were selected to cover an extensive range of projections in the years 2030 (2021–2040), 2050 (2041–2060), and 2090 (2081–2100). Historical simulations cover the years 1850–2014 and future projections under both emission scenarios cover the years 2015–2100. W5E5 is the observational reference dataset used for bias adjustment and statistical downscaling of ISIMIP3b. The GCMs included in ISIMIP3b are CANESM5, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, GFDL-ESM4, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL (Lange 2019; Lange and Büchner 2021).

#### 2.2.4 Tree-specific parameters

The tree requirements were obtained from the FAO Eco-Crop database. The available data comes from literature or expert knowledge (Ramirez-Villegas et al. 2013). Where possible, we adjusted the parameter to Cameroon-specific conditions (Wood and Lass 2008; AAC 2021). The soil pH data was derived from the International Soil Reference and Information Centre (ISRIC) and their SoilGrids platform (Hengl et al. 2017) and averaged pH values per grid cell over the entire soil profile. Besides soil pH, monthly average temperature, and rainfall sum, the presented model approach takes into consideration also an indicator for rainfall seasonality and consecutive dry months (CDM), which is very important for perennial crops such as cocoa. The ecological range for CDM was defined for cocoa according to Wood and Lass (2008), for safou according to Kengue et al. (2011), for mango according to the World Agroforestry database (Orwa et al. 2009), for oil palm according to Duke (1983), and for *Musa* spp. according to Robinson and Saúco (2010) and Ravi et al. (2013). Areas with more than three consecutive months of less than 100 mm of rainfall are less suitable for cocoa cultivation according to Wood and Lass (2008). As in West Africa cocoa is now mostly grown in climates that have a maximum of four consecutive dry months, one major biophysical driver for cocoa suitability seems to be the duration of drought periods (Schroth et al. 2016). According to Wood and Lass (2008), a short dry period fosters flowering development, whereas more than 3 months with less than 100 mm rainfall per month can be defined as a critical threshold for cocoa growth. This threshold has been applied also in other suitability assessments for the West African region (Läderach et al. 2013; Schroth et al. 2016). However, for the safou and mango tree, such thresholds have not been defined in suitability models before. According to literature, the safou can withstand a 4-month dry period, but prefers generally a highly humid climate (Kengue et al. 2011); thus, the thresholds Have been set at zero months for minimum growth and 4 months as maximum growth condition. Mango trees are characterized as drought tolerant, and a short dry period is necessary for flowering (Orwa et al. 2009); the thresholds are set accordingly with 1 month minimum for growth and 8 months as maximum threshold. Oil palms grow best in lowland Humid tropical regions and can withstand a dry season lasting 2 to 4 months (Duke 1983). As the EcoCrop database only provides information for the generic *Musa* spp. and not specifically for plantains or sweet bananas, we refer in this study always to the genus *Musa* spp. including both species (Table 1). *Musa* spp. are sensitive to drought and require an evenly distributed rainfall (Robinson and Saúco 2010). However, *Musa* × *paradisiaca* is part of the genotype subgroup AAB, which seems to be more resistant to drought than subgroups having only the genome A such as *Musa acuminata* (Ravi et al. 2013).

**Table 1** Tree and crop-specific requirements according to FAO Eco-Crop database and literature.

| Crop | Parameters | Min | Min.Opt | Max.Opt | Max |
|---|---|---|---|---|---|
| Cocoa | Duration [days] | 210 | NA | 180 | 365 |
| | Average temp. [°C] | 10 | 24 | 28 | 32 |
| | Precipitation sum [mm] | 89 | 125 | 350 | 940 |
| | Consecutive dry months | NA | 0 | 2 | 3 |
| | Soil pH | 4.0 | 5.0 | 6.5 | 8.0 |
| Safou | Duration [days] | 180 | NA | NA | 365 |
| | Average temp. [°C] | 14 | 18 | 28 | 35 |
| | Precipitation sum [mm] | 83 | 120 | 250 | 417 |
| | Consecutive dry months | 0 | 0 | 2 | 4 |
| | Soil pH | 4.0 | 5.0 | 6.5 | 8.0 |
| Mango | Duration [days] | 180 | NA | 150 | 365 |
| | Average temp. [°C] | 8 | 24 | 30 | 48 |
| | Precipitation sum [mm] | 31 | 66 | 186 | 343 |
| | Consecutive dry months | NA | 1 | 3 | 8 |
| | Soil pH | 4.3 | 5.5 | 7.5 | 8.5 |
| Oil palm | Duration [days] | 360 | NA | 365 | 365 |
| | Average temp. [°C] | 12 | 15 | 26 | 34 |
| | Precipitation sum [mm] | 54 | 82 | 115 | 208 |
| | Consecutive dry months | NA | NA | 2 | 4 |
| | Soil pH | 4.0 | 5.5 | 7.0 | 8.0 |
| *Musa* spp. | Duration [days] | 210 | NA | 180 | 365 |
| | Average temp. [°C] | 15 | 25 | 35 | 40 |
| | Precipitation sum [mm] | 99 | 146 | 280 | 619 |
| | Consecutive dry months | NA | NA | 1 | 3 |
| | Soil pH | 4.5 | 5.0 | 7.0 | 7.5 |

#### 2.2.5 Model validation

We evaluated the model for accuracy by comparing the binary suitable area with reference datasets, such as the occurrence data. We cleaned the occurrence data by removing points that were overlapping in one grid (0.5°×0.5° spatial resolution) to avoid overfitting of the model. The current distribution was validated using the area under the curve (AUC) of the receiver operating characteristic (ROC) which is a robust metric to assess the accuracy of predicted species occurrence (Hand and Till 2001). The AUC assumes values from 0 to 1, describing the relationship between the percentage of correctly predicted presence against that of incorrectly predicted absences. An AUC of 0.5 indicates that the performance was no better than random sampling, while 1.0 is a perfect fit (Peterson et al. 2008). The model fit was assessed by using the AUC, with the results all above 0.75. The best model performance was for cocoa (0.88) followed by oil palm (0.83), mango (0.77), safou (0.76), and *Musa* spp. (0.75). The results provided sufficient confidence in the application of the model for the climate impact assessment.

# 3 Results and discussion

## 3.1 Current and future climatic suitability for the individual species

The individual suitability thresholds for cocoa, mango, safou, palm oil, and *Musa* spp. were defined as 0.5, 0.3, 0.3, 0.25, and 0.2, respectively. The area analyzed as climatically suitable for cocoa production stretches from the western part towards the east, covering the forest and the southern parts of the forest-savannah-mosaic zones (Fig. 3). The savannah zone in the north of Cameroon is limited for cocoa growth. Mango can be found suitable in almost all regions of Cameroon, besides the western part. The highest suitability index is reached in the centre and the east of Cameroon for the land cover class forest. The area suitable for safou stretches in a south-north gradient, with the highest suitability index in the east of Cameroon, while the lowest index is in the southern areas of the North region, and no suitability is pronounced in the west part of the forest-covered area. The suitable area for oil palm covers the humid forest zone with the highest climatic suitability in the eastern part, which is a protected area. *Musa* spp. can be found suitable in the forest and forest-savannah zone, with the Highest suitability in the west and east of Cameroon. Suitable areas for cocoa cover 64% of the total area of Cameroon, while 36% of the total national area is defined as limited for cocoa growth. Mango and safou can be grown in 66% and 71% of Cameroon, respectively, *Musa* spp. in 60% of the national area, and oil palm only in 39%.

Future changes are generally more pronounced for all trees besides oil palm under the high emissions scenario SSP370 (Fig. 4b+d). For cocoa, the highest reduction occurs

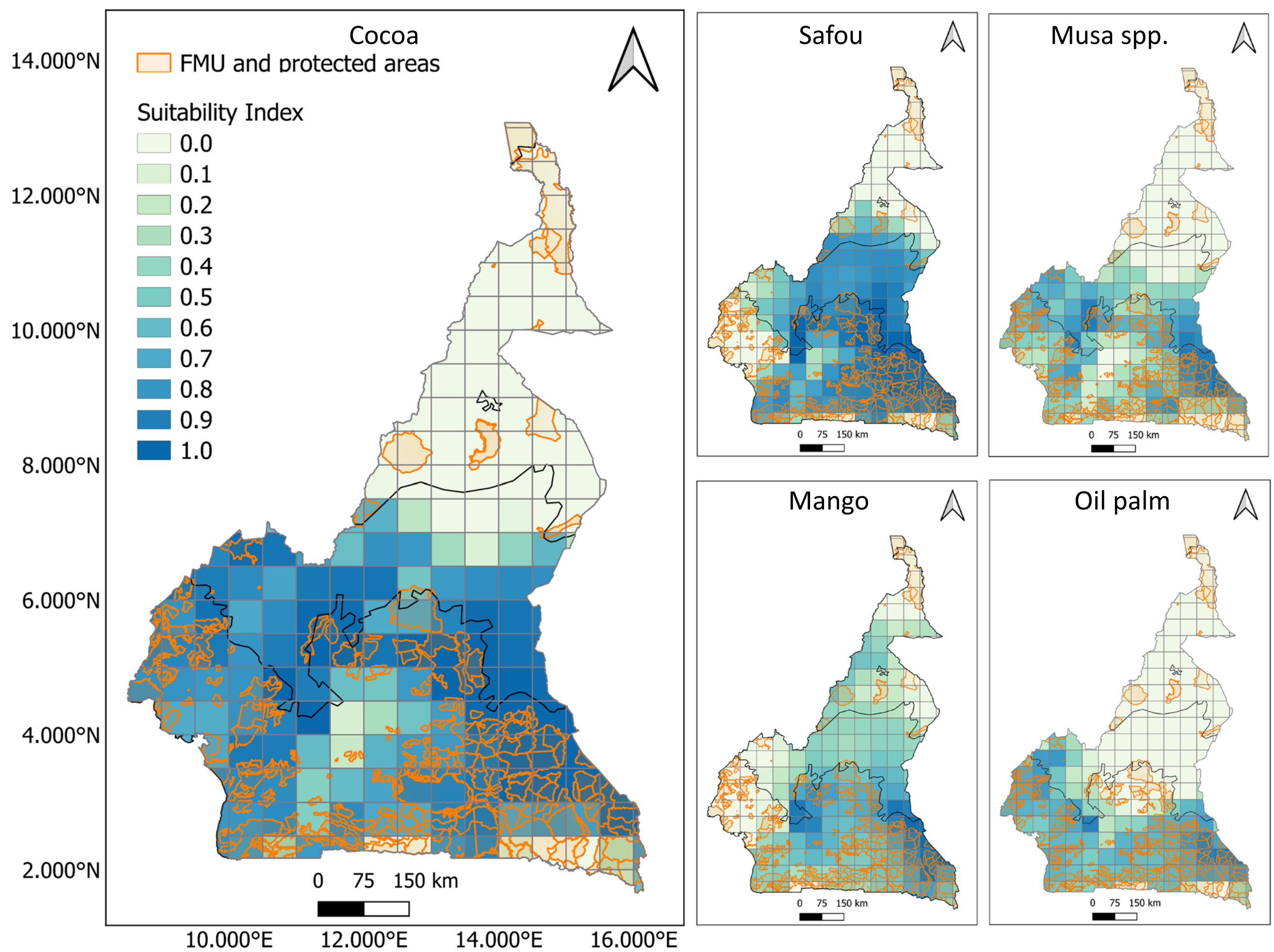



**Fig. 3** Distribution of spatial data on suitability for cocoa (threshold 0.5), mango and safou (threshold 0.3), *Musa* spp. (0.2), and oil palm (0.25) over the period 1995–2014 (historical period) overlaid by forest management units (FMU) and protected areas.

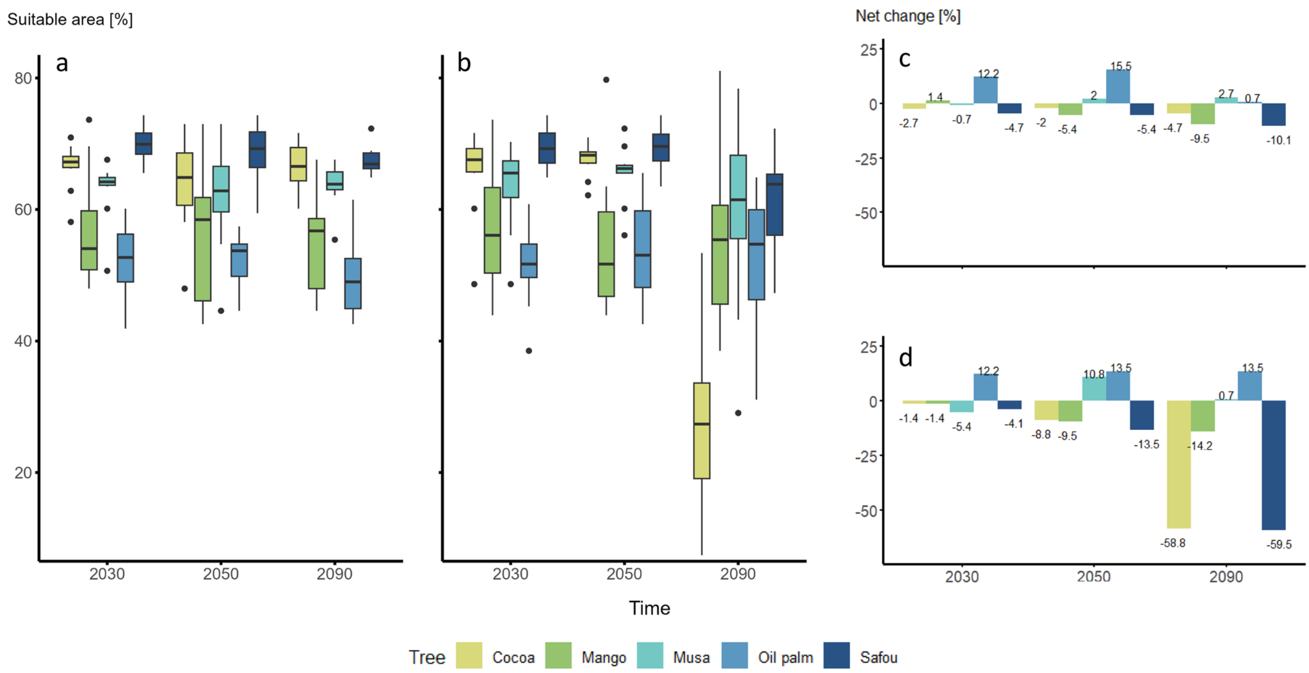



**Fig. 4** Future suitable area [%] under the low emission scenario SSP126 (**a**) and high emission scenario SSP370 (**b**) and net suitability changes [%] under SSP126 (**c**) and SSP370 (**d**) for all species.

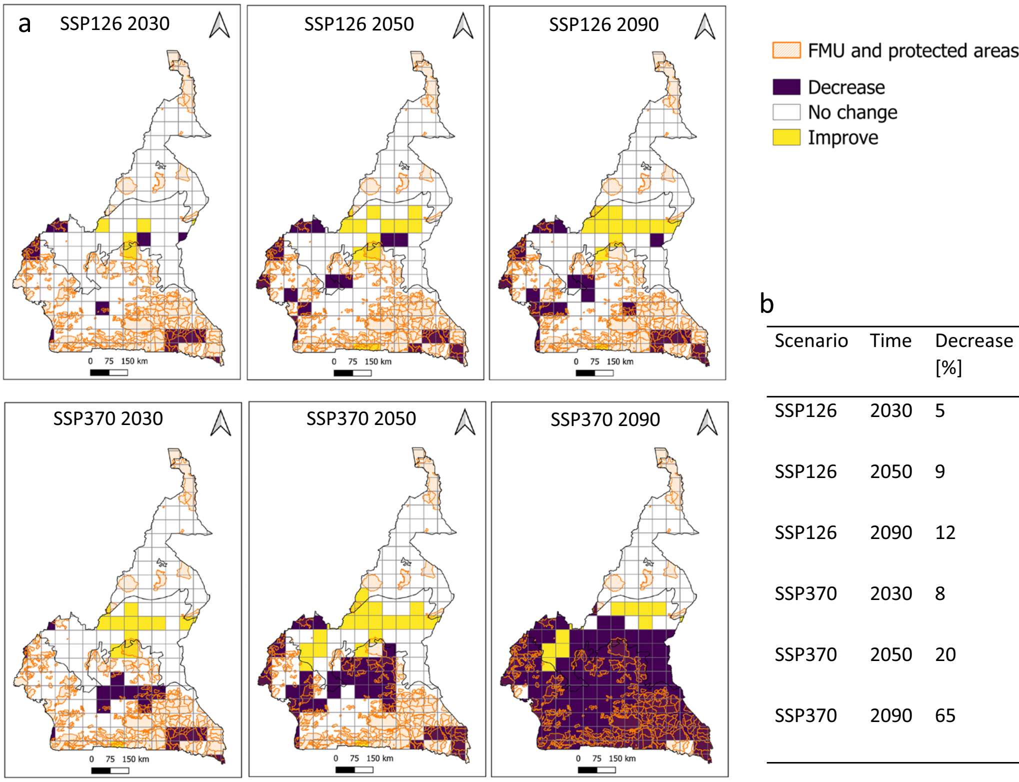
under SSP370 for 2090, where the conditions for cocoa deteriorate, such that only 27% remain suitable compared to 64% under current conditions (Fig. 4b). However, the results from the suitability model, as well as from the climate models, also show a higher disagreement between the different model runs, which leads to a wider range of the results. While the model ensemble median projects 27% of Cameroon's land area as suitable for cocoa production in 2090, the potential range lies between 7% (UKESM1-0-LL) and 53% (MPI-ESM1-2-HR). In contrast, areas suitable for mango trees are projected to experience deterioration, but with only slight diminishing of suitable areas to 55% for 2090 under SSP370 (Fig. 4b) compared to 66% under current conditions. For safou, the conditions deteriorate, explaining the negative net change under SSP370 (Fig. 4d), but the majority of the area remains suitable, with 64% by 2090 under SSP370 (Fig. 4a) compared to 71% under current conditions. For *Musa* spp., the projections show, for 2030 under SSP126, a slight increase in suitable areas (64%) compared to historical conditions (60%) (Fig. 4a) as well as under SSP370 (66%) with the Highest value for suitable area being reached in 2050 under SSP370 (Fig. 4b). Overall, the area for *Musa* spp. remains relatively stable (Fig. 4a+b). For oil palm, the net changes are overall positive (Fig. 4c+d), which is also reflected in the increase of suitable area over time, with the highest value for suitable area (55%) in 2090 under SSP370 (Fig. 4b). In general, the analysis shows for cocoa as well as mango and safou negative net changes, and for *Musa* spp. varying net changes under both scenarios for the three time periods, while the net changes for oil palm are constantly positive (Fig. 4c+d).

Our results are in line with previous studies that show that in general, the cocoa cultivation areas seem to sustain the climatic changes until 2050 with certain pronounced losses but also gains in the forest-savannah-mosaic zone (Ariza-Salamanca et al. 2023; Läderach et al. 2013; Schroth et al. 2016). Cocoa trees grow best in a stable warm and humid climate (Wood and Lass 2008) and are susceptible to climate extremes. In the past, temperature impacts did not play a considerable role in defining suitability compared to changes in rainfall patterns (Carr and Lockwood 2011; Lawal and Emaku 2007; Ojo and Sadiq 2010; Yoroba et al. 2019). Our results are in line with previous studies that found that the rainfall sum and especially its seasonal distribution are the most influencing factors for cocoa production (Yoroba et al. 2019) with increased rainfall up to 3000 mm annually favouring cocoa production (Nkobe et al. 2013). Cocoa is not very suited to deal with water limitations as the leaves of the cocoa tree lose water quickly under high radiation and the root system is relatively shallow (Moser et al. 2010). Perennial crops and trees are susceptible to weather changes during the whole year (Wood and Lass 2008). Therefore, especially precipitation seasonality is an important indicator for cocoa suitability (Schroth et al. 2016). Previous studies show that consecutive dry months (<100 mm of rainfall per month) longer than 3 months affect cocoa production negatively (Ofori et al. 2014). As climate projections show, Cameroon will also experience longer dry seasons which considerably affect the suitability for cocoa. A novelty in our study is the long-term perspective: By 2090, the changes in suitability are drastic as climate extreme events such as droughts and erratic rainfall patterns are projected to occur much more frequently, posing an immense threat also to the cocoa production (assuming no adaptation). Though the uncertainty of climate projections is increasing, it is important to consider potential long-term impacts, especially as cocoa agroforestry systems once planted can remain for more than 60 years (Jagoret et al. 2011). However, also high temperatures can cause stress either directly or indirectly by a higher evapotranspirative demand (Läderach et al. 2013). Heat and very low temperature can negatively affect cocoa by inhibiting photosynthesis (Zuidema et al. 2003) and affecting sprouting and ripening of the pods which leads to yield losses (Kimengsi and Tosam 2013). Therefore, also increases in maximum temperature will be a threat for cocoa suitability not only in Cameroon as shown by our study but throughout the whole West African cocoa belt (Schroth et al. 2016). While direct studies on Cameroon are limited, previous research on the impact of global warming on plantain suitability in West Africa recorded small decreases, but overall, the suitability remains stable which is in line with our results (Egbebiyi et al. 2020). A study in Côte d'Ivoire's eastern region projects negative impacts on plantain cultivation systems (Noufé et al. 2015), while studies in Uganda show mixed effects of global warming on banana suitability (Abigaba et al. 2024; Sabiiti et al. 2018) as increases in temperatures may favour banana growth but also lead to moisture deficit (Sabiiti et al. 2018). Regarding oil palm, research indicates that climate change may alter the suitability of certain regions in Africa for oil palm cultivation. A study focusing on Nigeria projected that by 2050, the most suitable climates for oil palm would shift towards the south and west of the country, suggesting that oil palm may find refuges in these areas in response to future climate conditions (Paterson 2021). While the global area suitable for oil palm may decrease by 2100 due to increased risk for drought and flooding, warmer temperatures could make certain highland regions more suitable (Fleiss et al. 2017). Our results project that more area will become suitable for oil palm while suitable area for cocoa will decrease drastically at the end of the century (SSP370), which may be explained by the fact that oil palm has a tolerance towards higher temperatures (Barcelos et al. 2015), has an extensive rooting system (Intara et al. 2018; Jourdan et al. 2000), and has a marginally higher tolerance towards consecutive drought (Duke 1983).

## 3.2 Implications for resilient land use planning

Future changes for cocoa indicate in some parts of Cameroon also increases in suitability: by 2050, both scenarios project the highest increases in suitability for cocoa (7% (SSP126) and 11% (SSP370)), which are found in the northern part of the forest-savannah-mosaic zone (Fig. 5a+b). The orange-dashed areas are protected areas or forest management units, which should not be considered potential areas for agricultural production. Climatic changes will lead to higher fragmentation of suitable areas for cocoa, especially in the central area of Cameroon.

Our results reveal the importance of considering climate change impacts on tree crop suitability when planning sustainable long-term adaptation for cocoa through agroforestry. A shift in suitability could lead to further deforestation and expansion of cocoa fields into areas that were designated for forest management (Asante et al. 2022). In Cameroon and other cocoa-producing countries in the West African cocoa belt, the majority of past and projected future deforestation was found in highly suitable areas for cocoa (Sassen et al. 2022). Nevertheless, cocoa production is also promoted in historically non-cocoa areas, including the savanna transition (forest-savannah-mosaic) zone to increase production and prevent deforestation (Government of Cameroon 2021). While current cocoa production areas are potentially suffering in the future from projected increased drought periods and high temperatures, our results showed that some areas further north located in the savannah transition zone are projected to become more suitable. Although cocoa production is not very common in savannah ecosystems (Yao Sadaiou Sabas et al. 2020), it has been reported already for Cameroon (Jagoret et al. 2014a, b). Setting up cocoa agroforestry systems in the savannah region with its naturally rather treeless landscape and grassland can thus also contribute to afforestation (Jagoret et al. 2011). However, it can also cause conflicts with other agricultural activities already practiced in this region. Therefore, assessing the potential land for agroforestry is essential for planning and interventions in the future (Singh et al. 2022). As cocoa was a major driver for deforestation in the past, future land use plans also need to consider the projected implications for this sector. Especially in the context of Cameroon, where the government Has aimed since 2014 to double the cocoa production in the near future while respecting international requirements for sustainable and deforestation-free cocoa (Republic of Cameroon 2014). The pressure on forests and other protected areas may even increase with climate-caused cocoa production losses in western Africa, leading to price peaks for cocoa as it was the case in 2023 and early due to El Niño and global warming (CNCB 2024; Worldbank 2023).




b

| Scenario | Time | Decrease [%] | No change [%] | Improve [%] |
|---|---|---|---|---|
| SSP126 | 2030 | 5 | 92 | 3 |
| SSP126 | 2050 | 9 | 83 | 7 |
| SSP126 | 2090 | 12 | 80 | 7 |
| SSP370 | 2030 | 8 | 85 | 7 |
| SSP370 | 2050 | 20 | 68 | 11 |
| SSP370 | 2090 | 65 | 29 | 6 |

**Fig. 5** **a** Spatial and **b** numeric distribution of future changes for cocoa under both emission scenarios (low emission scenario SSP126 upper row, high emission scenario SSP370 lower row) for 2030, 2050, 2090 overlaid by forest management units (FMU) and protected areas.

Considering the projected impacts of climate change with decreases in suitability but also yield (Agbenyo et al. 2022; Anning et al. 2022), there is a need to work on different levels of adaptation to stabilize and increase yield on existing cocoa production land (Asante et al. 2022). Furthermore, initiatives and policies such as REDD+ and the road map for deforestation-free cocoa are of major importance to sustain resilient production and protection of forest areas at the same time (Asante et al. 2022). Interestingly, some studies are underlining the idea that resilient land use planning should rather consider the intensification of cocoa and preservation of forests separately (Alemagi et al. 2015; Gockowski and Sonwa 2011). Our study showed that although it will still be climatically suitable to grow cocoa until 2050 in the majority of existing cocoa production areas, there will be a considerable deterioration, especially under the SSP370 scenario, which could affect the future yield development. Cocoa production areas that are projected to be affected should establish appropriate agroforestry systems as well as other incremental adaptations to resist climatic changes and sustain production. Furthermore, farmers' perception should be considered in the land use planning process, as it is still not clear how farmers will respond to the projected decreases in cocoa suitability: either by increasing the effort of adaptation in current growing regions or by continuing to expand their land into forest or protected areas despite political initiatives to ensure their livelihood (Asare et al. 2017; Sassen et al. 2022; Schroth et al. 2016). The results of this study can thus help to develop appropriate strategies for cocoa agroforestry systems together with stakeholders, especially farmers in Cameroon. In a further step, the approach could be applied to look at specific vulnerable regions to investigate locality-specific measures and requirements with regard to tree suitability.

## 3.3 Adaptation through multi-diverse agroforestry

Diverse cocoa agroforestry systems can enhance resilience to climate change impacts through multiple mechanisms (Fig. 6): On the one hand, we have the biophysical angle, mitigating negative effects of climate extremes on cocoa through shading and regulation of the microclimate (temperature and moisture regimes) (Chemura et al. 2021; Mbow et al. 2014; Niether et al. 2020). On the other hand, diverse agroforestry systems can increase and diversify the production and thus increase the income, which might have positive effects on the demand for further deforestation (Alemagi et al. 2014; Eboutou et al. 2010). Further contributions to

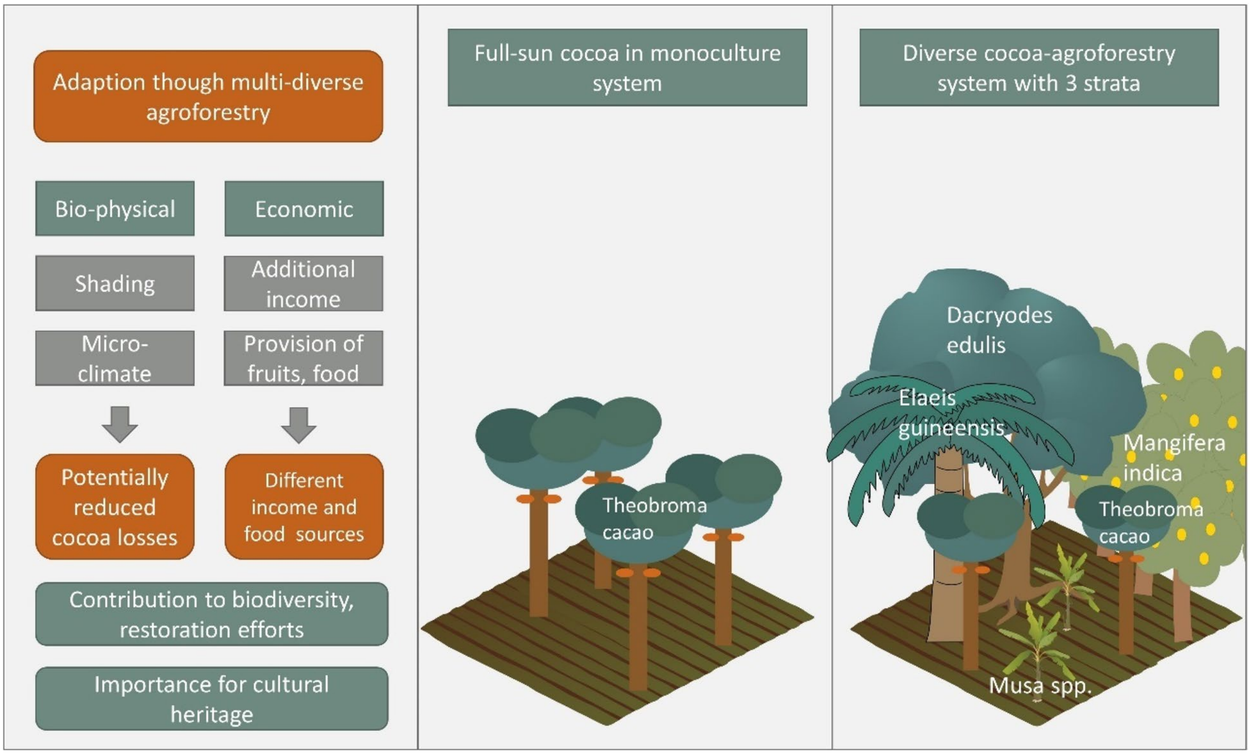



**Fig. 6** Adaptation mechanisms through agroforestry: biophysical, economic, as well as co-benefits for restoration and cultural heritage. Tree and plot icons created by UMCES (2025), cocoa tree icon and graph created by the author.

restoration and afforestation have been shown in several studies (Jacobi et al. 2017; Jagoret et al. 2011; Nadège et al. 2017; Saj et al. 2017) and are discussed in the following chapters.

#### 3.3.1 Climatic potential for diversification

Studies showed that the diversity in cocoa agroforestry systems in Cameroon on average is high compared to other countries (Alemagi et al. 2015; Gockowski and Sonwa 2011). Thus, to capture the complex reality of agroforestry systems in Cameroon, we assessed the suitability for growing all five species together as a diverse system. We define the diversity index (Fig. 7) based on how many species out of all selected species are present in the respective unit: zero to one species defines "limited," two to three "low diversity," four species including cocoa or oil palm (without cocoa) defines "moderate diversity," and the presence of all selected five species defines "high diversity." Under Historical conditions, 24% of the national area, mostly located in protected or forest management land, is suitable for the highly diverse system, while most of the eastern and central parts of Cameroon are suitable for a moderate diverse system including cocoa (Fig. 7a). By 2050, the suitable area for a Highly diverse system will increase to 34% and 35% under SSP126 and SSP370, respectively (Fig. 7b). By 2090, the oil palm-based system is dominant in 42% of the country due to the drastic decrease of suitable areas for cocoa, while only 8% of the national area remains suitable for a diversified system including cocoa.

Interestingly, Ariza-Salamanca et al. (2023) found that the western part of Cameroon holds high potential for tree diversity within cocoa agroforestry systems, which contrasts with our findings that identify the central and eastern parts as the most suitable. Nonetheless, both studies highlight Cameroon's future potential for diverse agroforestry systems. While oil palm appears to be more climate-resilient than cocoa, its global expansion has historically driven extensive forest loss (Ordway et al. 2017, 2019; Vijay et al. 2016). In Southwest Cameroon, a major oil palm-producing region, 67% of land expansion for oil palm cultivation between 2000 and 2015 was linked to forest loss (Ordway et al. 2019). Moreover, Africa still contains some of the largest areas of vulnerable forest, which are home to globally significant biodiversity (Vijay et al. 2016), highlighting the urgent need for government regulation and monitoring (Vijay et al. 2016). In this context, sustainable commitments from the oil palm sector such as Cameroon's Sustainable Oil Palm Initiative have been developed to align with broader cross-sectoral efforts including

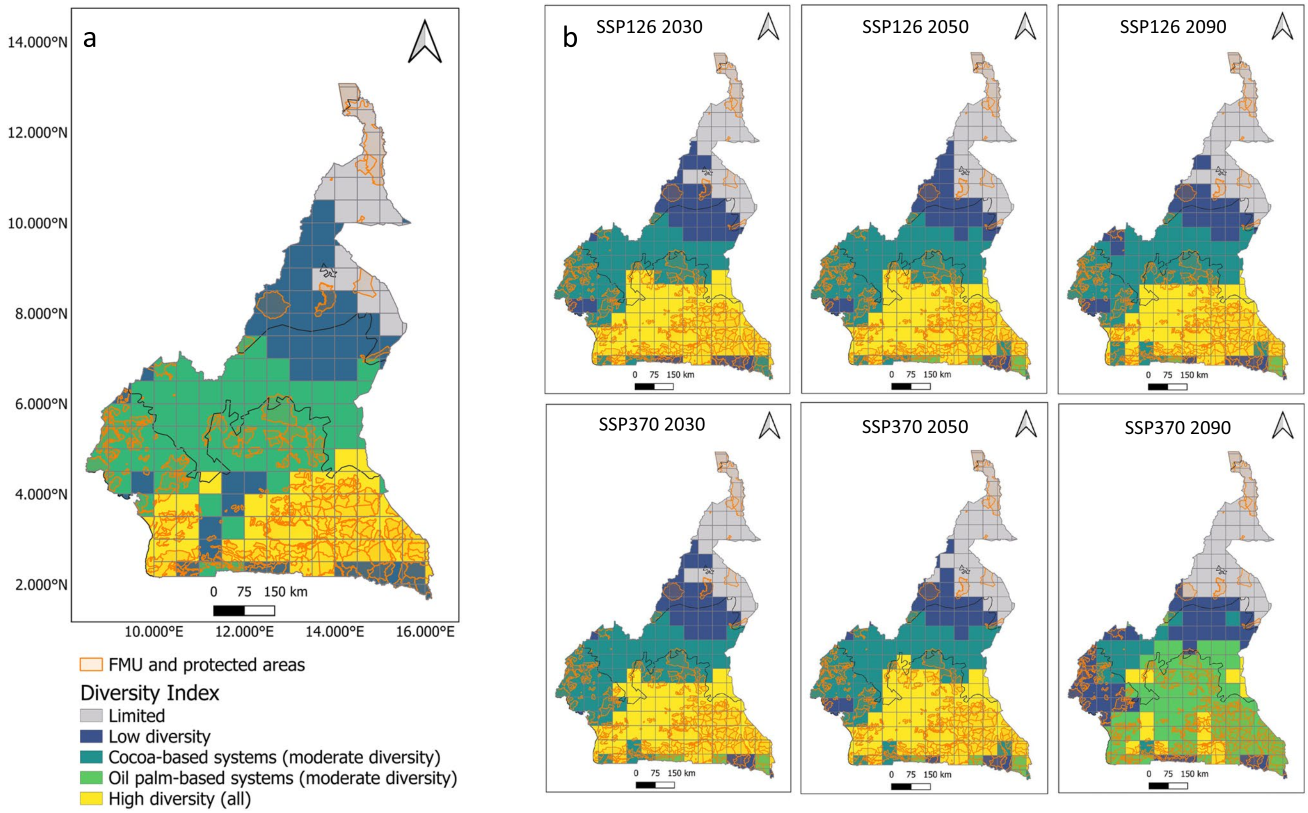



**Fig. 7** Model ensemble median for **a** historical and **b** projected future diversity index for an agroforestry system with cocoa, safou, mango, oil palm, and *Musa* spp. by 2030, 2050, and 2090 under the two emission scenarios and overlaid by forest management units (FMU) and protected areas.

zero deforestation pledges and international agreements (Republic of Cameroon 2021).

### 3.3.2 Potential for cocoa adaptation through shading trees

By overlaying the suitability maps of fruit trees with the projected loss areas for cocoa, we identified areas where fruit trees could potentially mitigate the negative impacts of climate change on cocoa. This was defined as the overlap between projected suitable areas for fruit trees and regions expected to experience cocoa loss. The shade tree canopy in agroforestry systems reduces solar radiation (Niether et al. 2018; Saj et al. 2023), creating a more stable microclimate where daily temperature extremes are moderated and mean temperatures remain lower (Niether et al. 2020). As oil palm is intercropped with cocoa for its economic advantages (Khasanah et al. 2020), the biophysical adaptation potential is only explored for mango and safou. Both trees show a high potential to cover cocoa loss areas in the central and eastern area of Cameroon whereas the Littoral and Western regions cannot be covered (Fig. 8a). The mango tree can cover slightly less areas than safou in the forest-savannah-mosaic zone under SSP370 (Fig. 8a). In general, the higher buffer potential is achieved under the SSP370 with 100% (both) by 2030, 77% (safou) and 70% (mango) by 2050, and 83% (safou) and 76% (mango) by 2090 (Fig. 8b).

However, only a few studies have assessed potential competition between cocoa and companion trees, and often the systems are too complex that findings cannot be transferred (Niether et al. 2020; Saj et al. 2023). Different tree species have different characteristics and need to be considered carefully in adaptation planning. However, there is limited information on the impact of climate change on companion trees and thus the feasibility of implementing agroforestry in the future. Recently, Ariza-Salamanca et al. (2023) investigated the most common companion trees such as mango, coconut, guava, and papaya for the entire West African cocoa belt. The projected impacts on mango (under SSP126 and SSP585 instead of SSP370) are in line with the presented results of this study, showing marginal changes by 2050 under both scenarios. Safou Has not been studied so far. Our study is thus the first to explore the climate change implications for safou suitability to assess the long-term potential as a companion tree

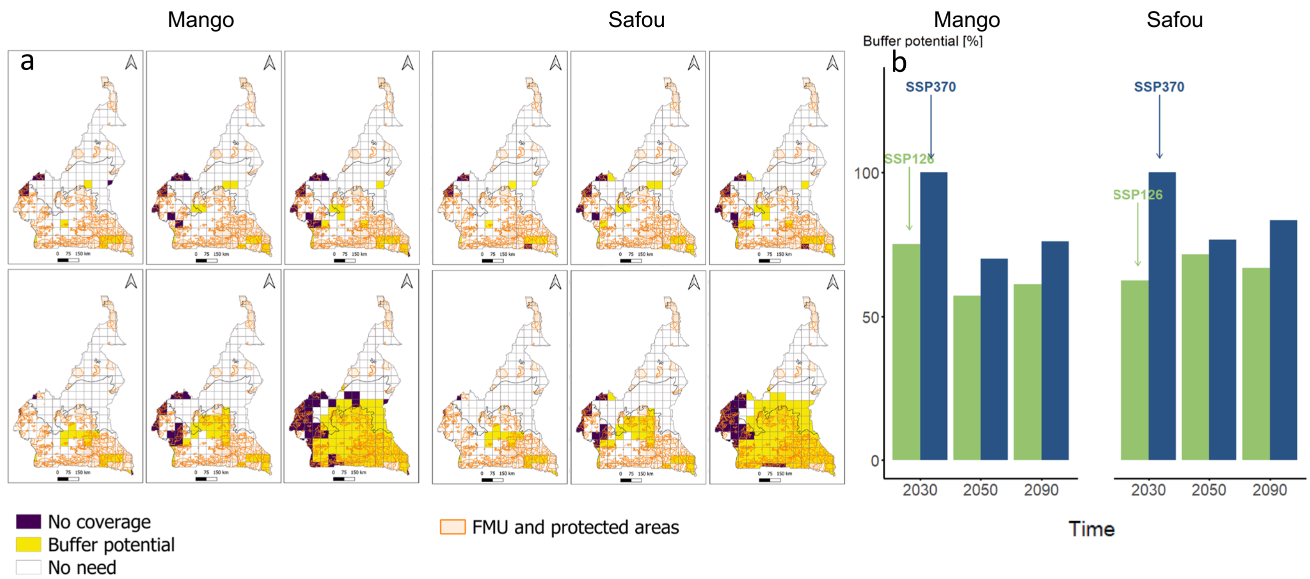
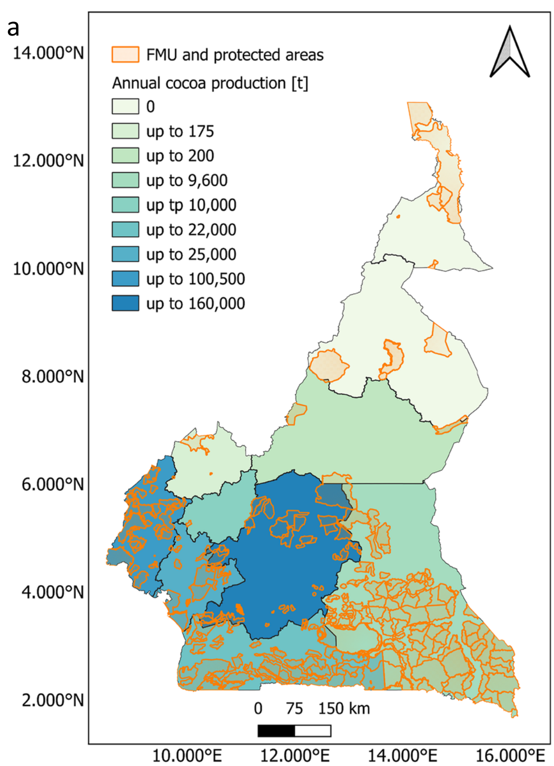



**Fig. 8** **a** Spatial mapping of the potential [%] of mango and safou to cover cocoa loss areas overlaid by forest management units (FMU) and protected areas and **b** calculated buffer potential (covered areas/total loss area) under SSP126 (low emission scenario) and SSP370 (high emission scenario) for 2030, 2050, 2090.




b

| Fruit | Yield t/ha | Price FCFA/ kg | Production t | Area ha | Ref |
|---|---|---|---|---|---|
| Cocoa | 0.3-0.5 | 3200 | 310 077 | 578 736 | Ayuk (1999), MINADER (2022), ONCC (2024) |
| Musa spp. | 7 | 650 | 5 441 460 | 566 062 | Dépigny et al. (2019), MINADER (2022) |
| Mango | 5.6 | 2500 | 891 | 157 | World Population Review (2024), MINADER (2022) |
| Oil palm | 1.9 | 650 (liter) | 456 | 150 809 | MINADER (2022), Orwa et al. (2009) |
| Safou | 14-34 | 2500 | NA | NA | Kengue (2002), Orwa et al. (2009) |

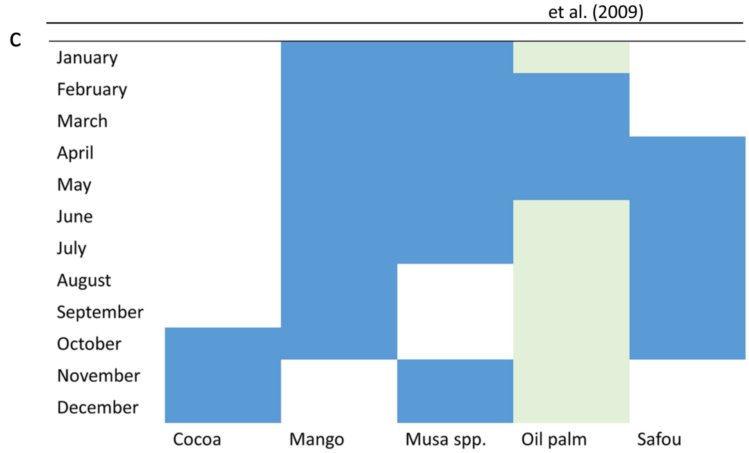



**Fig. 9** Annual production of cocoa in 2022 (**a**) (MINADER (2022)), information on prices and production for cocoa, safou, mango, oil palm, and *Musa* spp. (**b**), and harvest calendar for the respective species showing the seasonality of the fruits/crops (**c**) (Kengue 2002; MINADER 2022; Orwa et al. 2009).

in cocoa cultivation. Both mango and safou show a high potential to cover cocoa loss areas also in the long term, which is a promising perspective as 60% of the companion tree species investigated by Ariza-Salamanca et al. (2023) are projected to suffer a decrease in suitability within West Africa. The canopy of the safou is located in the intermediate stratum, such as the mango tree, but provides less dense shade (Saj et al. 2023). Although it grows best with High humidity, the safou tree can withstand a 4-month dry period (Kengue et al. 2011) which becomes in the future of high relevance.

### 3.3.3 Diverse agroforestry for economic resilience

The most important cocoa production zones in Cameroon are the Centre and West regions (Fig. 9a). However, our study shows that the Centre region, in particular, will experience a decline in its suitability for cocoa cultivation in the mid-term and far future (Fig. 5a), posing a significant challenge for the smallholder farmers cultivating cocoa. In general, cocoa monocultures generate higher short-term revenue than agroforestry systems; however, they are highly sensitive to market fluctuations and climate stress (Niether et al. 2020). In contrast, cocoa agroforestry systems, though yielding on average 25% less cocoa than monocultures, generate ten times higher total system yields by incorporating fruit-bearing trees and timber species, significantly improving food security and local trade (Niether et al. 2020; Pérez-Neira et al. 2023). The inclusion of diverse fruit trees not only enhances household food supply but also provides additional income opportunities, buffering against the volatility of cocoa prices (Pérez-Neira et al. 2023). However, farmers still get the highest price for cocoa compared to other commodities (Fig. 9b); thus, tree fruits remain a secondary income source as they cannot fully compensate for potential cocoa revenue losses (Niether et al. 2020). A key advantage of this system is that different species have staggered harvest periods, ensuring year-round fruit availability (Fig. 9c) and a more consistent income stream for farmers. For example, mango harvests begin as early as January, followed by peak production in May and June (MINADER 2022), while safou is predominantly harvested between April and October (Awono et al. 2002) and *Musa* spp. and cocoa during October to December (MINADER 2022). This seasonal diversity allows farmers to generate revenue beyond the cocoa harvesting period, reducing financial stress and increasing economic resilience.

Despite its economic importance, the intensification of agroforestry remains limited due to knowledge gaps in tree selection, seedling development, post-harvest processing, and market integration (Kengue 2002). Expanding the diversity of companion trees within cocoa agroforestry systems can further enhance productivity, but it requires improved knowledge transfer and targeted incentives to promote sustainable adoption (Alemagi et al. 2014; Eboutou et al. 2010; Tscharntke et al. 2011). In particular, safou holds untapped potential for industrial applications, including biofuel production, but its full economic benefits remain unrealized due to weak value chains and inefficient distribution networks (Kengue 2002). Additionally, oil palm–cocoa agroforestry systems present another opportunity for resilience, as they reduce price uncertainty for oil palm and serve as a buffer against production risks that affect either crop independently (Khasanah et al. 2020). Considerable economic and environmental improvements could be achieved through the diversification of such mixed cropping systems, which deserve greater research and policy attention (Khasanah et al. 2020). While agroforestry offers clear advantages in terms of income diversification, climate resilience, and ecological sustainability, supportive policies are needed to overcome challenges like lack of knowledge and training, high cost of inputs, disparities in access to high-quality seedlings, lack of extension services, and land tenure security (Dumas et al. 2025; Jacobi et al. 2014; Ngango et al. 2023; Tranchina et al. 2024; Petri et al. 2024) and consider the local socioecological context (Michel et al. 2024).

### 3.3.4 Contribution to restoration efforts and cultural heritage

While converting forest into agricultural land is one of the major reasons for the observable loss of forest cover in Cameroon, diverse agroforestry systems can maintain high species richness, including threatened species, and thus support afforestation (Jagoret et al. 2011) and long-term conservation efforts (Nadège et al. 2017; Saj et al. 2017). Cocoa agroforestry systems are among the densest in Africa in terms of trees and associated species compared to, for instance, Ghana, Nigeria, and Côte d'Ivoire (Michel et al. 2024). Especially, systems that are inherited and maintained by family labour tend to be more species rich and structurally diverse, managed with low to moderate inputs (Michel et al. 2024). Diverse cocoa agroforestry systems have been shown to increase soil organic matter compared to grasslands, which fosters long-term ecological stability (Jagoret et al. 2012). Non-native fruit trees like mango and avocado have been incorporated into restoration efforts in West Africa, where they attract seed dispersers, create favourable microclimates for native species, and support the regeneration of degraded landscapes (Jacobi et al. 2017) by improving soil nutrient cycling and supporting biodiversity, including termite communities that are vital for soil regeneration (Rodrigues et al. 2019; Coulibaly et al. 2020).

Beyond ecological benefits, agroforestry systems hold deep cultural significance, particularly among ethnic groups like the Beti in Cameroon (Rimlinger et al. 2021). Indigenous trees such as safou are not only valued for their economic potential but also for their symbolic meaning. Among the Beti, safou trees are traditionally planted to commemorate exceptional individuals, creating a living memory that links generations (Rimlinger et al. 2021).

### 3.4 Limitations and uncertainty

In this study, we assessed the suitability to grow cocoa and selected companion species with regard to climatic variables and soil pH. However, other factors such as farmer management, further soil characteristics, and access to markets are key resource constraints and can affect the suitability for cocoa (Singh et al. 2021; Sassen et al. 2022). The results of the model show a high robustness (high AUC); however, some limitations need to be considered. First, limited data availability may restrict model fitting, such as a lack of information on growing season dates, yields, land use allocation, intercropping, or information on fertilizer application (Müller et al. 2016). For instance, the lack of sufficient data with regard to cocoa-producing areas is restricting the validation of the model. This issue has been revealed also by previous studies (Lescuyer and Bassanaga 2021). Second, to our knowledge, the direct fertilization effect of $CO_2$ on cocoa growth is not yet considered in (suitability) models (Black et al. 2020). Third, our study does not capture the full complexity of agroforestry interaction and the adaptation effect of the shading trees. To better address crop–tree interactions, the use of plot-scale models such as Hi-SAFE (Dupraz et al. 2019), WaNuLCAS (Van Noordwijk and Lusiana 1999), or APSIM Next Generation (Holzworth et al. 2014; Smethurst et al. 2017) is recommended (Burgess et al. 2019). Nevertheless, our model results provide valuable insights of the climate change on the three trees and their performance in a multi-tree system.

## 4 Conclusion

There is no doubt that climate change will intensify in the future, with significant consequences for tree crop production and suitability, especially in highly vulnerable regions such as Sub-Saharan Africa. Robust information on these consequences is crucial for informing adaptation planning. In the case of cocoa production in Cameroon, such information can support initiatives aimed at preventing further deforestation. The aim of our study was to assess the future climate impacts on cocoa cultivation—both as a mono crop and within a diverse agroforestry system in Cameroon—to provide insights into potential losses and shifts in suitable areas, which are essential for sustainable land use planning. Furthermore, we identified areas where fruit trees such as mango and safou could potentially mitigate the negative impacts of climate change on cocoa. Additionally, we discuss how a diverse agroforestry system can enhance the economic resilience of farmers. Our findings contribute to the existing literature by advancing the EcoCrop model through the integration of CDM as well as by exploring the combination of different tree species with cocoa in Cameroon, while considering the boundaries of protected land and forest areas. Our study shows that climate change will significantly impact cocoa suitability in Cameroon, leading to pronounced losses, but also small gains within the forest-savannah mosaic ecosystem until the middle of the century. A novelty in our study is the long-term perspective: By 2090, major losses of suitable areas for cocoa are projected across the country as climate extreme events such as droughts and erratic rainfall patterns are projected to occur much more frequently. This, in turn, may increase deforestation pressure on surrounding forest management units and protected areas, which currently coincide with the most suitable land for cocoa cultivation. Due to the drastic decrease of suitable areas for cocoa, the oil palm-based agroforestry with moderate diversity will be dominant in the majority of the country. However, safou and mango show potential for covering cocoa loss areas, highlighting their role in adaptation strategies within existing cocoa production sites. This could help prevent further expansion into protected land and forests. Moreover, integrating different fruit trees, along with crops such as *Musa* spp., can enhance economic resilience by diversifying food availability and income sources. While this study primarily focuses on fruit trees as companion species, it is important to recognize that forest tree species—critical for biodiversity conservation and ecosystem restoration—also warrant further research attention. The study contributes to the existing knowledge of climate change impacts on cocoa and other fruit trees and can inform land use and adaptation planning to develop climate-resilient cocoa agroforestry systems that sustain cash crop production, protect livelihoods, and mitigate deforestation in Cameroon. The methodology can be replicated elsewhere by adjusting to the local context.

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**Authors' contributions** Conceptualization: N.G. and C.G. Methodology: N.G., A.C., and M.T. Formal analysis: N.G. Validation: N.G. Writing—original draft: N.G. Writing—review and editing: N.G., A.C., M.T., and C.G. Funding acquisition: C.G. Supervision: C.G. All authors read and approved the final manuscript.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Code availability** The code generated during and/or analyzed during the current study is available from the corresponding author on reasonable request.

## Declarations

**Ethics approval** Not applicable

**Consent to participate** Not applicable

**Consent for publication** Not applicable

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



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