Evaluation of potential threats to natural forest areas by shifts in expected global land suitability for cacao due to climate change

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submitted by

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Preface

The content of this work contributes to the field of land suitability modelling for a tropical plantation crop, namely cacao *Theobroma cacao*, the effects of climate change on land suitability and the assessment of the threat to natural forests associated with shifts of suitable land.

In summary, the contributions of this thesis are as follows:

- Development of a model for the evaluation of land suitability for cacao (*Theobroma cacao*) cultivation on a global scale inspired by the FAO Land evaluation approach (1976) and based on the land evaluation model CONSUS developed by Jaisli et al. (2019).
- Assessment of the potential effects of climate change on future land suitability for cacao cultivation, using an intermediate emission scenario (SSP 2-4.5) for the future climatic conditions of 2050
- Giving an estimate on the development of the pressure on protected areas by shifting areas of cacao cultivation due to climate change between 2000 and 2050.

This manuscript-style thesis was written to fulfil the requirements of the degree of Master of Science (Geographical Information Science & Systems) and consists of two parts: (1) a manuscript suitable for publication in a peer reviewed journal, and (2) a technical report that documents the methodological steps in detail.

The manuscript was authored by Nora Kägi (first author) and Dr. Christoph Traun (second author). The second author provided inputs during the conceptualisation and assisted with the revision of the draft manuscript.

The following scientific journals are considered for a future publication:

- <u>Agriculture, Ecosystems & Environment</u> (impact factor 6.4), an interdisciplinary journal publishing research on the interactions between agroecosystems and the environment.
- <u>Agronomy for Sustainable Development</u> (impact factor 6.4), a journal focusing on "studies at the intersection of agronomy, cropping and farming system research with ecological, genetic, environmental, economic or social sciences".

The manuscript was written to comply with author guidelines for the journal Agriculture, Ecosystems & Environment.

Contents

Manuscript

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Abstract Cacao is a key crop for many tropical economies and generates income for millions of smallholders. Increasing air temperatures and changes in precipitation patterns, as predicted for the near future by global climate models, are known to potentially affect cacao production. To devise targeted adaptation strategies, it is crucial to assess the impact of climate change on the biophysical suitability of cacao-growing regions.

In this study, the current and future global land suitability for cacao was modelled using a land evaluation approach that incorporates bioclimatic and soil requirements. It was found, that climatic factors – mainly pronounced dry seasons, high and low mean air temperature and low annual precipitation – restrict suitability much more than soil and topographical parameters, such as low soil pH and steep slopes. This study further suggests that the total global suitable area for cacao production under climate change will remain stable until 2050, though considerable regional shifts can be expected, with both expansions and contractions of suitable areas, as well as regional shifts within countries. Thus, many of the major growing areas will face considerable challenges in the near future as the bioclimatic cacao suitability shifts, foremost due to changes in precipitation patterns.

Historically cacao production contributed heavily to the destruction of natural forests. Climate change impacts on land suitability, combined with a further increase in demand, may lead to expansion of production into areas of natural forests. For current production hotspots, the model showed a decline of overlaps of suitable area with natural forests, while in minor producing countries new overlaps are emerging. Targeted efforts will be necessary to prevent shifts in production areas from contributing to further deforestation.

Keywords: *Theobroma cacao*, climate change vulnerability, land suitability modelling, deforestation

1 Introduction

Cacao (*Theobroma cacao*) is a relevant cash crop in humid tropical regions. In 2022 a total of 5.9 Mio t of cacao beans were produced on over 11.9 million ha of land (FAO, 2023), generating income for 5-6 millions of mainly smallholder farmers and their families and contributing significantly to the GDP of producing countries (Kongor et al., 2024; Lernoud et al., 2018). In the same year 60 countries reported cacao production, with over 90% of the production stemming from only 8 countries: Côte d'Ivoire (30%), Ghana (19%), Indonesia (11%), Ecuador (6%), Cameroon (5%), Nigeria (5%), Brazil (5%) and Peru (3%) (FAO, 2023).

In its natural habitat, cacao is a lower storey tree in the lowland evergreen rainforest of the western Amazon basin (Clay, 2004; Nieves-Orduña et al., 2023). It prefers to grow within 15° of the equator, under dense shade, with heavy, well-distributed rainfall and relatively uniform temperature (Allen, 1988; Wood and Lass, 1985). As a tropical tree crop, coca has competed for land surface with natural forests for a long time, and remains a non-negligible source of deforestation until today, (Carr and Lockwood, 2011). Cacao is responsible for the conversion of an estimated 15 million ha of tropical forest globally in the past 5 decades (Somarriba and López Sampson, 2018) and is suspected to have contributed more than 60 % to the deforestation in cacao producing regions of Ghana, Côte d'Ivoire and Cameroon since 2000 (Parra-Paitan et al., 2024). Worldwide, there is growing concern about how cacao and other commercially important commodities contribute to deforestation. This concern has led to a range of recent commitments by governments, traders and chocolate manufacturers to combat deforestation in the agricultural supply chains (for example the Cocoa and Forests Initiative, established in 2017) (Carodenuto, 2019; Somarriba and López Sampson, 2018). Despite these efforts, Goldman et al. (2020) identified an increase in forest area replaced by cacao after 2010, mainly in Ecuador, Peru, Brazil, the Dominican Republic, Honduras, Nicaragua, West Africa, Cameroon, DRC, Uganda, Indonesia, Malaysia and PNG. A development confirmed by reports of recent increases in disturbance of tropical moist forest (2015-2019), with highest rates in West Africa and Latin America (Vancutsem et al., 2021).

Shade is essential for growing cacao saplings, but mature trees produce higher yields in unshaded conditions (Tscharntke et al., 2011). In the past cacao farmers would initially only clear the understorey and then gradually thin the natural forest canopy following seedling establishment (Tscharntke et al., 2011). This change of shade needs with crop age, specific for cacao, combined with an increasing demand for cacao beans, has made cacao a typical forest frontier crop, spearheading deforestation (Ruf et al., 2015). Recently cleared forest initially provides the farmers with fertile soil, low weed and pest pressure and a suitable microclimate for the establishment of new cacao plantations (Ruf and Schroth, 2004). Thus, the cultivation of cacao has always been characterized by shifts of production centres, from one region to another, but also from one country to another or even to a different continent (Somarriba and López Sampson, 2018).

Cacao, as most agricultural crops, is heavily dependent on favourable climatic conditions to produce profitably. The expected changes in mean annual temperature and precipitation patterns due to climate change will modify cultivation area characteristics and are expected to have profound impacts on crop production (Cilas and Bastide, 2020). More frequent droughts and rising air temperatures, as predicted for this century, will increase the vulnerability of cacao plantations (Carr and Lockwood, 2011). As a result, some of today's cacao cultivation areas might become unsuitable for growing cacao by the near future, while other areas might exhibit more favourable conditions than today (Ariza-Salamanca et al., 2023; de Sousa et al., 2019; Läderach et al., 2013).

Considering the commodity's importance to the economies of many tropical countries, its sensitivity to changes in climatic variables, and the expected further increase in demand (Kongor et al., 2024), assessing cacao's vulnerability to climate change is garnering increasing interest. Predicting the future suitability of land for cacao farming has so far been done at various regional levels focusing mainly on current production hotspots in West and Central Africa (Côte d'Ivoire, Ghana, Cameroon), South and Central America (Ecuador, Peru, Brazil) and Southeast Asia (Indonesia) (Ariza-Salamanca et al., 2023; Bunn et al., 2019a, 2017; Ceccarelli et al., 2024, 2021; Heming et al., 2022; Igawa et al., 2022; Läderach et al., 2013; Schroth et al., 2016b; Singh et al., 2021). At a global level, peer-reviewed research is scarce, although such information would allow international stakeholders to compare the prospects of different cacao producing regions and to identify the most critical areas to focus their attention on.

Modelling land suitability, especially for agricultural systems, has a long history, with scientists from different disciplines contributing with concepts and tools (FAO, 2007; Jones et al., 2017). Based on the FAO land evaluation approach (FAO, 1976) a wide range of models have emerged, matching land characteristics and crop growth requirements (Antle et al., 2017; FAO, 2007; Sys et al., 1991). Advances in GIS as tool to store, retrieve, manipulate, and visualise large data sets have improved simulations further (El Baroudy, 2016). Modelling land suitability with predicted climatic conditions under climate change thus allows an estimation of possible future areas of crop production.

Climate change impacts on cacao suitability, combined with a further increase in demand, may lead once more to a shift and an expansion of cacao production into areas of natural forests (Ordway et al., 2017; Parra-Paitan et al., 2024). To counteract the negative effects of increased pressure on natural forests with suitable governance interventions, it is mandatory to first identify regions of possible future conflict. Thus, the aim of this study is to investigate, whether expected changes in land suitability, due to climate change will further increase the pressure on natural forests by shifting of cacao cultivation. The objectives are to a) identify biophysical requirements of cacao and corresponding climate and soil characteristics, b) model current and future land suitability and its determinants according to predictions of climate change and c) compare results with the extent of protected areas to gain insights on shifts in suitable cacao area (SCA) overlapping natural forests.

2 Materials and Methods

Modelling crop responses to climate change, including cacao, has been widely studied in recent decades. The present model is based on the land evaluation framework developed by FAO (FAO, 1976) and was inspired by recent work on suitability modelling by Jaisli et al. (2019) and Grüter et al. (2022). It aims at identifying suitable cacao growing areas on a global scale while focusing on the evaluation of biophysical variables.

The procedure to model suitability consists of four steps: description of crop requirements (1), description of the conditions on site (2), matching the two (3) and aggregation of the parameters into suitability maps (4). Suitability is modelled for current and predicted future climatic conditions using the same procedure, thus enabling to estimate the change in suitability. Intersecting the suitability maps with the extent of protected areas highlights regions of potential conflict between agricultural and conservational interests.

2.1 Identifying crop requirements and corresponding parameters

Crucial biophysical crop requirements of *T. cacao,* such as prevailing climatic and soil conditions, were defined based on a literature review. Subsequently, each parameter was classified into one of four suitability classes as suggested by the land evaluation approach (FAO, 1976): S1 (Highly suitable), S2 (Moderately suitable), S3 (Marginally suitable) and N (Not suitable (currently or permanently)). Classification and optimisation of thresholds was based on Sys et al. (Sys et al., 1993) taking into account further sources for verification (Laird et al., 1996 in Clay, 2004; FAO, 2003; Hardy, 1958; Nieves-Orduña et al., 2023; Syahri et al., 2020; Wood and Lass, 1985). Table 1 lists the crop requirements that were used in the model.

To describe the conditions on site, publicly available global high-resolution data sets matching selected crop requirements were identified (Table 2). Most global raster datasets used in this study are available with a resolution of 30 arc seconds. The choice of the parameters used in the model was based on the presence of an adequate definition of thresholds for the crop requirement in literature and the availability of global datasets with sufficiently high resolution in space and time. For most crop requirements, a directly corresponding dataset could be found, with the exception of the dry season length. This parameter was computed using monthly precipitation data and counting the longest unbroken stretch of consecutive dry months (i.e. monthly precipitation <100 mm (Wood and Lass, 1985)).

Table 1: Biophysical requirements of cacao (*T. cacao*) classified into four suitability classes (S1 (Highly suitable), S2 (Moderately suitable), S3 (Marginally suitable) and N (Not suitable) (FAO (1976)) as used in the model (adapted from Laird et al., 1996 in Clay (2004), FAO (2003), Hardy (1958), Nieves-Orduña et al. (2023), Syahri et al. (2020), Wood and Lass (1985))

Indicator	**S1**	**S2**	**S3**	**N**
Climate (= changing parameters)				
Mean annual temperature (°C)	23 – 29	22 – 23 29 – 30	21 – 22	<21 >30
Mean minimum temperature of coldest month (°C)	>15	13 – 15	13 – 10	<10
Mean annual precipitation (mm)	1600 – 2500	1400 – 1600 2500 – 3500	1200 – 1400 3500 – 4400	<1200 >4400
Length of dry season (months)	0 – 2	2 – 3	3 – 4	>4
Topography and Soil (= constant parameters)				
Soil texture (USDA class)	3, 4, 5, 7, 8, 10	6, 1	11, 9	2, 12
Coarse fragments (vol%)	0 – 15	15 – 35	35 – 55	>55
Soil pH	5.0 – 7.0	4.5 – 5.0 7.0 – 7.6	4.0 – 4.5 7.6 – 8.0	<4.0 >8.0
Soil Organic Carbon (%)	>1.5	0.8 – 1.5	>0.8	
Slope (%)	0 – 8	8 – 16	16 – 30	>30
Landcover				
Artificial surfaces (%)	0	1 – 25	25 – 50	>50
Water bodies	not present	-	-	present

Table 2: Data sources used to model the current and future biophysical suitability for cacao. Unless specified otherwise, the datasets typically have a resolution of 30 arc seconds.

Data set	**Data source and Reference**
Climate	
Mean annual temperature (℃) (BIO 1), current (1970–2000) and future (2041–2060)	WorldClim: Global climate and weather data, version 2.0 (Fick and Hijmans, 2017)
Mean minimum temperature of the coldest month (℃) (BIO 6), current (1970–2000) and future (2041–2060)	
Mean annual precipitation (mm) (BIO 12), current (1970–2000) and future (2041–2060)	
Monthly precipitation (mm), current (1970–2000)	
Monthly precipitation (kg/m2), future (2041–2060); resolution: 5 arc minutes	Envidat; CHELSA CMIP5 ts (Karger et al., 2020)
Topography and Soil	
Soil texture (USDA class)	ISRIC SoilGrids 2.0 (Poggio et al., 2021)
Coarse fragments (vol%)	
Soil pH	
Soil organic carbon	
Slope	WorldClim: Global climate and weather data, version 2.0 (Fick and Hijmans, 2017)
Artificial surfaces	FAO Global Land Cover (GLC-SHARE) Beta-Release 1.0 Database (Latham et al., 2014)
Water bodies	Derived from ISRIC SoilGrids 2.0 ("No Data" cells) (Poggio et al., 2021)

2.2 Modelling suitability

2.2.1 Current suitability modelling

To identify site suitability, the model matches each crop requirement (Table 1) with the corresponding dataset (Table 2) by reclassifying each raster cell value into one of the defined suitability classes. Thus, a suitability map for each investigated parameter is obtained. The single parameter suitability datasets are then aggregated based on the most limiting factor, with the lowest suitability score dictating the overall suitability, following the limitation approach for land evaluation by Sys et al. (1991). Likewise, empty raster cells overrule any suitability ranking, resulting in a final No Data value.

This aggregation is done for constant parameters (i.e. soil and topographical conditions) and for changing parameters (i.e. climate) respectively. The constant suitability is then paired with the changing suitability following the same method. The result is a suitability map showing the current potential land suitability for the production of cacao. The resulting suitability disregards ameliorative agricultural management practices, e.g. liming or irrigation.

2.2.2 Future suitability modelling

To assess how climate change might impact future suitability, datasets based on an intermediate emission scenario (SSP 2-4.5) for the future climatic conditions of 2050 (average of projected climate from 2041–2060) was selected. SSP 2-4.5 is based on the representative concentration pathway RCP4.5 (Thomson et al., 2011) and shared socioeconomic pathway SSP 2 (Riahi et al., 2017), assuming the continuation of carbon dioxide emissions around current levels until 2050 followed by a slow decrease, reflecting a slow progress towards achieving the sustainable development goals. Meanwhile all constant suitability parameters listed in Table 1 were left as is.

For the bioclimatic variables (BIO 1, 6 and 12) the datasets of WorldClim version 2.0 (www.worldclim.org), available in 30 arc second resolution, were used (Fick and Hijmans, 2017). The downscaled CMIP5 data (Eyring et al., 2016) of 14 global climate models (GCMs: BBC-CSM1-1, CCSM4, CNRM-CM5, GFDL-CM3, GISS-E2-R, HadGEM2-AO, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3 and NorESM1-M) was averaged over all GCMs.

For the future length of dry season, the datasets of Envidat, available in a spatial resolution of 5 arcminutes and a temporal resolution of single calendar months, was used (Karger et al., 2020). The data for each of the 4 available global climate models (GCMs: ACCESS1-3, CESM1-BGC, CMCC-CM, MIROC5) was first converted to mm/month and then averaged for each calendar month for the years 2041 – 2060, thus resulting in the average precipitation per calendar month for this period. The results were averaged over all GCMs and classified into suitability classes. To integrate these results, provided at a lower spatial resolution than the other datasets, in the overall suitability classification, the data was resampled to match the resolution of the other parameters.

All parameters contributing to the changing suitability under future climatic conditions were aggregated by the most limiting factor. Lastly, the future climate suitability (i.e. "changing suitability") and the topographical and soil suitability (i.e. "constant suitability") were again aggregated by the same method, to acquire the overall future suitability.

2.3 Calculation of expected changes

The difference between the overall suitability under current and future climatic conditions was calculated for each raster cell, to visualise the expected suitability change. The resulting values indicate whether the suitability of an area is expected to decrease or increase (e.g. a negative value indicating reduced future suitability), including complete loss and gain of suitability.

Additionally, the changes in suitability were calculated for each cacao-producing region (Latin America, Africa, Asia) and for selected producing countries. The selection accounting for spatial distribution (representation of the global producing regions), total production quantity and specialty cacao regions. Côte d'Ivoire, Indonesia and Brazil were selected as some of the largest cacao producing countries (i.e. total quantity produced in 2022) as indicated in FAOSTAT data (FAO, 2023). Ecuador, the Dominican Republic and Cameroon were selected as important origin countries of fine flavour cacao (ICCO, 2023).

After reprojection of the data to an equal-area projection (Homolosine) (Moreira de Sousa et al., 2019) quantified changes in area per suitability class were calculated.

2.4 Calculation of overlap with protected areas

The analysis of overlaps of SCA with protected areas (PA) under current and future climatic conditions was done under the assumption, that current PA will persist and will not undergo changes regarding their extent. PA were acquired from the World Database on Protected areas (UNEP-WCMC and IUCN, 2024). To visualise potential threats, the PA were coloured according their suitability for cacao cultivation. Additionally, the raster cells in overlapping areas were summarised for each suitability class and each cacao producing region and selected producing country respectively, as for the calculation of expected changes in cacao suitability. To analyse the changes in pressure on protected areas, we compared the changes in overlapping areas under current and future cacao suitability.

2.5 Software

All analyses were performed with a combination of stand-alone Python scripts and the ESRI ArcGIS Pro software version 3.1.2. To improve computational performance the analysis was limited to 40° N/S latitude as it was deemed highly unlikely for cacao to grow in higher latitudes in the nearer future (Wood and Lass, 1985). Nevertheless, processing of the large datasets was repeatedly impeded by the limited capacity of the available hardware (primarily RAM), which in turn limited feasibility of extensive exploratory analysis.

3 Results

3.1 Current regional cacao suitability

Globally, the highest overall current cacao suitability (S1 & S2) is found in South and Central America (e.g. Peru, Colombia, Suriname, Nicaragua and Honduras), in Central and West Africa (e.g. Senegal, Cameroon, Republic of Congo, DRC), and in Southeast Asia (Indonesia, Malaysia, Philippines, Papua New Guinea) (Figure 1).

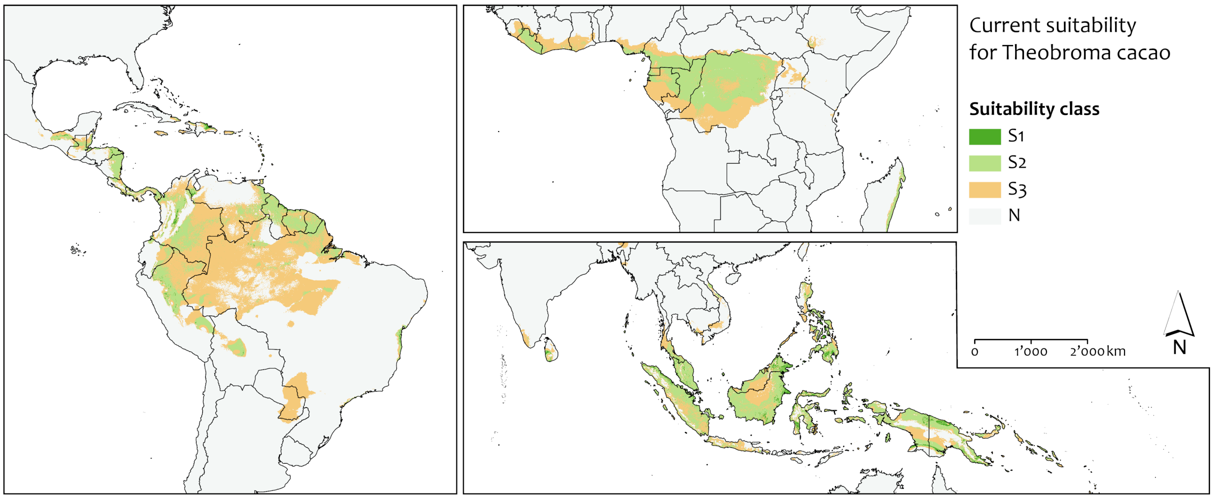

Figure 1: Current overall suitability for *T. cacao* cultivation in the main producing regions in America, Africa and Asia.

Table 3: Current and future suitable growing areas for *T. cacao* globally and in the main producing regions and countries (S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: Not suitable). Projected changes in suitable areas are shown as percentages.

Suitability Class	2000	2050 (SSP 2-4.5)	Delta	2000	2050 (SSP 2-4.5)	Delta
	x10³ km²	x10³ km²	%	x10³ km²	x10³ km²	%
	World			**Southeast and South Asia**		
S1	200.3	265.9	32.7%	192.6	100.7	-47.7%
S2	4'492.1	4'349.5	-3.2%	1'525.0	1'404.7	-7.9%
S3	6'475.5	7'170.9	10.7%	1'028.1	1'535.2	49.3%
Σ (S1-S3)	11'167.9	11'786.3	5.5%	2'745.6	3'040.5	10.7%
	America			**Africa**		
S1	75.2	56.3	-25.0%	13.6	108.9	702.0%
S2	1'487.6	1'380.1	-7.2%	1'668.6	1'564.7	-6.2%
S3	4'222.5	3'815.8	-9.6%	1'383.1	1'820.0	31.6%
Σ (S1-S3)	5'785.3	5'252.2	-9.2%	3'065.8	3'493.6	14.0%
	Côte d'Ivoire			**Cameroon**		
S1	-	-		-	35.2	
S2	10.1	12.2	21.1%	145.5	166.6	14.5%
S3	89.9	86.3	-4.0%	74.3	133.4	79.5%
Σ (S1-S3)	100.0	98.5	-1.5%	219.8	335.2	52.5%
N	223.9	225.3	0.7%	248.2	132.9	-46.5%
	Indonesia			**Dominican Republic**		
S1	71.8	40.7	-43.3%	5.6	4.2	-23.9%
S2	909.0	902.0	-0.8%	5.4	4.7	-12.3%
S3	524.2	577.5	10.2%	8.4	6.9	-18.9%
Σ (S1-S3)	1'505.1	1'520.2	1.0%	19.4	15.8	-18.5%
N	390.8	375.6	-3.9%	29.2	32.8	12.3%
	Brazil			**Ecuador**		
S1	4.1	0.3	-93.5%	1.0	0.5	-47.1%
S2	234.8	169.0	-28.0%	34.3	36.1	5.2%
S3	2'373.8	1'965.4	-17.2%	54.8	58.2	6.1%
Σ (S1-S3)	2'612.8	2'134.7	-18.3%	90.1	94.8	5.2%
N	5'910.3	6'388.4	8.1%	166.6	161.9	-2.8%

Climate factors prove to be far more limiting than soil and topographical factors and severely restrict northern and southern extents of the global suitable areas. The dry season length is the most crucial restricting parameter, defining the northern and southern borders of the suitable areas in Africa and Asia and stretching far into the tropics in South America and Eastern Africa. Mean annual precipitation further restrains cacao cultivation in some places, with either too little (Côte d'Ivoire) or too high overall precipitation (Western Colombia, Papua New Guinea). Mean annual temperature and mean minimal temperature of the coldest month define the northern and southern borders in Latin America and Southern Africa and distinctly restrict suitability in tropical areas of higher altitude (Ecuador, Colombia, New Guinea).

On a global scale, the soil and topographical parameters show few total limitations (N) for cacao cultivation, with suitable areas stretching well beyond the commonly set lateral boundaries for cacao cultivation of ±20° N/S limited by climatic suitability. It is mainly low soil pH, noticeably prevalent in soils under rainforest, limiting cacao suitability in the Amazon and Congo basins and in Southeast Asia on Sumatra and Borneo, regions commonly known for widespread cacao cultivation. Soil texture is shown to limit suitability foremost in areas with sandy soils (Colombia, Brazil, Western Africa). Both soil coarse fragments and soil organic carbon content are not relevant limitation criteria in terms of global land suitability for cacao, classifying mostly as S1 or S2. Slope restricts suitability where it is above 16% (S3) and above 30% (N), representing mountainous and hilly regions, which are present across all growing regions. Artificial surfaces, classified as not suitable (N), account for a small portion of globally suitable areas and are mainly concentrated near metropolitan regions.

The marked agro-climatic diversity among **six main producing countries** (Côte d'Ivoire, Brazil, Indonesia, Ecuador, Dominican Republic, Cameroon) means that different climatic requirements (annual temperature, annual precipitation, length of dry season and minimum temperature of coldest month) determine regional variations in current suitability.

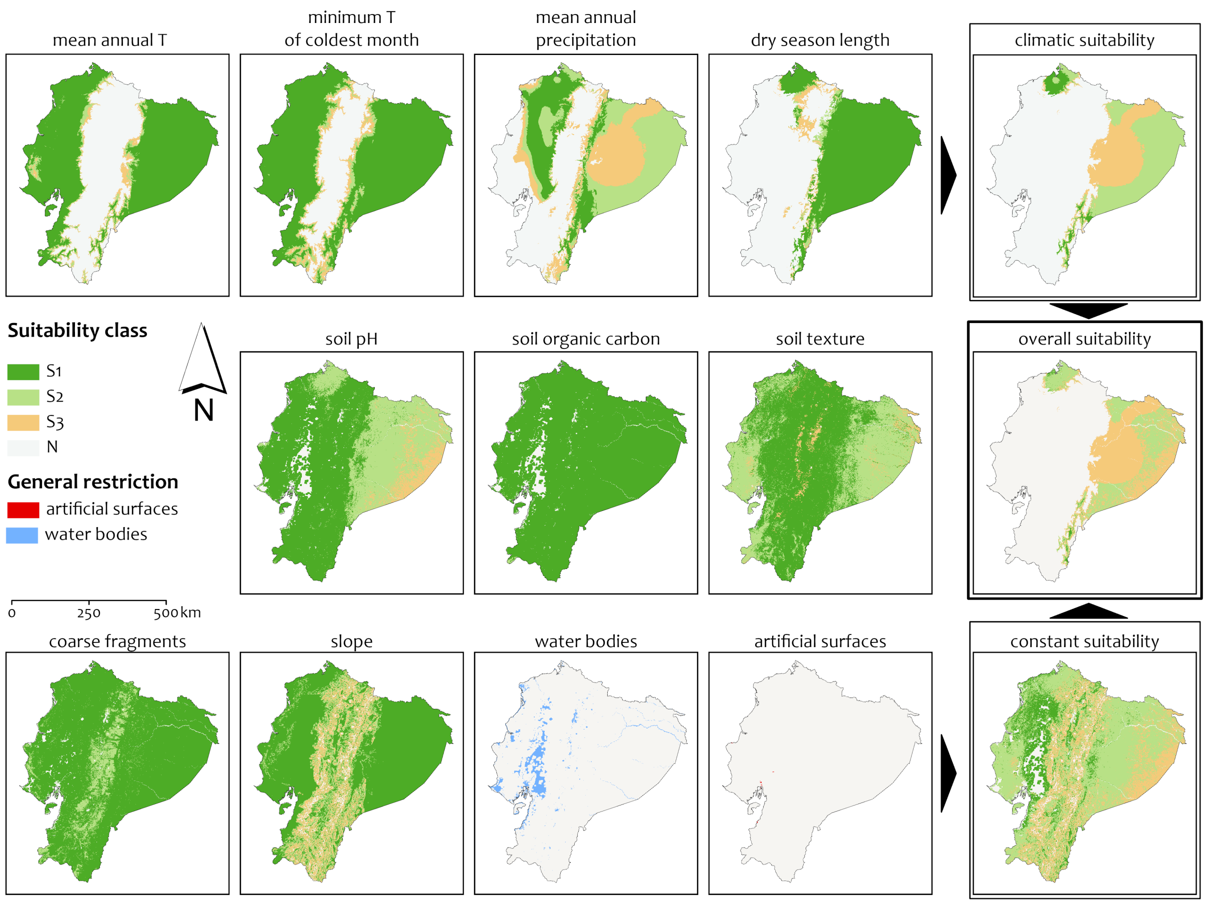

Figure 2: Single parameter suitability for *T. cacao* cultivation for Ecuador.

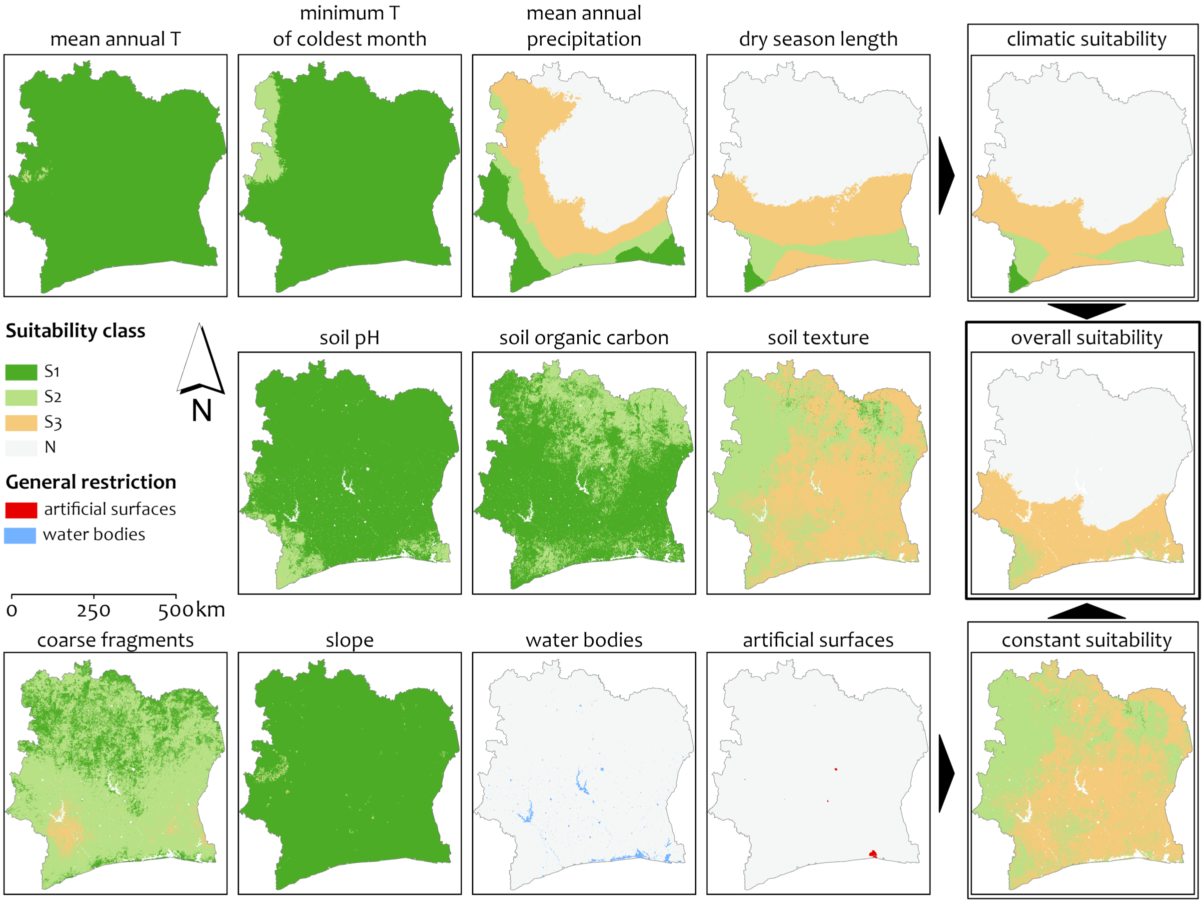

Figure 3: Single parameter suitability for *T. cacao* cultivation for Côte d'Ivoire.

Latin America

Figure 2 shows the current suitability of different climate, soil and topography parameters for **Ecuador**. Here, constant parameters do not limit suitability considerably. Although some areas classify only as marginally suitable caused by too high slope scores in the Andes and low soil pH in the Amazon basin. Climatic parameters on the other hand greatly affect suitability, whether it is in mountainous areas, where the mean annual temperature is too low, in the Amazon basin, where annual rainfall is too high and in the Pacific coast, where the dry season is too pronounced. The combination of which leads to very few and scattered areas of high suitability in the country. Also in **Brazil** suitability is mainly hampered by climatic factors. Most of the area outside of the Amazon basin is rendered unsuitable due to dry season length. Only in the very South this restraint is replaced by the low mean annual temperature of the higher latitudes. In the upper Amazon basin, it is, similar to Ecuador, the predominant low soil pH limiting suitability.

Africa

Climatic factors also play a crucial role in **Côte d'Ivoire** (Figure 3). While temperature parameters do not impede suitability, dry season length and mean annual precipitation limit suitability severely in the north and east of the country. While not causing complete unsuitability, soil and topographical parameters still declare wide stretches of the country as only marginally suitable. This affects overall suitability in coastal areas, where soil texture is only marginally suitable. **Cameroon** shows virtually no constraint due to soil and topographical parameters. For the climatic parameters, the increasing dry season length again prevents expansion towards the northern regions.

Asia

Most of **Indonesia** qualifies at least marginally for cacao cultivation, with 79 % of the land surface classifying in suitability classes S1 – S3. In the mountainous areas in central Papua, Sulawesi and on the western coast of Sumatra and Java suitability is limited by low mean annual temperatures. On the Lesser Sunda Islands and southern Papua suitability is impaired due to increasing dry season length. Soil and topographical parameters (soil texture, soil pH and slope) play a marginal role in limiting suitability locally. In addition, annual precipitation poses some constraint to suitability in Central Kalimantan and Central Papua.

3.2 Future cacao suitability

The expected shifts in cacao suitability due to climate change are shown in Table 3 and Figure 4. Taking into account a climate change scenario of SSP 2-4.5, the global suitability for cacao cultivation will slightly increase by 2050 by 5.5%. Most notable is the increase of areas of the highest suitability (S1) by 33 %. In the future, dry season length remains the most limiting parameter. In some regions (Eastern Africa, Eastern and Southern Brazil, Northern Philippines) changes in precipitation patterns lead to positive changes due to a shortening of the dry season. Positive changes due to a warmer climate occur mainly in mountainous regions, as higher altitudes become more suitable.

When centring on a regional scale, trends towards both negative and positive changes can be observed, depending on the growing region. While the share in moderately suitable areas will decrease in all three regions, Asia, with presently the largest share of highly suitable areas (S1), will see a decrease of -48 % in this class. Also in Latin America S1 areas are decreasing by -25 %. On the other hand, Africa can expect an impressive increase of 702 % in this class. Positive changes concentrate foremost at the northern and southern boundaries of the suitable area, which seem to benefit from climate change. The main regions of positive change (Figure 4) are to be found in Southern Brazil, Paraguay, Bolivia and some parts of Peru, Venezuela, Ghana, Cameroon, DRC, Uganda, Sri Lanka and Indonesia, but also extending into countries which have not yet reported any notable cacao production, such as Paraguay, Argentina, Kenya, Madagascar, Vietnam, Bangladesh, and Southern China. These changes mostly constitute of previously not suitable areas becoming marginally suitable. While Africa and Asia are expected to exhibit net increases of 14.0% and 10.7% in SCA, Latin America is facing a considerable decrease by -9.2% of total SCA.

Looking at the results for the selected countries it becomes clear, that predictions for regions cannot easily be downscaled to country level. All of the major cacao-producing countries examined are significantly impacted by climate change with considerable shifts in suitable areas by 2050 (Table 3, Figure 4 and 5).

Latin America

Brazil will experience a dramatic decline of its suitable areas, losing surface in all suitability classes and most markedly -93.5 % of the S1 area. The main driver of the negative trend is the prolonged dry season in the central states of Pará and Mato Grosso. **Ecuador** on the other hand is not greatly affected by climate change, albeit there is a shift from S1 to S2. While the future will bring the **Dominican Republic** positive effects of warmer temperatures, precipitation will simultaneously decrease and lengthen the dry season, leading to a net loss of suitable areas of -18.5 %.

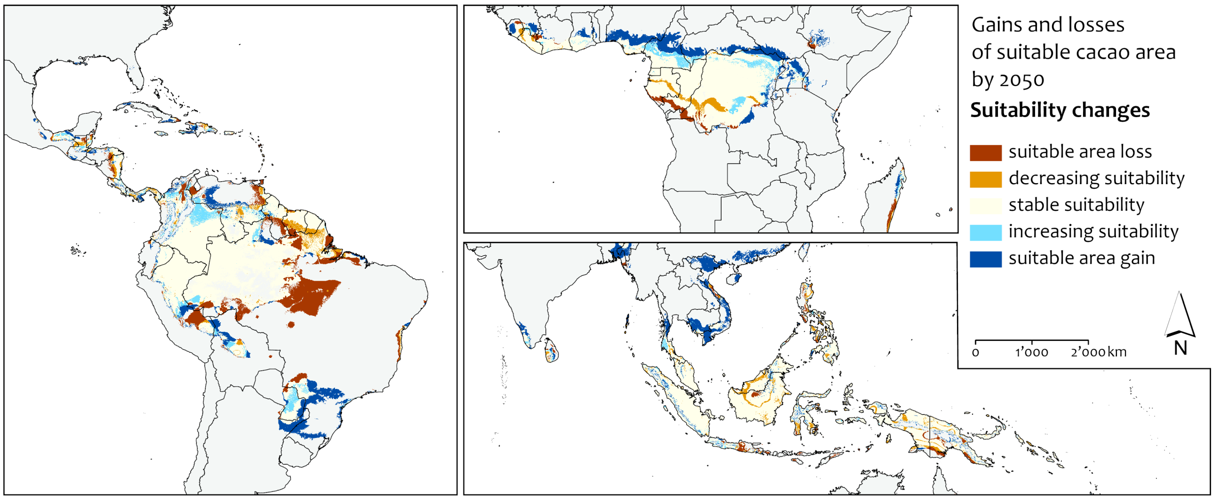

Figure 4: Suitability changes including gains and losses of suitable area for *T. cacao* cultivation between current (2000) and future (2050; SSP 2-4.5 - intermediate emission scenario) conditions in the main producing regions.

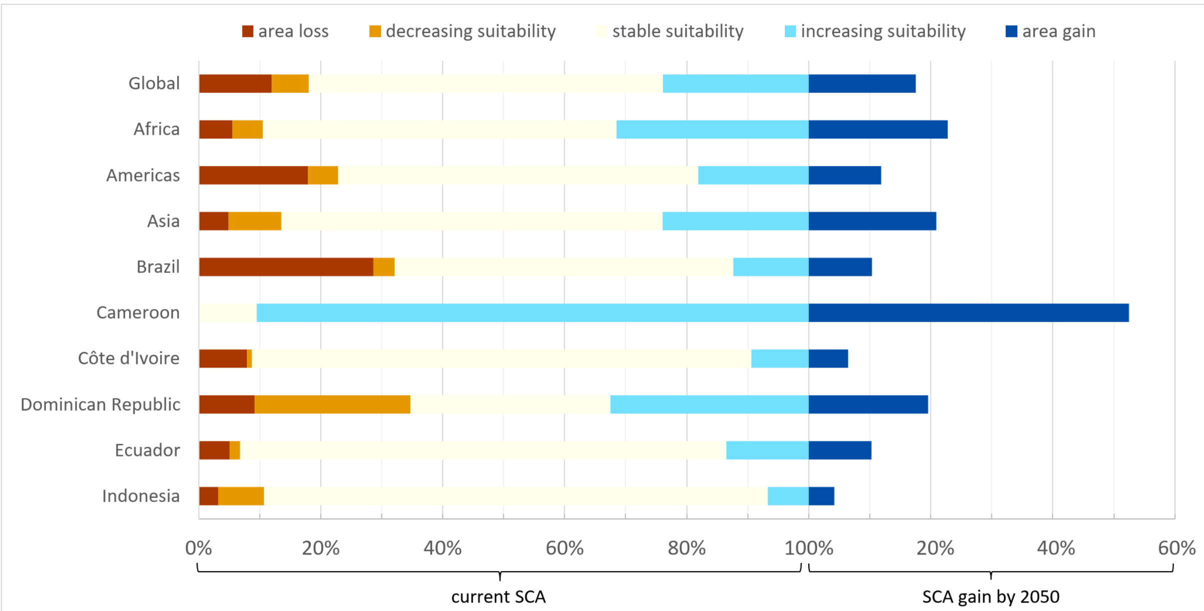

Figure 5: Positive and negative changes in suitability in percent of currently suitable area (S1 – S3), including net gains and losses of SCA

Africa

Côte d'Ivoire, currently the biggest producer of cacao, does not have any areas classifying as S1 in the present, nor in the future, but is expected to experience considerable increase in S2 areas (+21 %). Meanwhile in **Cameroon**, SCA in general will expand considerably under climate change (+53 %), most notably with 35'000 km2 newly classifying as S1. All climate parameters show a positive development under climate change, with dry season length still greatly limiting suitability, especially in the Northern parts of the country (Figure 6).

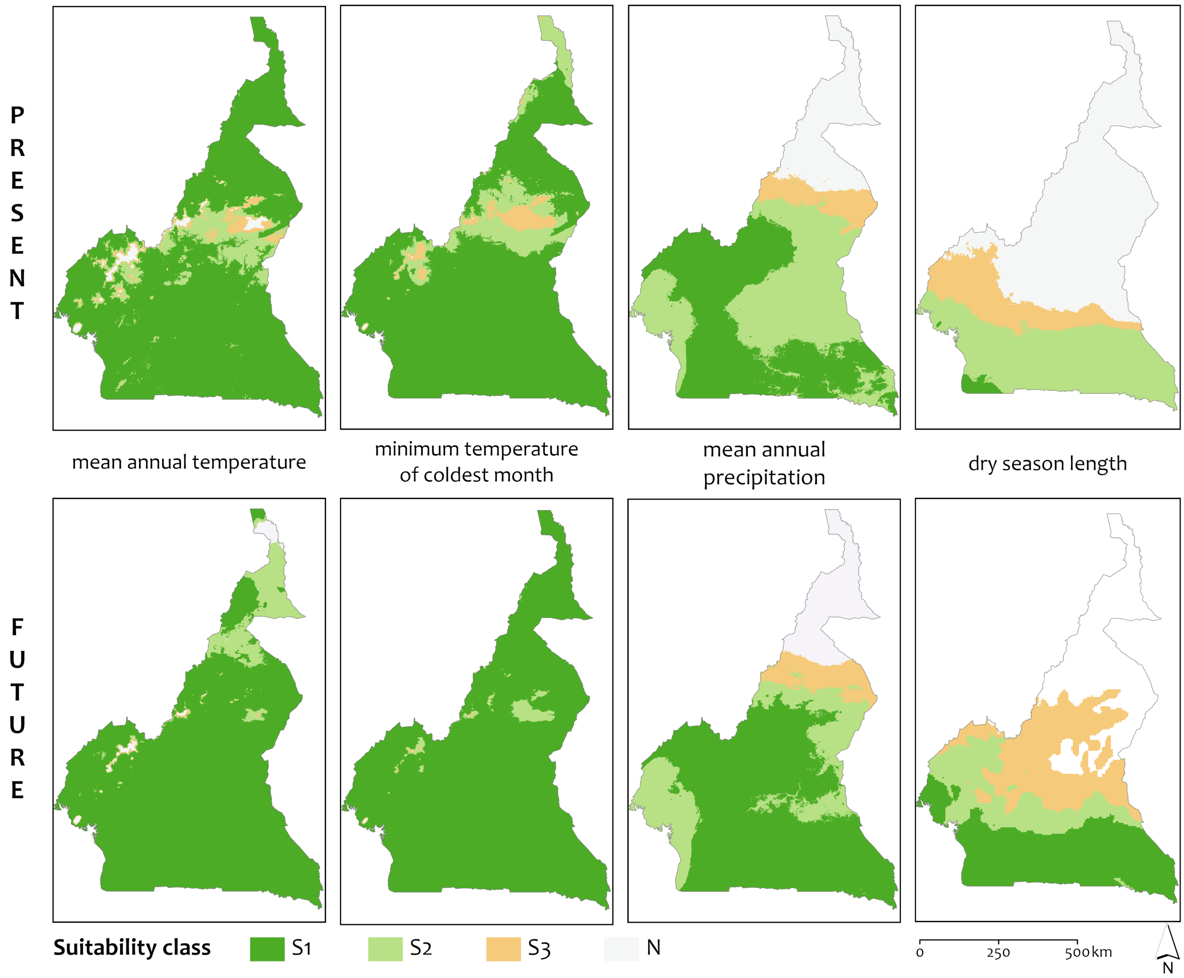

Figure 6: Current and future climate suitability for *T. cacao* cultivation in Cameroon (2000 – 2050).

Asia

In accordance with trends on the regional scale, **Indonesia** is experiencing a marked decrease in S1 area, with a loss of -43 %, even though overall SCA remains stable. Many areas transition to marginal suitability (S3), gaining even from previously unsuitable areas. Nevertheless, Indonesia remains the country with the by far largest share of SCA (84 %) compared to the total land surface.

3.3 Overlap with protected areas

With a total global terrestrial coverage of over 16%, the protected areas (PAs) also represent a substantial share of the land surface in all cacao growing regions (UNEP-WCMC and IUCN, 2024).

3.3.1 Current cacao suitability in protected areas

Under current conditions around 29 % of the global SCA (S1-S3) is overlapping with protected areas. (Table 4 and Figure 7) Most overlaps concern moderately and marginally suitable areas. Equally, all three cacao regions register overlaps with PAs foremost on moderately and marginally SCAs.

In Latin America an enormous 42 % of SCA lie within PAs (with 15% of S1-SCA overlapping PAs). The most extensive overlapping areas are located in Northwestern Brazil, with fewer spots in adjoining countries bordering on the Amazon basin. While overlaps in Brazil mainly occur in S3 areas, Peru, Colombia, Venezuela and the Guianas see larger overlaps in moderately suitable areas. In Central America mainly the cacao regions of Honduras and Nicaraga, as well as Costa Rica, northern Guatemala and Belize are concerned with overlaps. In Africa on the other hand, only around 17 % of the SCA is within PAs, with barely 2 % of the S1 area concerned. While in West Africa large stretches of the growing region of Senegal, Côte d'Ivoire and Ghana are catalogued as PAs, in Central Africa, namely Cameroon, Gabon, Republic of Congo and DRC, protected areas are scarcer and spread further apart, though affecting land of better suitability classes. In Asia smaller patches of PAs are scattered throughout Indonesia, Malaysia and Thailand, with overlaps occurring on 10 % of the SCA.

Table 4: Overlap of current and future suitable growing areas for *T. cacao* with protected areas globally and in the main producing regions and countries (S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: Not suitable) Projected changes in suitable areas are shown as percentages.

Suitability Class	2000		2050 (SSP 2-4.5)		Δt	2000		2050 (SSP 2-4.5)		Δt
	x10³ km²	% of tot. suit. area	x10³ km²	% of tot. suit. area	% change	x10³ km²	% of tot. suit. area	x10³ km²	% of tot. suit. area	% change
	World					**Asia**				
S1	21.4	10.7%	35.8	13.5%	67.4%	9.7	5.0%	8.0	7.9%	-17.7%
S2	1'000.8	22.3%	924.5	21.3%	-7.6%	131.7	8.6%	151.8	10.8%	15.3%
S3	2'223.3	34.3%	2'057.5	28.7%	-7.5%	127.6	12.4%	170.5	11.1%	33.7%
Total S1 – S3	3'245.5	29.1%	3'017.8	25.6%	-7.0%	268.9	9.8%	330.3	10.9%	22.8%
	America					**Africa**				
S1	11.5	15.3%	12.6	22.4%	9.5%	0.2	1.7%	15.3	14.0%	6'541.3%
S2	536.6	36.1%	424.3	30.7%	-20.9%	332.5	19.9%	348.4	22.3%	4.8%
S3	1'904.9	45.1%	1'647.2	43.2%	-13.5%	190.5	13.8%	239.8	13.2%	25.9%
Total S1 – S3	2'452.9	42.4%	2'084.0	39.7%	-15.0%	523.2	17.1%	603.4	17.3%	15.3%
	Côte d'Ivoire					**Cameroon**				
S1	-	-	-	-	-	-	-	5.4	15.3%	-
S2	4.2	41.4%	5.4	43.8%	28.1%	21.5	14.8%	18.4	11.0%	-14.5%
S3	25.3	28.1%	23.8	27.6%	-5.8%	5.4	7.2%	7.7	5.8%	42.9%
Total S1 – S3	29.4	29.4%	29.2	29.6%	-1.0%	26.9	12.2%	31.5	9.4%	17.0%
	Indonesia					**Dominican Republic**				
S1	3.1	4.3%	1.3	3.3%	-56.2%	0.9	15.4%	0.9	21.3%	7.1%
S2	82.1	9.0%	86.6	9.6%	5.5%	0.5	9.4%	0.4	8.7%	-13.8%
S3	61.0	11.6%	71.7	12.4%	17.5%	1.1	12.5%	1.3	10.6%	21.1%
Total S1 – S3	146.2	9.7%	159.7	10.5%	9.3%	2.4	12.5%	2.6	12.3%	8.8%
	Brazil					**Ecuador**				
S1	2.1	52.1%	0.1	24.3%	-96.9%	0.1	6.4%	0.1	18.3%	50.0%
S2	144.6	61.6%	89.5	53.0%	-38.1%	11.8	34.4%	12.6	34.8%	6.4%
S3	1'394.7	58.8%	1'092.8	55.6%	-21.6%	12.1	22.0%	13.1	22.5%	8.7%
Total S1 – S3	1'541.5	59.0%	1'182.4	55.4%	-23.3%	23.9	26.6%	25.8	27.2%	7.7%

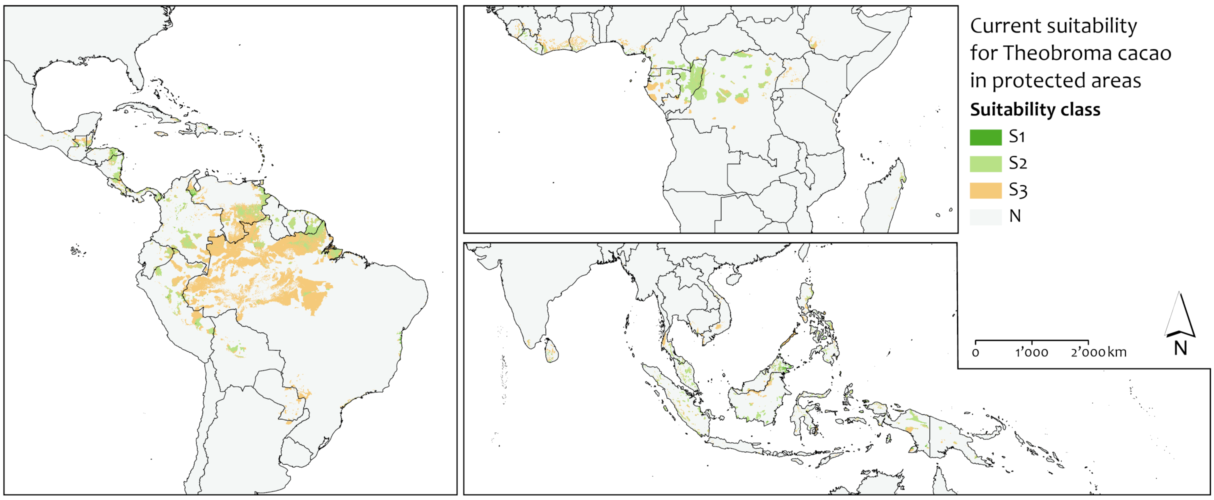

Figure 7: Current overall suitability for *T. cacao* cultivation overlapping protected areas in the main producing regions of America, Africa and Asia.

Latin America

Compared to the whole continent, **Ecuador** is less affected with 27 % overlaps of PAs with total SCA. The biggest areas lie in the eastern part of the country in the provinces of Sucumbíos, Orellana and Pastaza, where several national parks and wildlife reserves are located (Figure 7). SCA in **Brazil** has presently very large overlaps with PAs, encompassing 59 % of the total SCA with all suitability classes reaching well over 50 %. The Dominican Republic has only 12.5 % overlap of total SCA, but is affected with considerable overlaps of 15 % in S1areas lying in the eastern provinces of Samaná, Hato Mayor and Monte Plata.

Africa

Côte d'Ivoire sees overlaps of 29 % for the total SCA, with moderately suitable areas being most affected with an overlap of 41 %. The largest overlapping area occurs in the districts Montagnes and Bas-Sassandra, where the Taï National Park encompasses one of the last areas of primary rainforest in West Africa. **Cameroon** is less affected with 12 % of the total SCA overlapping PAs. The largest areas are again in the vicinity of national parks and wildlife reserves in the East department.

Asia

As in Asia in general, **Indonesia** sees fewer overlaps than the other selected countries, amounting to 10 % of the total SCA. The overlapping areas are small-sized and evenly distributed over Sumatra, Kalimantan, Sulawesi and Papua. The biggest overlaps on highly and moderately suitable land occur on southern Kalimantan and Papua.

3.3.2 Future cacao suitability in protected areas

Globally, the highly suitable SCA (SCA-S1) in protected areas will increase by 67 % or 14'400 km^2 by 2050 (i.e. overlaps increasing from presently 10.7 % to 13.5 % of S1-SCA) (Table 4, Figure 8). On the other hand, overlaps with total SCA are decreasing by -7 %, resulting in a net loss of overlaps of roughly 230'000 km^2. The scale of these changes in relation to the total SCA is also shown (Figure 9).

This trend is reflected and enhanced in Latin America, where overlaps of S1-SCA and PAs is increasing by 9.5 % (+1'100 km^2), while overlaps with total SCA are reducing by -15 % simultaneously. Total SCA overlapping PAs is reducing from 42 % to 40 %, thus overlaps remain at a high level. Increasing overlaps can be observed in Guatemala, Bolivia, central Venezuela and southern Brazil, while decreasing overlaps are to be expected in central and northern Brazil, southern Peru, eastern and western Venezuela and Honduras. In Africa overlaps of S1-SCA are increasing more drastically, by a staggering 6541 % (+ 15'500 km^2), with the total SCA also increasing by 15 %. While longstanding cacao producing regions in West Africa as well as Gabon and the Republic of Congo see a decrease in overlaps, they are increasing in northern Ghana, Nigeria, eastern DRC and Uganda in accordance with increasing suitability of the whole region. In Asia on the other hand, overlaps in the S1-SCA category are diminishing by 17 % (-1'700 km^2), while overlaps in PAs with marginal SCAs are gaining, resulting in an overall increase of SCAs of 22.8 %. Overlaps decrease albeit moderately in the Philippines, Papua and Borneo, while mainly Sumatra, Cambodia and Vietnam will see marked increases. Sri Lanka and Sulawesi show differing trend depending on the region.

Latin America

In **Brazil**, the states bordering the Amazon basin show differing trends (Figure 10). While Roraima and Acre expect a shift of overlaps to new areas, Pará, Amapá, Rondônia and the well established cacao region of Bahia on the Atlantic coast see a loss of large overlaps of SCA with PAs. In the southern states of Mato grosso do Sul, Paraná and São Paulo new overlaps emerge in conformity with the expansion of suitability to these latitudes. Overall Brazil is experiencing an net loss of overlaps of 23 % by 2050, with the biggest decrease in S1-SCA area (-87 %, -2'100 km^2). Notwithstanding 55 % of its SCA will still be overlapping PAs. In **Ecuador** overlaps in total SCA are expected to increase only slightly (+8 %). Areas of overlaps with

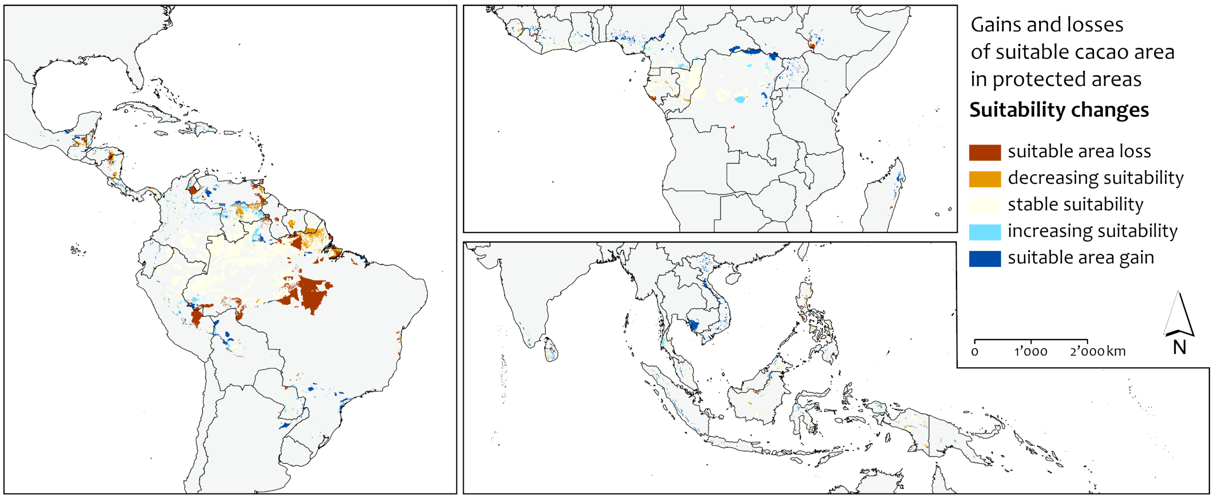

Figure 8: Gains and losses of suitable area for *T. cacao* cultivation overlapping protected areas between current (2000) and future (2050; SSP 2-4.5 - intermediate emission scenario) conditions in the main producing regions.

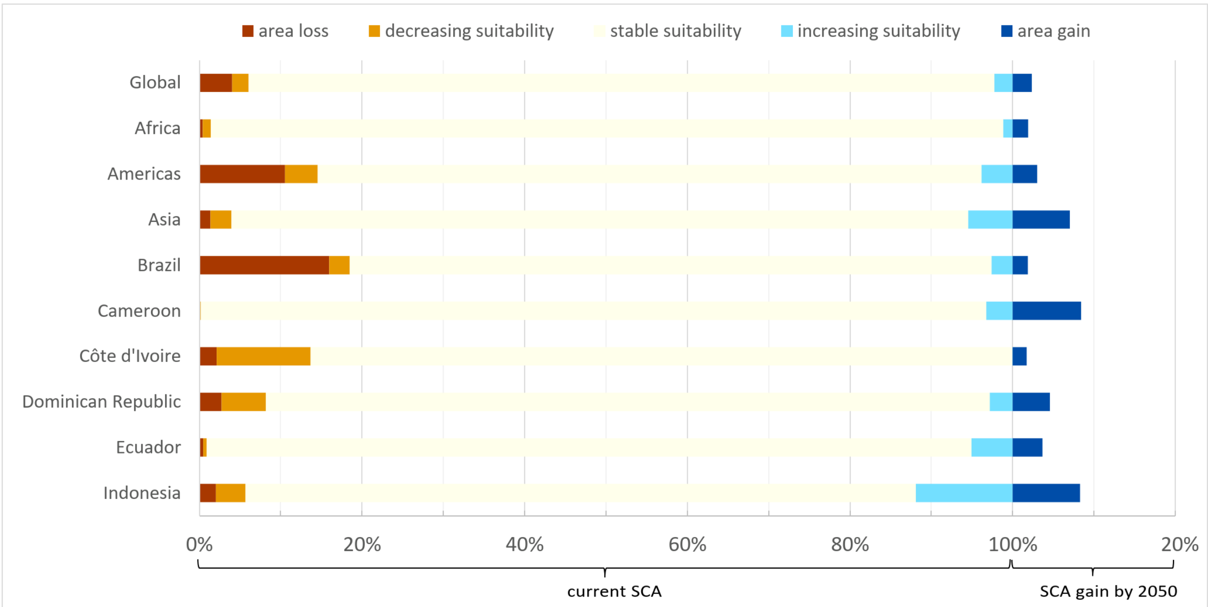

Figure 9: Positive and negative changes in suitability overlapping protected areas in percent of current suitable area (S1 – S3)

increasing suitability are spread along the eastern and western slopes of the Andes. The Dominican Republic is also expecting a 9 % increase of total SCA overlapping PAs (+200km^2)As total SCA is also expected to expand, the share of overlaps on total SCA remains constant at 12.5 %.

Africa

For **Côte d'Ivoire** the share of overlapping area on total SCA remains stable at 30 %, though there is a shift from S3-SCA to S2-SCA in the overlaps. S2-SCA overlaps are increasing markedly with 28 % (+1'200 km^2). The situation in **Cameroon** reflects the trends for the whole region. A total of 5'400 km2 within PAs newly classify as S1-SCA and the total SCA overlapping PAs is increasing markedly by 17 %. Because total SCA is expanding in the country, the share of overlaps on total SCA is decreasing slightly from 12.4 % to 9.4 %. The changes are concentrated in the central and western departments.

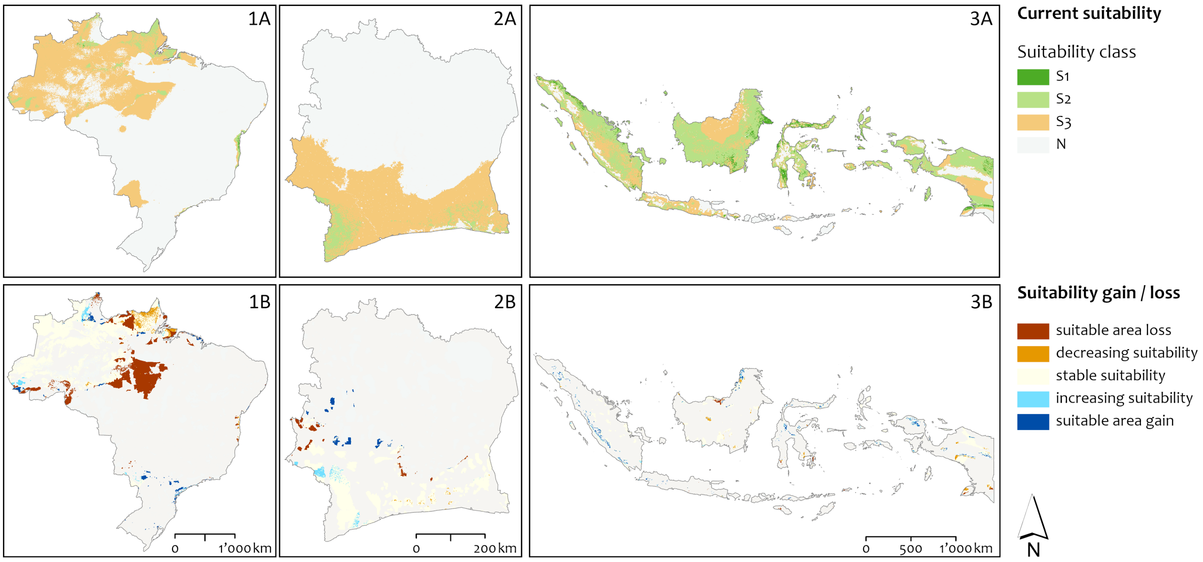

Figure 10: Current overall suitability for *T. cacao* cultivation overlapping protected areas (A) and suitability changes by 2050 (SSP 2-4.5 - intermediate emission scenario) (B) for Brazil (1), Côte d'Ivoire (2) and Indonesia (3)

Asia

Even though S1-SCA overlaps will decrease by 56 % in **Indonesia**, the country will see a 9 % increase of total SCA area overlapping PAs. The areas changing suitability is evenly distributed over the whole country. The share of overlaps on the total SCA will remain constant at 10.5 %.

4 Discussion

4.1 Factors determining suitability

Consistent with the biophysical requirements of cacao outlined in Table 1, climatic variables are the primary limiting factors affecting suitability for cacao cultivation. Of those, dry season length is the most crucial, restricting cacao suitability mostly to the tropical rainforest zone (FAO, 2012). This finding is in league with other studies, which showed that rainfall during the driest months is more important than the annual average precipitation (Läderach et al., 2013; Wood and Lass, 1985; Zuidema et al., 2005). For regions without a marked dry season, temperature parameters limit further latitudinal and altitudinal expansion, proving their importance as main limiting factors for cacao production (Daymond and Hadley, 2004). However, low soil pH was found to be another critical factor, mainly in the central Amazon basin, but also in the Congo basin, Sumatra and Borneo. Hence, in the case of cacao, sole focus on climatic factors for modelling crop suitability is not advised.

4.2 Comparing modelled current crop suitability to present cacao production

The modelled spatial distribution of SCA seems to provide a reliable representation of the present distribution of cacao-growing areas, covering all major producing countries based on FAOSTAT (FAO, 2023). The model predicts large areas of good suitability for cacao in the western Amazon basin, coinciding with regions of high genetic variability in wild cacao stands in Peru, Ecuador, Bolivia, Colombia and Brazil (Nieves-Orduña et al., 2023; Thomas et al., 2012), where *T. cacao* is native.

However, the model predicted generally low suitability for Côte d'Ivoire and Ghana, the two biggest producers of cacao in 2022, supplying 49 % of the global production (FAO, 2023). Some of the cacao regions in these countries (Quaye et al., 2021; Schroth et al., 2016a) were rated as unsuitable or only marginally suitable by the model due to insufficient precipitation and dry season length. This could indicate too restrictive model parameters, with cacao being more drought tolerant than assumed. The fact, that irrigation to relieve water stress is not currently widely practiced in this region (Carr and Lockwood, 2011; Van Oosten et al., 2022) , supports this notion. Furthermore, findings of regional studies focusing solely on West Africa and applying a species distribution model approach (Ariza-Salamanca et al., 2023; Läderach et al., 2013; Schroth et al., 2016a), identified similar extents of SCA but ascribe the region more favourable conditions.

In some countries, the model identified considerable suitable areas in regions outside of known production hotspots. For example, in Brazil the model correctly predicted suitability for the main producing regions in the states of Pará and Bahia (Heming et al., 2022; Igawa et al., 2022), as well as for smaller production centres in the states of Amazonas and Rondônia (CEPLAC, 2023; Igawa et al., 2022). The identification of larger areas of moderate suitability in the states of Roraima and Amapá is supported by recent efforts of the Brazilian government to expand and increase cacao production in said states (CEPLAC, 2023).

Low correspondence between the model and current production hotspots is especially notable in Ecuador, where the main producing region on the pacific coast is absent from the resulting map due to dry season length. An explanation could be that Ecuadorian farmers alleviate climatic constraints with management practices. As Ceccarelli et al. (2024) point out, cacao production would not be profitable in some parts of the coastal areas without irrigation during the dry season.

4.3 Expected shifts in suitability due to climate change

The model projects a rise in net SCA by 5.5 % by 2050 due to climate change. Nevertheless, considerable shifts in suitability are to be expected, leading to the loss of some of the current centres of cacao production and the emergence of new ones. Expected changes in precipitation patterns, especially in dry season length, are the main driver for contractions of existing growing regions, while new regions in higher latitudes and altitudes become suitable due to rising mean annual temperatures. As research investigating global cacao suitability under climate change is scarce, in the following our results are compared to studies on a regional scale.

For West Africa the model predicts considerable losses in suitability for some areas, mainly in the far West (Sierra Leone, Liberia, Côte d'Ivoire) as well as Southern Central Africa (Gabon, Republic of Congo and DRC). This aligns with earlier studies predicting a contraction of the SCA in West Africa (Läderach et al., 2013; Omotayo et al., 2024; Schroth et al., 2016a). On the other hand, some studies have found suitability in West Africa to remain constant or slightly increase (Ariza-Salamanca et al., 2023; Black et al., 2020). Our results also indicate considerable expansion of SCA in parts of West Africa, namely in Ghana, Nigeria and Cameroon, due to shortening of the dry season. In eastern DRC and Uganda suitable areas are also expanding, mainly towards the East and South.

The model predicts an overall decrease of suitable area of 10 % for Latin America, which makes the region the most affected by climate change. This matches findings of previous studies that predicted a reduction of the suitable cacao-growing areas in Latin America (Bunn et al., 2019b; Ceccarelli et al., 2021; de Sousa et al., 2019; Heming et al., 2022; Igawa et al., 2022). Extensive losses in suitability are expected in Pará/Brasil and at the western border of the cacao region in Bahía, as predicted by Igawa et al. (2022) and Heming et al. (2022). In Ecuador the model predicts suitability changes as found for the habitat of wild cacao in the study by Ceccarelli et al. (2024). While Bunn et al. (2019b) predict a considerable increase of suitable area for the Dominican Republic - as the only country in the region - the results of our model are more nuanced, indeed predicting a total increase of suitable area albeit paired with a simultaneous loss of areas of higher suitability.

In Asia two causes for suitability changes can be observed. While higher mean annual temperatures promote an expansion to higher elevations (e.g. on Sumatra, Java, Sulawesi and New Guinea), shifts in precipitation patterns and the duration of the dry season is causing differing trends, depending on the region. An expansion of suitable area can be observed in Vietnam and Cambodia and a contraction in the Philippines, Borneo, the Lesser Sunda Islands and Papua New Guinea. Comparable studies on cacao suitability mapping under climate change for the subcontinent are still scarce. Contrary to my findings, Bunn et al. (2017) identified Sulawesi as the most affected region in Indonesia, with the Northern part losing most of its suitability for cacao production.

4.4 Expected shifts in pressure on protected areas

Historically cacao production contributed heavily to the destruction of forests in all major production regions (Clay, 2004; Ruf, 2001; Somarriba and López Sampson, 2018). Although the model predicts an increase of global SCA, the overlaps with PAs are slightly decreasing, which suggests a trend to decrease overall pressure on remaining natural forest reserves in the future. On a regional level, the main producing regions, and the countries within, show diverging trends, which in turn need to be evaluated against local circumstances to determine their potential threat.

Diminishing overlaps can be found in the lower Amazon basin of Brazil and Peru, Venezuela, Central America, parts of West Africa and Western Central Africa and imply reducing pressure on forests by cacao production. Of all examined countries, Brazil currently has the largest share of overlaps compared to total SCA. In the future total overlapping area as well as its share of total SCA are diminishing, hinting at a reduction of the pressure on PAs. Furthermore, specific legislations supporting agroforestry systems with local tree species have recently been put in place, promoting sustainable cultivation on current cacao land as a method of forest restoration (Hütz-Adams et al., 2022). However, although research confirmed the high potential of shaded and diversified cacao systems for conservation, especially when compared to alternative land uses, the overall conservation value of such systems is inconclusive and heavily depends on the applied management practices (Franzen and Borgerhoff Mulder, 2007). On the other hand, as Clay (2004) remarks, the loss of suitability and subsequent abandonment of cacao production can provoke further destruction of the remaining forest patches by conversion to pasture and annual crops, as shown in the past in the state of Bahía in Brazil.

Increases of suitability as well as expansion of SCA in PAs are particularly apparent in Bolivia, Colombia, Venezuela, Southern Brazil, Ghana, Nigeria, Cameroon, DRC, Uganda, Cambodia, Vietnam and Indonesia. The largest areas of increasing suitability in Africa, including newly suitable areas, lie in Cameroon, Nigeria, eastern DRC and Uganda. Kamath et al. (2024) identified the same regions in DRC for possible future cacao expansion. The Congo basin has so far been relatively untouched by deforestation and according to Megevand et al. (2013, p.75) has "the greatest reserve of uncultivated, nonprotected, and low population density land suitable for cultivation in Sub-Saharan Africa". Experiences from recent increases in cacao production in central DRC going in hand with increasing deforestation (Batsi et al., 2023; de Beule et al., 2014) underline the risks associated with an expansion of suitable area. In Indonesia, Vietnam, Cambodia and Sri Lanka shifts of SCA to higher altitudes increase overlaps with PAs. Similar results of increased risk of deforestation were observed by Parra-Paitan et al. (2024). In Colombia and Peru recent increases in cacao production are directly related to new government initiatives and international development programs to stabilise post-conflict areas and to promote the replacement of coca (*Erythroxylum coca*) production (Hütz-Adams et al., 2022). The relatively high shares of production under agroforestry systems and organic certification in the region (Hütz-Adams et al., 2022) gives hope, that the increase in production will not lead to further deforestation.

In West Africa, the centre of present cacao production, cacao contributed heavily to the deforestation in the past, with estimates of losses of one third of forest area in Ghana and a quarter of forest area in Côte d'Ivoire between 2001 and 2015 alone (Goldman et al., 2020; Parra-Paitan et al., 2024). Only few intact forest patches remain, many of them registered as PA (Bitty et al., 2015; Franzen and Borgerhoff Mulder, 2007), thus efforts to conserve the remaining forest are highly important. In Côte d'Ivoire, where livelihoods are highly dependent on cacao, the total area of overlaps of SCA in PAs and the share of overlaps on total SCA remain relatively constant. Shifting suitability patterns suggest further concentration and contraction of SCA to the south-west of the country, where the largest national park (Taï National Park) is situated, so far relatively untouched by encroachment (Schneider et al., 2023). Consequently, the overall contraction of SCA could still increase pressure on the remaining PAs, as farmers are forced to move their plantation due to climate change, even if the land is of marginal suitability.

4.5 Considerations concerning the modelling approach

The chosen model yielded sensible results for all objectives of this study. Nevertheless, it has some limitations, which should be considered. Unlike species distribution models, this study is based on the land evaluation approach (FAO, 1976), matching crop requirements with bioclimatic and soil data. Setting appropriate thresholds for cacao suitability classes is a major challenge. Often scientific literature and management handbooks either recommend very general conditions or focus on specific regions, exhibiting substantial variability in optimal growing conditions even for widely accepted crucial variables such as air temperature and precipitation. Thus, the model focuses on a minimal set of biophysical factors that need to be fulfilled. The model does not take into account interdependencies between different parameters, for example between precipitation and soil parameters affecting drainage and water retention capacity, and does not allow weighting of variables to distinguish between hard and soft criteria and/or thresholds. Neither does the model include adaptive management practices such as irrigation, liming or improved varieties which can broaden the climatic range for profitable cacao production. Some of the current cacao production areas may therefore be classified as not or only marginally suitable. The model further disregards the importance of socio-economic, demographic, institutional, political and cultural context improving or hampering the suitability of an area for cacao production. For example, factors such as political stability, rural infrastructure or government support have been identified as one of the main drivers in differences in cacao production between Cameroon in comparison to other countries in the Congo basin (Megevand et al., 2013). Such preconditions also determine the prospects of the producers to adapt to climate change and deal with changing cacao suitability (Dang et al., 2019; Schroth et al., 2016a; Yiridomoh et al., 2022) Especially when assessing risk for deforestation, it is advisable to take into account socio-economic and infrastructure parameters. It has been proven that the risk of deforestation is much higher when access is created (Ruf, 2001).

5 Conclusions

This study presents one of the few global evaluations of cacao suitability combining climate, soil and topography characteristics and climate change. In all growing regions climate requirements were shown to be more limiting than soil and topographical requirements. High annual temperatures, low minimum temperatures, low precipitation and especially long dry seasons are the most relevant climate criteria. However, low soil pH and steep slopes also contribute to limit suitability in some areas. The results for 2050 suggest that the total global suitable area for cacao production will remain relatively stable, though considerable regional shifts due to climate change with both reduction and expansion of suitable cacao area were found. Based on this analysis, many of the major cacao production areas face considerable challenges in the near future, as the bioclimatic suitability of the regions shift, especially due to changes in precipitation patterns. Actions to mitigate the effect of climate-change and support cacao farmers to adapt to future growing conditions are crucial. The model also showed consequences for natural forests, with losses of overlaps and thus anticipated land use conflicts in current cacao producing hotspots and emerging new overlaps in minor producing countries. The disproportionally high gain of overlaps in the highest cacao suitability class is especially concerning. Thus, efforts will be required to ensure that shifts in suitable areas will not lead to further deforestation.

Overall, the need for future research on impacts of climate change on cacao production, as well as future deforestation risk hotspots, is apparent. More specific studies using similar criteria at a regional and/or local level are needed to make recommendations for on-the-ground interventions and adaptation measures. This study provides a starting point by allowing broad prioritisation of focus areas.

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Technical Report

Technical Report

This report constitutes the second part of the manuscript-style Master Thesis. It is complementary to the first part, the manuscript suitable for publication in a peer-reviewed journal.

The report focuses on the technical implementation of the model predicting global suitability for cacao under current and future conditions and evaluating the potential impact on protected areas. It intends to document in depth the methodological steps taken in the development of the presented research.

1 Land suitability Modelling

Agricultural systems modelling studies the behaviour of complex agricultural systems from field to farm up to a global level. In a historically interdisciplinary approach crop, livestock and economic models are combined to study and predict biophysical, socioeconomic, and environmental responses of crops, livestock and farming systems and as such pose important tools providing predictive and assessment capability (Jones et al., 2017). The land evaluation and agroecological zoning methods developed by the FAO (FAO, 1976), provided the "first methodology for land evaluation on a global basis, integrating soil, climate, vegetation, and socio-economic factors" (Jones et al., 2017, p.243). The Land Evaluation Framework centres on the key concept of matching crop requirements with site characteristics to determine suitability of production at a given location and thus depends on extensive knowledge regarding the biophysical requirements of the studied crop. Sys et al. (1993) have summarised the requirements for many commonly cultivated crops of the tropics and subtropics for application in land evaluation models.

Based on the FAO land evaluation approach (FAO, 1976) a wide range of models have emerged, matching land characteristics and crop growth requirements (Antle et al., 2017; FAO, 2007; Sys et al., 1991)). Advances in GIS as tool to store, retrieve, manipulate, and visualise large data sets have improved simulations further (El Baroudy, 2016). Recently Jaisli et al. (2019) reinterpreted FAOs land evaluation model to predict changes in suitability for (sub-)tropical crops such as avocado, coffee and cashew (Grüter et al., 2022). The model developed here aims at adapting their approach to predict biophysical suitability for cacao on a global scale for current and future conditions. The procedure consists of four steps, which are explained in detail: description of crop requirements, description of the conditions on site, matching and aggregation. The resulting suitability maps are then intersected with the extent of protected areas to identify areas of conflicting interest. The model workflow is shown in Figure 1.

2 The model approach

2.1 Identifying crop requirements

As a first step, the biophysical requirements of cacao (*Theobroma cacao*) have to be identified based on a literature search. Subsequently four suitability classes must be defined for each factor: S1 (Highly suitable), S2 (Moderately suitable), S3 (Marginally suitable) and N (Not suitable), as mandated by the land evaluation approach (FAO, 1976; Sys et al., 1991).

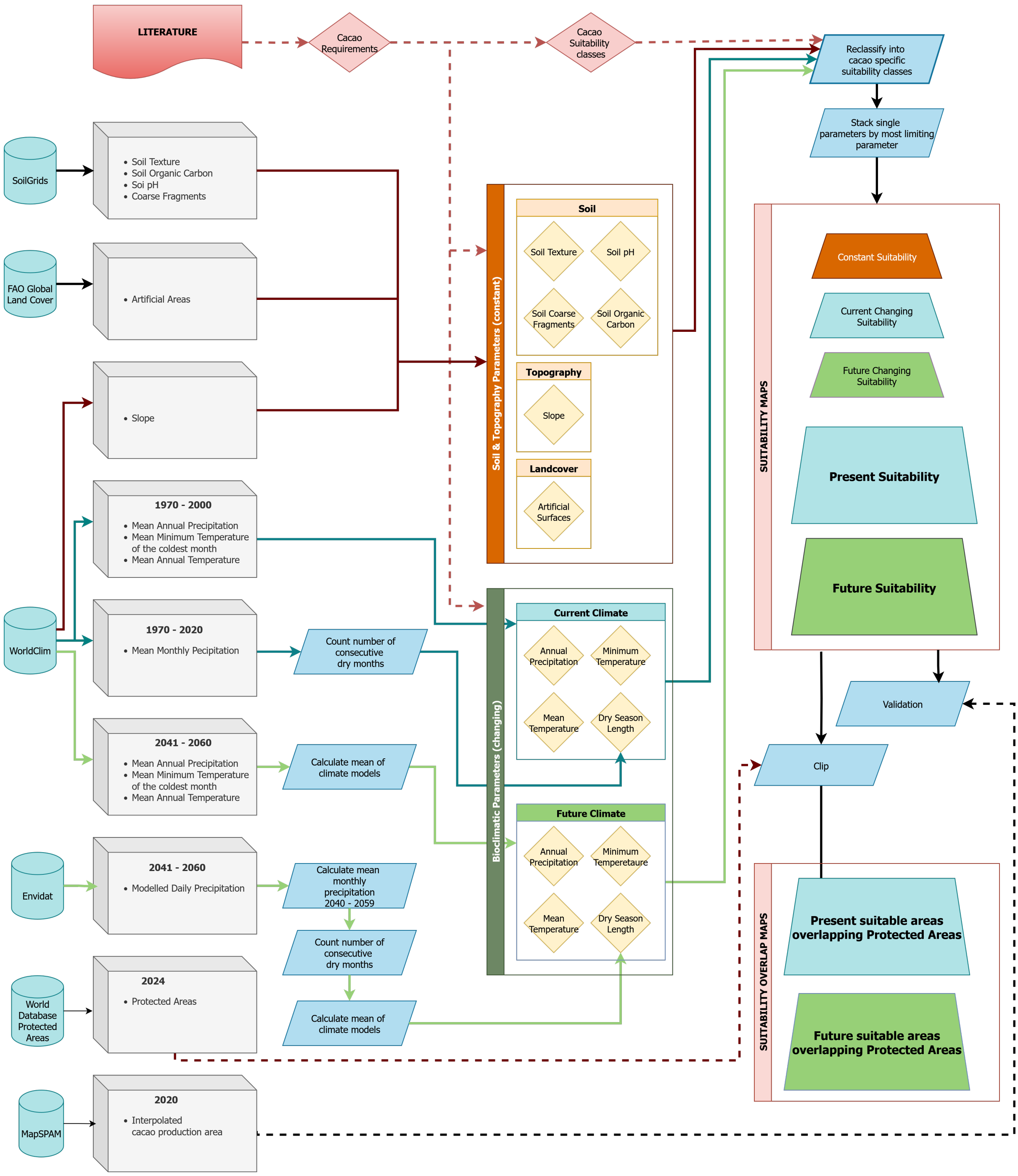

Figure 1: Model workflow

Sys et al. (1993) compiled crop requirements with regard to climate, landscape and soil conditions for a wide range of crops, including cacao, to be applied on land evaluation for agricultural purposes. Based on these requirements, indicators for cacao suitability and - if available - their thresholds were validated, complemented and refined with findings of further studies and technical handbooks (Table 1). If different authors proposed varying thresholds between suitability classes, the threshold was either set to the widest value, ensuring higher crop suitability, or chosen to reflect the consensus of the majority of sources. However, for some indicators the stated thresholds diverged so severely, that an informed decision was difficult and the indicator was dismissed from the model.

However, recommendations for suitable growing conditions have often been found to be vague and not quantified ("evenly distributed" precipitation, "minimal" temperature seasonality, no "persistent, strong" winds) or adapted to the characteristics of a specific region and thus not adequate for a global model depending on the definition of set thresholds differentiating suitable from unsuitable land, let alone different suitability classes. Several recent studies looking into cacao suitability, such as Ariza et al. (2023), Läderach et al. (2013) and Lahive et al. (2018), used species distribution modelling to determine the ecological niche

Table 1: Non-exhaustive list of biophysical recommendations for *T. cacao*, including their relative importance for cacao production and, if available, threshold values classified into four suitability classes of the land evaluation approach (S1 (Highly suitable), S2 (Moderately suitable), S3 (Marginally suitable) and N (Not suitable)) (FAO (1976). Indicators not considered in the model are shown in italic; bold values indicate the thresholds set in the model.

Indicator	Importance	S1	S2	S3	N	Source
Climate						
Mean annual temperature (°C)	II	20 – 30			<22	Hardy (1958), Nieves-Orduña et al. (2023)
		23 – 29	22 – 23 29 – 30	21 – 22	**<21 >30**	Sys et al. (1993)
Mean minimum temperature of coldest month (°C)	I	21	18 – 21		<10	Wood and Lass (1985)
		>15	**>13**	>10	<10	Sys et al. (1993)
Mean maximum temperature of warmest month (°C)	*II*	*<28*	*28 – 30*	*>30*		Sys et al. (1993), Wood and Lass (1985), Läderach et al.(2013)
Optimum temperature for photosynthesis	*I*	*31 – 33 33 – 35*				Zuidema et al. (2005)
Mean annual precipitation (mm)	II	1500 – 2000	1300 – 1500 2000 – 2800			Wood and Lass (1985)
		1600 – 2500	**1400 – 1600 2500 – 3500**	1200 – 1400 3500 – 4400	<1200 >4400	Sys et al. (1993)
Length of dry season (no. months <100mm prec.)	III	none	0 – 3			Wood and Lass (1985)
		0 – 2	**2 – 3**	3 – 4	>4	Sys et al. (1993)
Mean relative humidity of driest month (%)	*I*	*40 – 65*	*35 – 40 65 – 75*	*30 – 35 75 – 85*	*<30 >85*	Sys et al. (1993)
Topography and Soil						
Artificial surfaces (type)	I	0	1 – 25	25 – 50	>50	
Water bodies	III	absent			present	
Slope (%)	I	0 – 8	8 – 16	16 – 30	>30	Syahri et al.(2020)
Latitude (°)	*II*		*±15*			Wood and Lass (1985)
					>20	Lockwood and Carr (2011)
Altitude (masl)	*I*	*<1000*		*<1400*		Nieves-Orduña et al.(2023)
Soil texture (USDA class)	I	3,4,5,7,8,10	6,1	11,9	2,11,12	Sys et al. (1993)
Coarse fragments (Vol%)	II	0 – 15	15 – 35	35 – 55	>55	Syahri et al.(2020)
Soil organic carbon (%)	II	>1.5	0.8 – 1.5	<0.8		Sys et al. (1993)
Soil pH	II	±6.5		4.5 – 7.0		Wood and Lass (1985)
		6.0 – **7.0**	5.5 – 6.0 7.0 – **7.6**	5.0 – 5.5 7.6 – 8.2	<4 (5) >8.2	Sys et al. (1993)
		5.0 – 6.5	**4.5 – 5** 6.5 – 7.0	**4.0 – 5.0 7.0 – 8.0**	**<4.0 >8.0**	FAO (2003)
Soil salinity (ECe)	*I*	*<0.5*	*0.5 – 1.0*	*1.0 – 2.0*	*>2.0*	Sys et al. (1993)
		<1.1	*1.1 – 1.8*	*1.8 – 2.2*	*>2.2*	Syahri et al.(2020)
CEC	*III*				*<12.0*	Wood and Lass (1985)
		>16	<16			Sys et al. (1993), Ariza-Salamanca et al. (2023)
Soil depth (m)	*II*				*<1.5*	Wood and Lass (1985)
		>1.5	1.0 – 1.5	0.5 – 1.0	*<0.5*	Sys et al. (1993)

of cacao. They identified crucial biophysical indicators explaining the current distribution of cacao (e.g. temperature seasonality, precipitation in the warmest quarter, evapotranspiration, nitrogen soil content) but unfortunately did not aim at defining thresholds limiting suitability for a set indicator.

Not surprisingly air temperature and precipitation parameters, as well as general soil characteristics were rated highly important for cacao suitability by many authors. They are relatively easy to measure and can serve as proxies for more complex indicators, such as evapotranspiration or cation exchange capacity. Thus, efforts to find meaningful indicator thresholds and corresponding datasets was focused on covering those (indicators in non-italic script in Table 1).

2.2 Identifying corresponding parameters

To be considered in the model, each of the above-defined indicators has to be matched with an open-source dataset with global coverage and sufficient resolution. The final set of 11 indicators and corresponding parameter datasets is shown in Table 2, the choice is justified in the sections below.

2.2.1 Climate Parameters

A recently published and widely used database providing high spatial resolution global weather and climate data by WorldClim (Fick and Hijmans, 2017) is freely available for academic use. WorldClim version 2.1 was released in January 2020 and offers both historical and projected future climate data for various climatic variables including 19 bioclimatic variables (Table 3) at four different spatial resolutions between 30 arcseconds to 10 arcminutes.

Table 2: Datasets used for the modelling of the biophysical suitability for cacao. Unless specified otherwise, the datasets typically have a resolution of 30 arc seconds.

Indicator	Data set	Data source	Reference
Climate			
Mean annual temperature	Mean annual temperature (℃) (BIO 1), current (1970–2000) and future (2041–2060)	WorldClim: Global climate and weather data, version 2.0 (www.worldclim.org)	Fick and Hijmans, (2017)
Mean minimum temperature of coldest month	Mean minimum temperature of the coldest month (℃) (BIO 6), current (1970–2000) and future (2041–2060)		
Mean annual precipitation	Mean annual precipitation (mm) (BIO 12), current (1970–2000) and future (2041–2060)		
Length of dry season	Monthly precipitation (mm), current (1970–2000)		
	Monthly precipitation (kg/m2), future (2041–2060); resolution: 5 arc minutes	Envidat; CHELSA CMIP5 ts (envidat.ch/#/metadata/chelsa_cmip5_ts)	Karger et al., (2020)
Topography and Soil			
Soil texture	Soil texture (USDA class)	ISRIC SoilGrids 2.0 (www.isric.org/explore/soilgrids)	Poggio et al. (2021)
Coarse fragments	Coarse fragments (vol%)		
Soil pH	Soil pH		
Soil organic carbon	Soil organic carbon		
Slope	Slope	WorldClim: Global climate and weather data, version 2.0 (www.worldclim.org)	Fick and Hijmans, (2017)
Artificial surfaces	Land Cover	FAO Global Land Cover (GLC-SHARE) Beta-Release 1.0 Database (www.fao.org/geonetwork/)	Latham et al., (2014)
Water bodies	Soil pH	ISRIC SoilGrids 2.0 ("No Data" cells) (www.isric.org/explore/soilgrids)	Poggio et al. (2021)

Table 3: Bioclimatic variables supplied by WorldClim (Fick and Hijmans, 2017)

BIO1	Annual Mean Temperature	BIO8	Mean Temperature of Wettest Quarter	BIO14	Precipitation of Driest Month
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	BIO9	Mean Temperature of Driest Quarter	BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO3	Isothermality (BIO2/BIO7) (×100)	BIO10	Mean Temperature of Warmest Quarter	BIO16	Precipitation of Wettest Quarter
BIO4	Temperature Seasonality (standard deviation ×100)	BIO11	Mean Temperature of Coldest Quarter	BIO17	Precipitation of Driest Quarter
BIO5	Max Temperature of Warmest Month	BIO12	Annual Precipitation	BIO18	Precipitation of Warmest Quarter
BIO6	Min Temperature of Coldest Month	BIO13	Precipitation of Wettest Month	BIO19	Precipitation of Coldest Quarter
BIO7	Temperature Annual Range (BIO5-BIO6)				

Historical data is provided as averages for the years 1970-2000 at monthly intervals for minimum, mean, and maximum temperature, precipitation, solar radiation, wind speed, water vapour pressure, total precipitation and the bioclimatic variables are also averaged for the same period.

Future data are CMIP6 downscaled future climate projections using WorldClim v2.1 as baseline climate. Monthly values of minimum temperature, maximum temperature, and precipitation as well as bioclimatic variables are available for 14 global climate models (GCMs) and four Shared Socio-economic Pathways (SSPs): 1-2.6, 2-4.5, 3-7.0 and 5-8.5. However, not all GCMs cover all SSPs and all parameters. The monthly values are available as averages over four 20-year periods (2021-2040, 2041-2060, 2061-2080, 2081-2100).

For the model, three historical and future datasets were chosen from the WorldClim database, as they directly correspond to three indicators for cacao suitability: BIO1, BIO6 and BIO12 (Table 2). Additionally, for the indicator *length of the dry season*, monthly precipitation dataset was selected, to calculate said indicator.

For future climates, there is also a monthly dataset for precipitation available per GCM from WoldClim. Each BigTIFF weighs 20GB, which made processing with the available means (download bandwidth, disk space and, most importantly, memory) all but impossible. Thus, a leaner dataset had to be found to derive future dry season length. The choice fell on the CHELSA dataset released by Envidat in December 2019 (Karger et al., 2020), a recent high resolution monthly precipitation and temperature timeseries for the period 2006-2100. The disadvantages of this dataset are the coarser resolution of 5 arc minutes and the consideration of only four GCMs and two Representative Concentration Pathways RCPs (4.5 and 8.5).

For the future projections, the period of 2040-2060 was selected as a reasonable planning interval for international stakeholders of the cacao sector. The SSP selected for the model represents an intermediate scenario (SSP 2-4.5), rather than the unmitigated continuation of greenhouse gas emissions (SSP 5-8.5). Comparing land suitability results for different SSPs was briefly considered in the course of this study, as it would certainly give more insights to the overall range of expected suitability losses and gains. Ultimately, it was deemed to overreach the scope of the present study.

2.2.2 Topographical & Soil Parameters

The Global Land Cover-SHARE (GLC-SHARE) (Latham et al., 2014) is a database on global land cover created by the Land and Water Division of FAO. It provides a set of eleven layers (artificial surfaces (01), cropland (02), grassland (03), tree covered areas (04), shrubs covered areas (05), herbaceous vegetation, aquatic or regularly flooded (06), mangroves (07), sparse vegetation (08), bare soil (09), snow and glaciers (10), and water bodies (11)) at a spatial resolution of 30 arc-seconds. GLC-SHARE thus covers two indicators considered to prevent land suitability in general; the presence of artificial surfaces and water bodies. In the final model, only the data on artificial surfaces was used, as I discovered that water bodies are already excluded from the data on soil indicators.

To integrate slope requirements into the model I used a dataset of SRTM derived elevation data provided by WorldClim (Fick and Hijmans, 2017). This data was used to produce WorldClim 2.1 and was considered feasible to integrate in the model.

SoilGrids (Poggio et al., 2021) is a system for global digital soil mapping that uses soil profile observations to model the spatial distribution of soil properties and was lastly updated in May 2020 (SoilGrids 2.0). SoilGrids provides global maps at a spatial resolution of 250 m for standard soil properties (pH, organic carbon (content, density and stock), cation exchange capacity (CEC), bulk density, soil texture fractions (sand/silt/clay) and coarse fragments content) at six standard depths between 0 and 200 cm, in addition to predictions of depth to bedrock and distribution of soil classes based on the World Reference Base (WRB) and USDA classification systems. All four selected soil indicators (soil texture, coarse fragments, soil pH and soil organic carbon) can be represented with SoilGrids datasets. As 80% of the roots of cacao are concentrated in the uppermost 15 cm of the soil (Sys et al., 1993), threshold values are applied to the dataset covering that depth.

No relevant shifts in topography and soil properties are to be expected until 2050, so the same datasets can be used for current and future suitability mapping.

2.2.3 Natural Forest

The World Database on Protected Areas (WDPA) (UNEP-WCMC and IUCN, 2024) is a comprehensive global database of marine and terrestrial protected areas in vector format. It is a joint project between the UN Environment Programme (UNEP) and the International Union for Conservation of Nature (IUCN). The WDPA is updated on a monthly basis and is free to access. As cacao is a tropical tree crop, foremost competing with natural forest for land, I worked under the assumption that most protected areas overlapping land suitable for cacao production are in fact areas with natural forest.

2.2.4 Country boundaries

The geoBoundaries Global Database of Political Administrative Boundaries (Runfola et al., 2020) provides an online, open license resource of information on administrative boundaries for every country in the world. The dataset used in the model, the Comprehensive Global Administrative Zones (CGAZ), is a set of global composites for administrative boundaries in vector format. It has to be noted, that simplification of boundaries has been applied to reduce file size and that disputed areas are replaced with polygons following US Department of State definitions. This is not perceived to affect the result of my study in any significant way.

2.3 Data preparation

Data preparation for each dataset followed the same steps as outlined in Figure 2. The first part of the analysis was done with standalone Python scripts due to better performance. These scripts could be combined and easily adapted as needed, to process each dataset individually. The second part of the analysis was conducted with ArcGIS models, allowing easier visualization and predefined parameters.

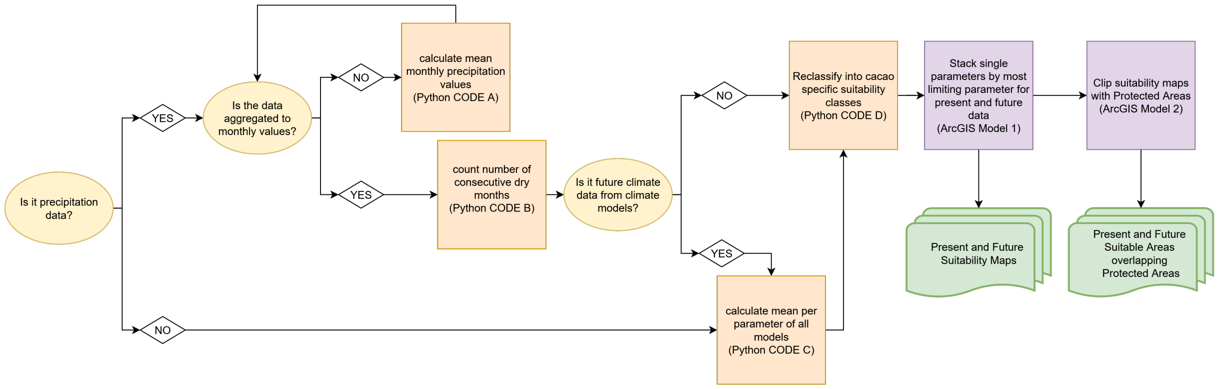

Figure 2: Model decision tree**.**

Depending on the dataset, all or only a part of the processing steps were necessary. For example, the SoilGrid datasets on soil properties correspond directly to the chosen suitability indicators and could be classified into cacao suitability classes immediately. On the other hand, the dataset used to determine future dry season length needed more preliminary data preparation.

To outline the application of all the processing steps, the code snippets below pertain to the processing of future precipitation data to acquire a dataset corresponding to the suitability indicator of future dry season length.

2.3.1 Step 1: Preparing datasets to fit the corresponding indicator (CODE A and CODE B)

One of the chosen indicators, the dry season length, does not correspond directly to an available dataset and has to be calculated from monthly precipitation data. By definition, a dry season comprises all months with average precipitation levels below 100 mm (Wood and Lass, 1985).

While the precipitation dataset for the present by WorldClim is available as monthly averages, which makes derivation of the dry season length straightforward (see CODE B), the dataset for the future by Envidat contains projected data for every single month over the whole period for four GCMs. Thus, before determining the dry season length, the average monthly precipitation per calendar month for the investigated period (2040 to 2059) has to be determined first (CODE A). This is achieved by calculating the mean precipitation for each calendar month of the selected 20-year period per GCM-dataset. Furthermore, the Envidat data is provided in kg*m2/s and has to be converted to mm/month by multiplying with the seconds per month assuming an average length of 30 days/month. The resulting raster dataset contains the average monthly precipitation per calendar month.

```
CODE A

import xarray as xr
import rioxarray as rio
### get files
ACCESS = ['CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2030-2049_V1.1.nc','CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2050-2069_V1.1.nc']
CESM = ['CHELSAcmip5ts_pr_CESM1-BGC_rcp45_2030-2049_V1.1.nc','CHELSAcmip5ts_pr_CESM1-BGC_rcp45_2050-2069_V1.1.nc']
CMCC = ['CHELSAcmip5ts_pr_CMCC-CM_rcp45_2030-2049_V1.1.nc','CHELSAcmip5ts_pr_CMCC-CM_rcp45_2050-2069_V1.1.nc']
MIRO = ['CHELSAcmip5ts_pr_MIROC5_rcp45_2030-2049_V1.1.nc','CHELSAcmip5ts_pr_MIROC5_rcp45_2050-2069_V1.1.nc']
models = [ACCESS, CESM, CMCC, MIRO]
modelnames = ["CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1",
              "CHELSAcmip5ts_pr_CESM1-BGC_rcp45_2040-2059_V1.1",
              "CHELSAcmip5ts_pr_CMCC-CM_rcp45_2040-2059_V1.1",
              "CHELSAcmip5ts_pr_MIROC5_rcp45_2040-2059_V1.1"]
no = 0
for model in models:
  First = True
  ### create and fill array with monthly data for the selected time period (2040-2059)
  for timeframe in model:
    nc_time = rio.open_rasterio(timeframe)
    if First == True:
      First = False
      for i in range(120, 240, 1): # access data for second decade in dataset -> 2040-2049
        if i == 120:
          sumMths = nc_time.isel(time=slice(i, i+12)) # generates new array with 12 months data of 2040
        elif i > 120 and i < 132:   # adjust i to skip first 12 months
          continue
        else:
          sumMths[i%12] += nc_time.isel(time=i)
    else:
      for i in range(0, 120, 1): # access data for first decade in dataset => 2050-2059
        sumMths[i%12] += nc_time.isel(time=i)
    ### calculate mean monthly precipitation for the selected time period (2040-2059) for each calendar month
  for i in range (0,12):
    month = i + 1          # needed for naming resulting file
    sumMth = sumMths[i]
    # calculate mean of the 20 year period
    meanMth1 = xr.where(sumMth < 0, -9999, sumMth/20)
    # convert from kg*m2/s to mm/mth
    meanMth2 = xr.where(meanMth1 < 0, -9999, meanMth1 * (60 * 60 * 24 * 30))
    # save resulting raster as TIFF
    meanMth2.rio.to_raster(str(modelnames[no]) + "_mean_" + str(month) + ".tif")
  no += 1
```

With the dataset of the average monthly precipitation per calendar month, the number of consecutive dry months can be derived (CODE B). Each monthly precipitation value is classified as either "dry season" i.e. <100 (1), "not dry season" i.e. ≥100 (0) or No Data (9) and added to a string of values, where each value represents one month. To allow detection of dry seasons overlapping the end of the year, the first 4 values of the resulting string are duplicated and re-appended after the last value. Areas with more than 4 months of dry season classify as unsuitable for cacao; therefore, the analysis of 16 consecutive monthly values is sufficient and saves computation time. The maximum length of the main dry season is then determined by the highest unbroken count of ones.

CODE B

```
tiff_names = []
# Envidat Future Tiffs - ACCESS
model = 'ACCESS1-3_rcp45_2040-2059'
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_1.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_2.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_3.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_4.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_5.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_6.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_7.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_8.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_9.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_10.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_11.tif')
tiff_names.append('CHELSAcmip5ts_pr_ACCESS1-3_rcp45_2040-2059_V1.1_mean_12.tif')
# reclassify each month and combine all into binary string
first = True
for tiff_name in tiff_names:
    tiff = gdal.Open(tiff_name)
    dm = tiff.GetRasterBand(1).ReadAsArray()
    # reclassification in dry months
    dm[np.where((dm >= 0) & (dm < 100))] = 1
    dm[np.where(dm >= 100)] = 0
    dm[np.where(dm < 0)] = 9
    # concatenate classification of all months
    if first:
        first = False
        dm_12m = dm.astype('|S1')
    else:
        dm_12m = np.char.add(dm_12m, dm.astype('|S1'))
dm_4m = dm_12m.astype('|S4')
dm_16m = np.char.add(dm_12m, dm_4m)
dm_16ms = dm_16m.astype(str)
# calculate length of dry season
def findDrySeason(dm_string):
    count = 0
    longestCount = 0
    for digit in dm_string:
        if digit == "9":
            return -32768
        elif digit == "1":
            count += 1
            if count == 12:
                break
        else:
            longestCount = max(count, longestCount)
            count = 0
    return max(count, longestCount)
dryseason = np.vectorize(findDrySeason)(dm_16ms)

# save resulting raster as TIFF
outputfilename = 'lengthdryseason ' + model + '.tif'
proj_file = 'CHELSAcmip5ts_pr_' + model +'_V1.1_mean_1.tif'
file = gdal.Open(proj_file)
rasterX = file.RasterXSize
rasterY = file.RasterYSize
proj = file.GetProjection()
georef = file.GetGeoTransform()
output_tiff = driver.Create(outputfilename, rasterX, rasterY, 1 , gdal.GDT_Int32)
output_tiff.GetRasterBand(1).WriteArray(dryseason)
output_tiff.SetProjection(proj)
output_tiff.SetGeoTransform(georef)
```

2.3.2 Step 2: Aggregation of climate model datasets (CODE C)

All the future parameters comprise multiple datasets calculated using different global climate models (GCMs). For this study, the parameter values were averaged over all available models (CODE C). For the parameter dry season length four different GCM datasets are available.

```
CODE C

### calculate mean values over all models
tiff_names = []
tiff_names.append('lengthdryseason_ACCESS1-3_rcp45_2040-2059.tif')
tiff_names.append('lengthdryseason_CESM1-BGC_rcp45_2040-2059.tif')
tiff_names.append('lengthdryseason_CMCC-CM_rcp45_2040-2059.tif')
tiff_names.append('lengthdryseason_MIROC5_rcp45_2040-2059.tif')
tiff_no = len(tiff_names)
first = True
for tiff_name in tiff_names:
    tiff = gdal.Open(tiff_name)
    dms = tiff.GetRasterBand(1).ReadAsArray()
    if first:
        first = False
        sumValues = dms
    else:
        time.sleep(1)
        sumValues = np.add(sumValues, dms)
dms_mean = np.divide(sumValues, tiff_no)
# save resulting raster as TIFF as in CODE B
```

2.3.3 Step 3: Reclassification into cacao suitability classes (CODE D)

When the parameter dataset is suitably prepared, its values can be reclassified according to the predefined threshold values S1 (i.e. 1), S2 (i.e. 2), S3 (i.e. 3) and N (i.e. 100) as listed in Table 1.

```
CODE D

tiff = gdal.Open('lengthDrySeason_fut.tif')
prm = tiff.GetRasterBand(1).ReadAsArray()
# reclassification in suitability classes
prm[np.where((prm >= 0) & (prm <= 2))] = 1
prm[np.where((prm > 2) & (prm <= 3))] = 2
prm[np.where((prm > 3) & (prm <= 4))] = 3
prm[np.where(prm > 4)] = 100
prm[np.where(prm < -1000)] = 999
prm[np.where(np.isnan(prm))] = 999
prm2 = prm.astype(int)
# save resulting raster as TIFF as in CODE B
```

2.3.4 Step 4: Resampling to standardize cell sizes

The dataset on future dry season length is provided at a resolution of 5 arc minutes. For proper integration and equal weighting of the parameters it was decided to resample the dataset at the higher resolution of 30 arc seconds, thus matching the resolution of the other climatic parameters. Even though this approach does not comply with commonly accepted good practice, the loss of level of detail, when resampling the rest of the parameters to a coarser resolution, was deemed to outweigh the risks of working with one dataset at an artificially finer resolution. The indicator with the lowest suitability class determines the overall suitability rating of a cell. The artificial finer resolution of the coarser dataset, will not affect this rating, while allowing an underlying indicator of a lower suitability class, to contribute to the result.

2.4 Suitability modelling

The parameter datasets, reclassified according to cacao suitability classes, are aggregated to generate overall suitability maps. The aggregation follows the method of the limitation approach for land evaluation as defined by Sys et al. (1991). With this well-established, straightforward approach the principle of the most limiting factor is followed, whereby the overall suitability of the land is determined by the class of the parameter with the least suitability (de la Rosa and van Diepen, 2002) (Figure 3). As suggested by Jaisli et al. (2019), aggregation of the single parameters was done stepwise, first for land and topographical parameters on one hand and climatic parameters on the other, before combining the two to obtain overall suitability. These steps were completed using the ArcGIS Modelbuilder.

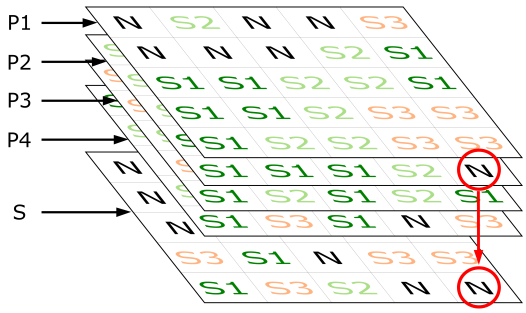

Figure 3: Aggregation of parameters (P1-P4) to suitability map (S) following the limitation approach

2.4.1 Compiling suitability maps

In a first step, using the Cell Statistics Tool (Figure 4) single parameter datasets were aggregated by the most limiting factor for the constant parameters (soil and topography) and the present and future changing parameters (climate) respectively. The changing suitability datasets were then reprojected to the Goode Homolosine projection with interrupted oceans (Figure 5), to match the projection of the constant suitability dataset. The Homolosine projection is an equal-area projection that preserves relative area measure and is suitable for small-scale thematic and statistical maps, especially along the equator (Steinwand, 1994). Further aggregation of constant and changing suitability, again by the most limiting factor, leads to overall present suitability and overall future suitability maps.

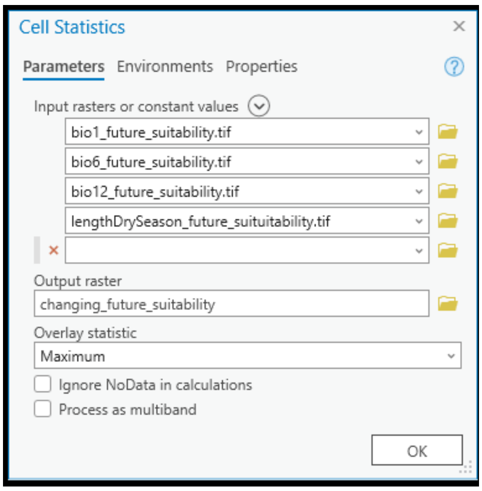

Figure 4: Settings ArcGIS Tool "Cell Statistics".

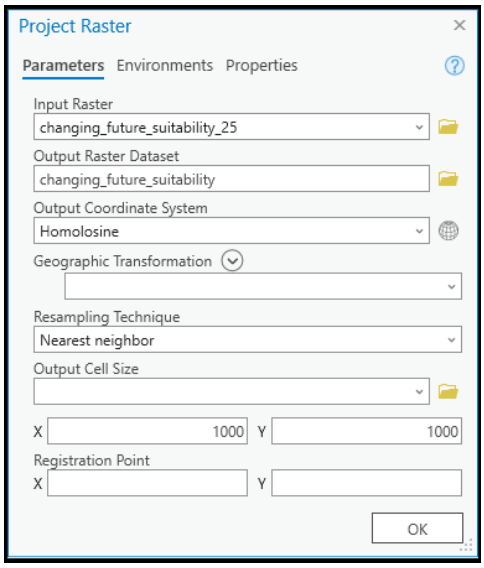

Figure 5: Settings ArcGIS Tool "Project Raster".

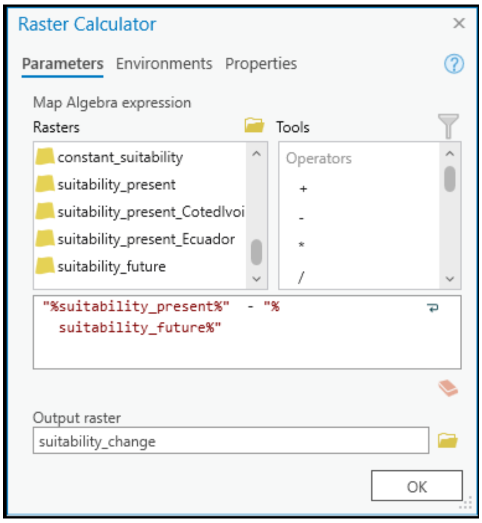

Figure 6: Settings ArcGIS Tool "Raster Calculator".

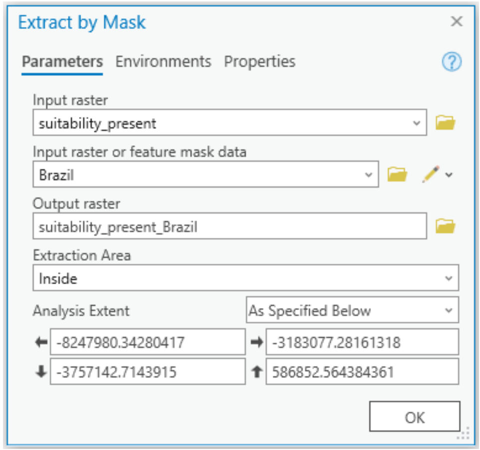

Figure 7: Settings ArcGIS Tool "Extract by Mask".

Subtraction of the future suitability from the present suitability (Figure 6) gives a measure of the suitability change, with values ranging from +99 to -99, where a positive value signifies suitability gain and a negative value a suitability loss. The values between -2 and +2 indicate a change from marginal to moderate or high suitability and vice versa, whereas values between 97 and 99 indicate a complete gain of suitability, i.e. a previously unsuitable cell becomes suitable, and a value between -99 and -97 indicate a complete loss of suitability.

2.4.2 Determining suitable cacao area

For regional analysis, total present and future suitable area and changes in suitability by 2050 are calculated for each cacao-producing region (Latin America, Africa, Asia) and for selected producing countries, the selection taking into account distribution over all three producing regions, the total production and specialty cacao regions. Côte d'Ivoire, Indonesia and Brazil were selected as some of the largest cacao producing countries (i.e. total quantity produced in 2022) as indicated in FAOSTAT data (FAO, 2023). Ecuador, the Dominican Republic and Cameroon were selected as important origin countries of fine flavour cacao (ICCO, 2023).

The suitability maps are intersected with the dataset for each region and country to extract the correspondent area for each suitability class, using the "Extract By Mask" Tool from the ArcGIS Toolbox (Figure 7).

2.4.3 Overlaps with natural forests

To determine overlaps of suitable cacao area with protected areas the suitability maps were intersected with the WDPA dataset, and again the area for each class was extracted.

3 Preliminary results

3.1 Indicator suitability maps

3.1.1 Constant indicators

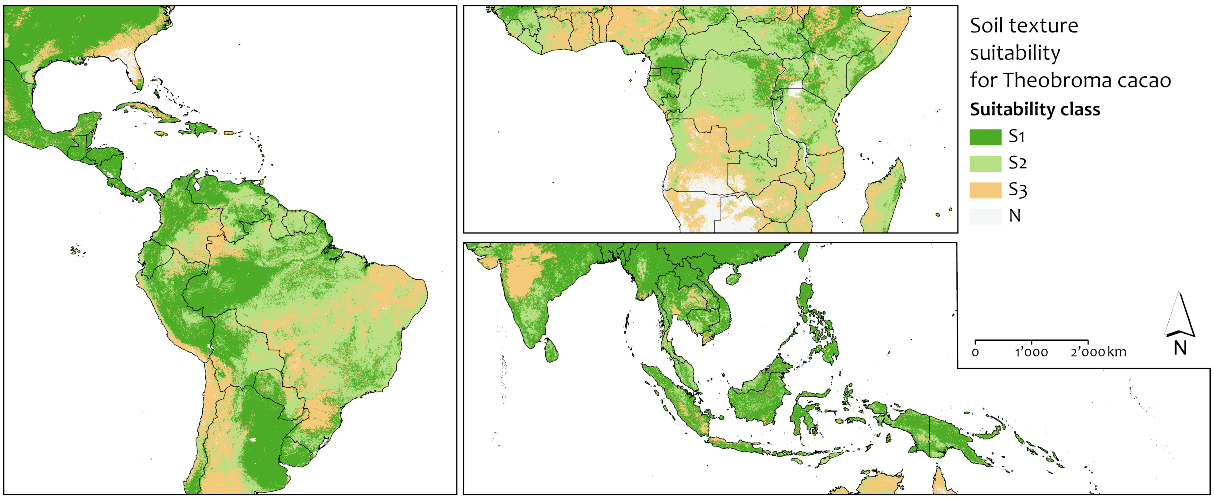

Figure 8: Soil texture suitability for *T. cacao* cultivation.

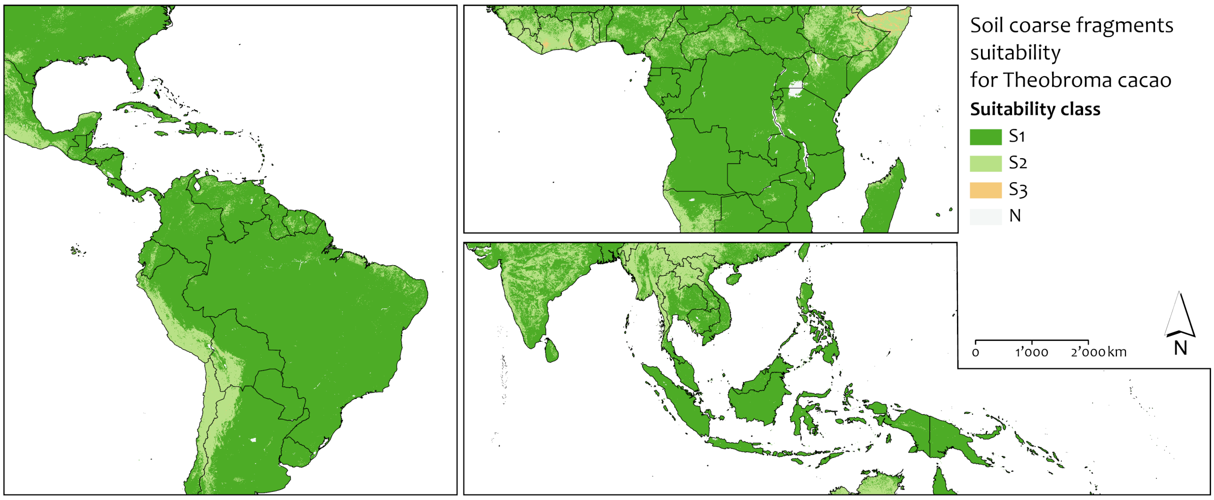

Figure 9: Soil coarse fragments suitability for *T. cacao* cultivation.

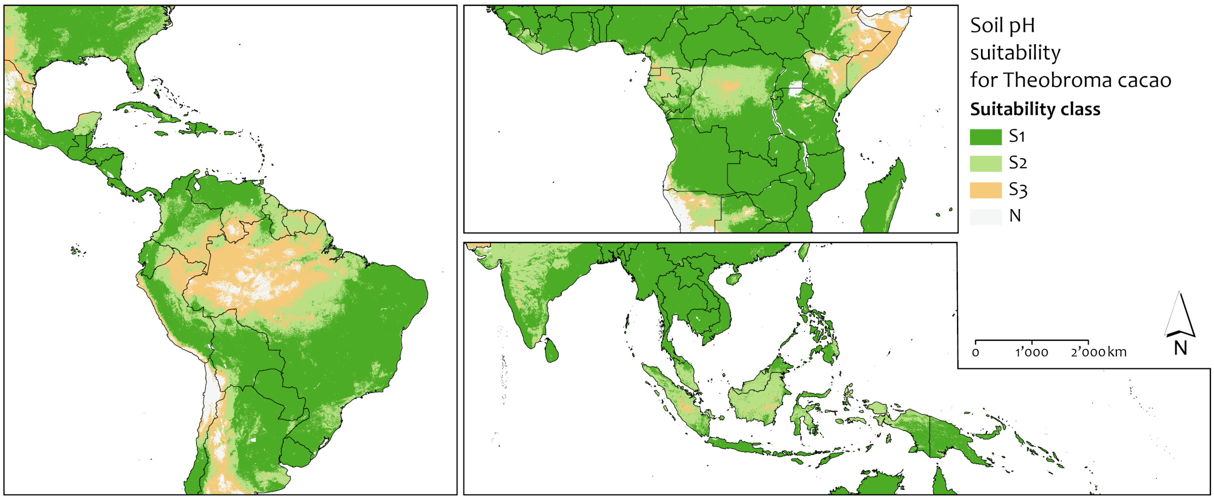

Figure 10: Soil pH suitability for *T. cacao* cultivation.

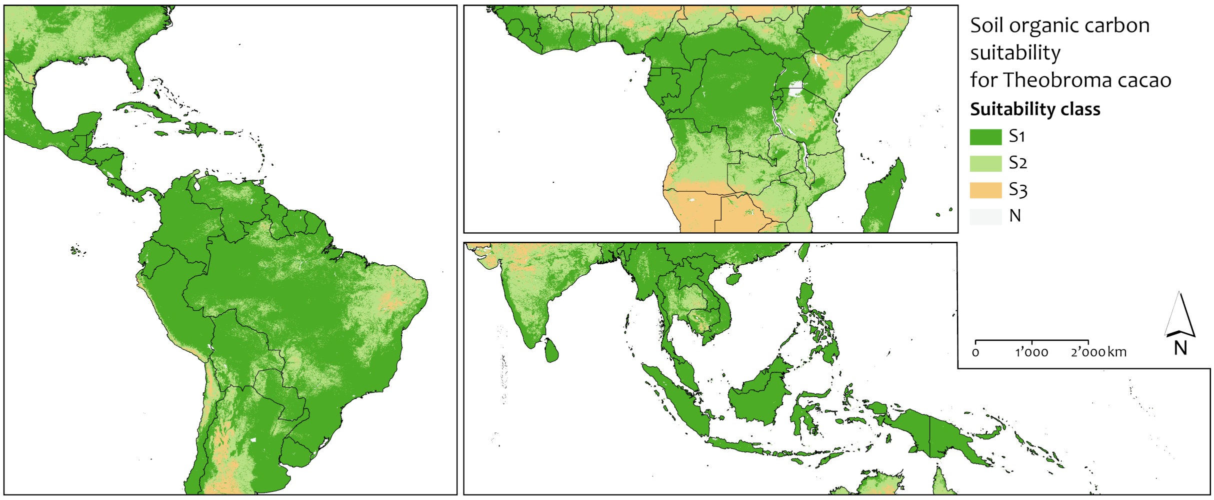

Figure 11: Soil organic carbon suitability for *T. cacao* cultivation.

Figure 12: Slope suitability for *T. cacao* cultivation.

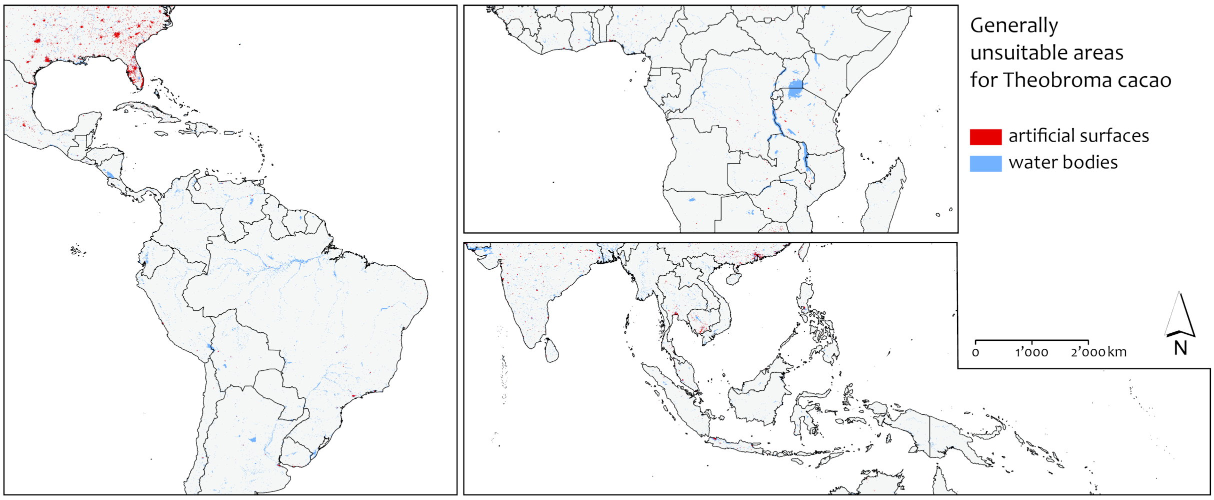

Figure 13: Landcover types preventing suitability for *T. cacao* cultivation.

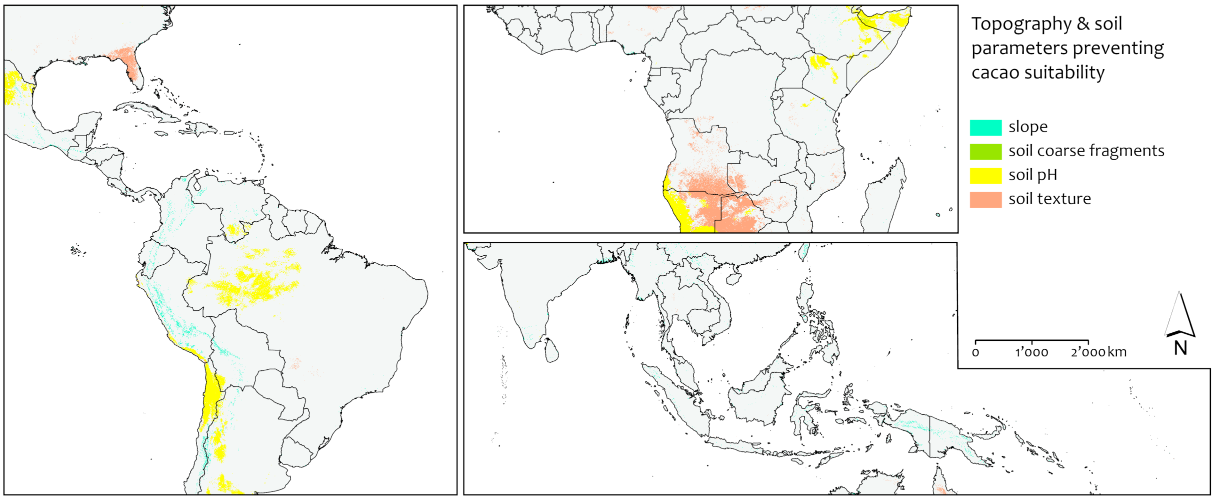

Figure 14: Topography and soil parameters preventing constant suitability for *T. cacao* cultivation.

3.1.2 Bioclimatic parameters – current conditions

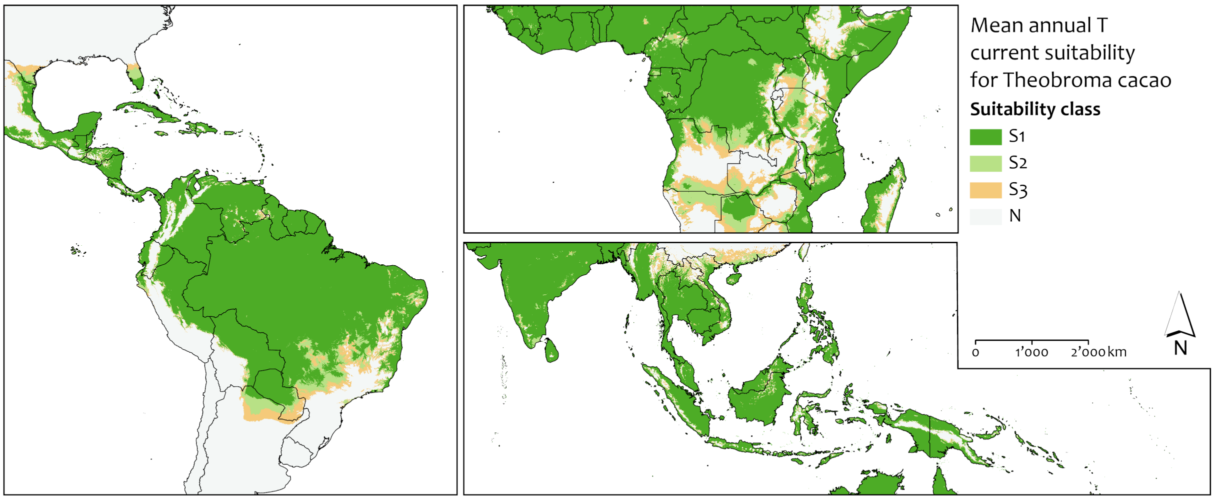

Figure 15: Current mean annual temperature suitability for *T. cacao* cultivation.

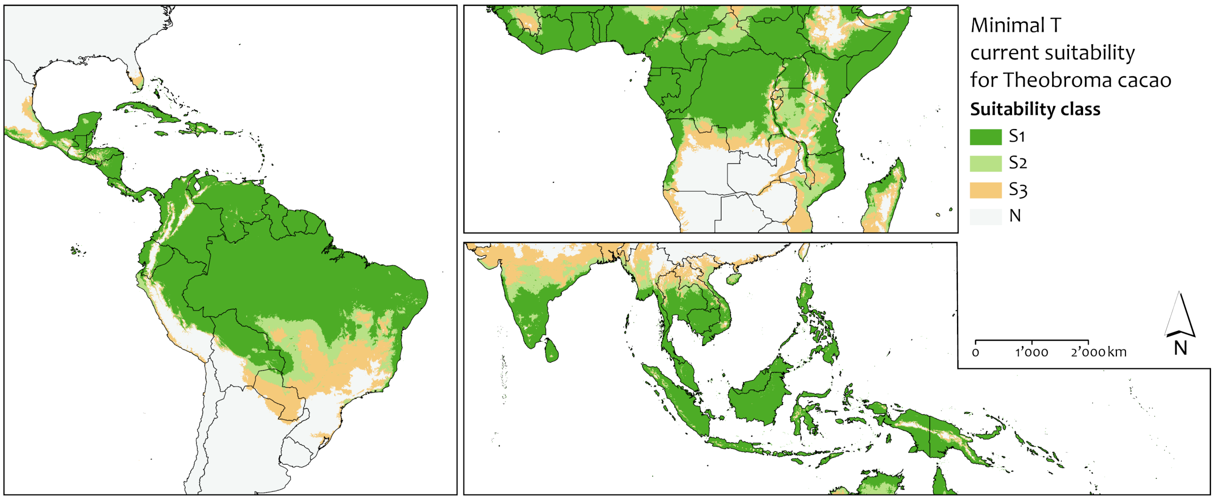

Figure 16: Current minimal temperature suitability for *T. cacao* cultivation.

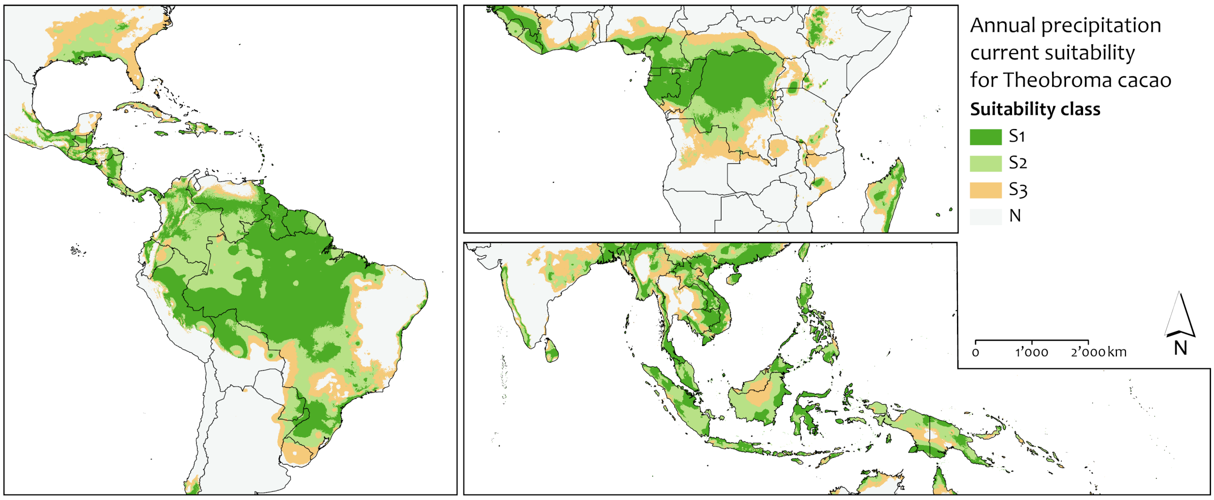

Figure 17: Current annual precipitation suitability for *T. cacao* cultivation.

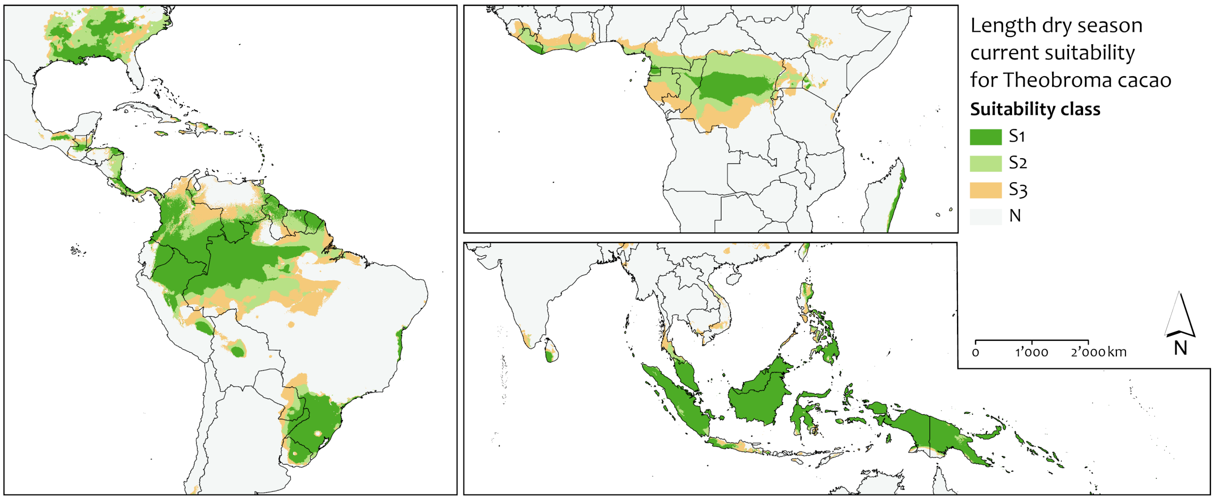

Figure 18: Current dry season length suitability for *T. cacao* cultivation.

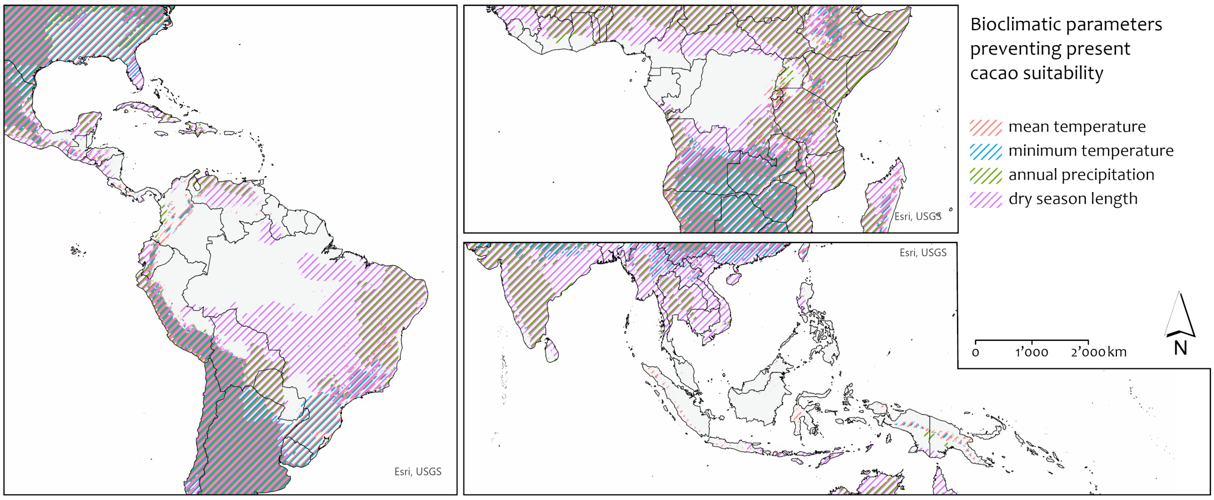

Figure 19: Bioclimatic parameters preventing current suitability for *T. cacao* cultivation.

3.1.3 Bioclimatic parameters – future conditions

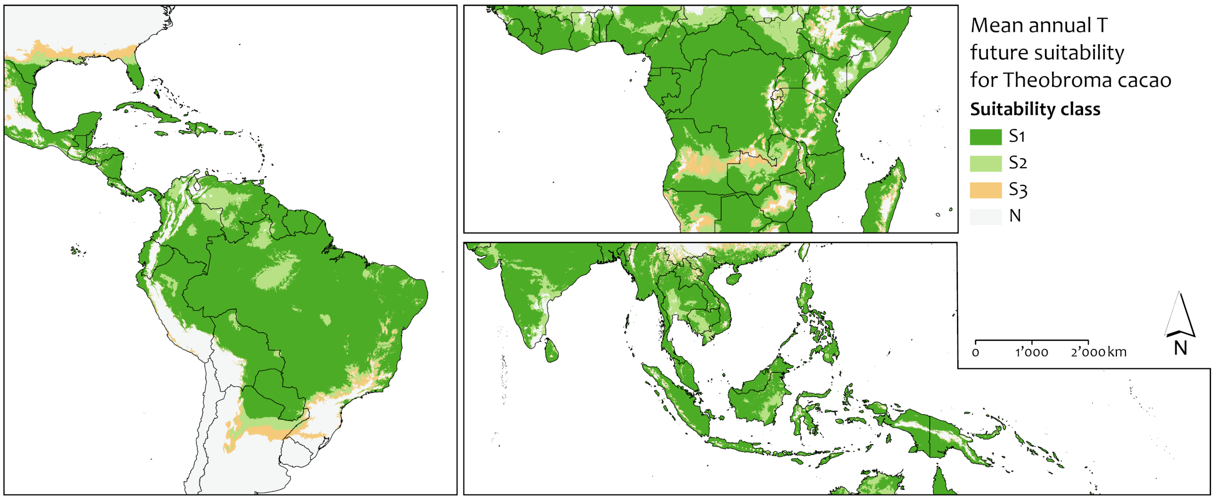

Figure 20: Future mean annual temperature suitability for *T. cacao* cultivation.

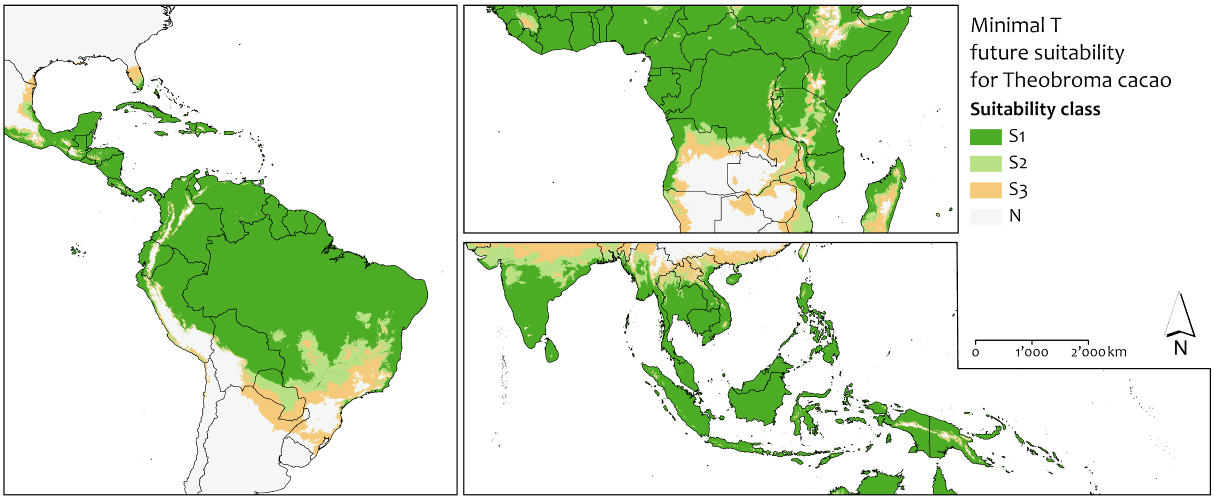

Figure 21: Future minimal temperature suitability for *T. cacao* cultivation.

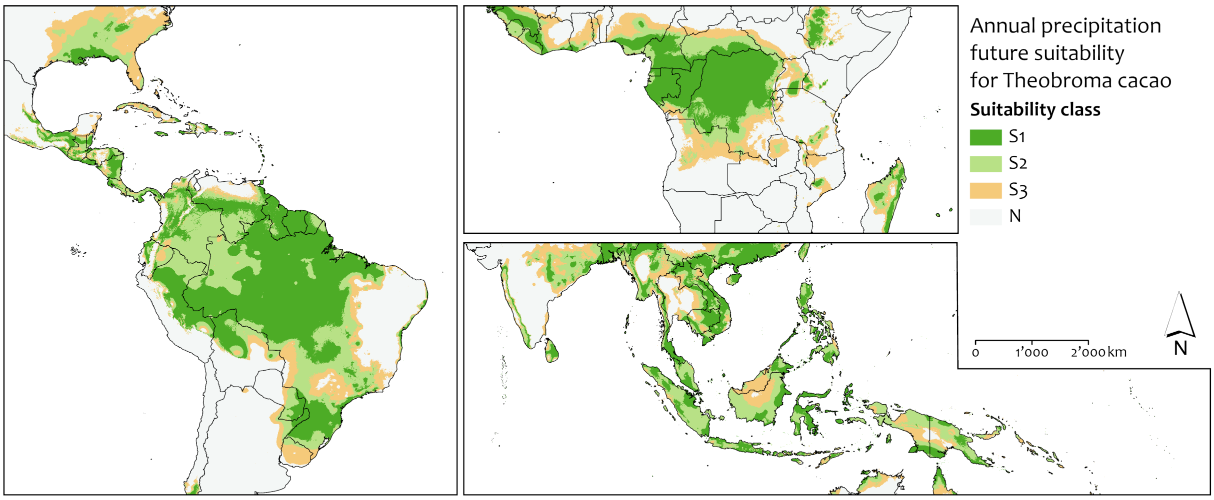

Figure 22: Future annual precipitation suitability for *T. cacao* cultivation.

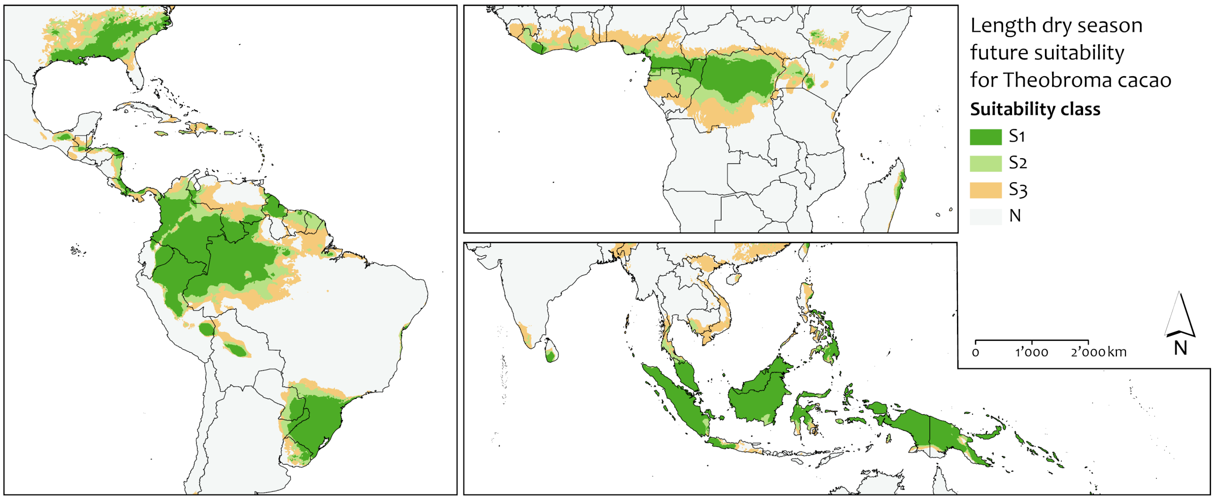

Figure 23: Future dry season length suitability for *T. cacao* cultivation.

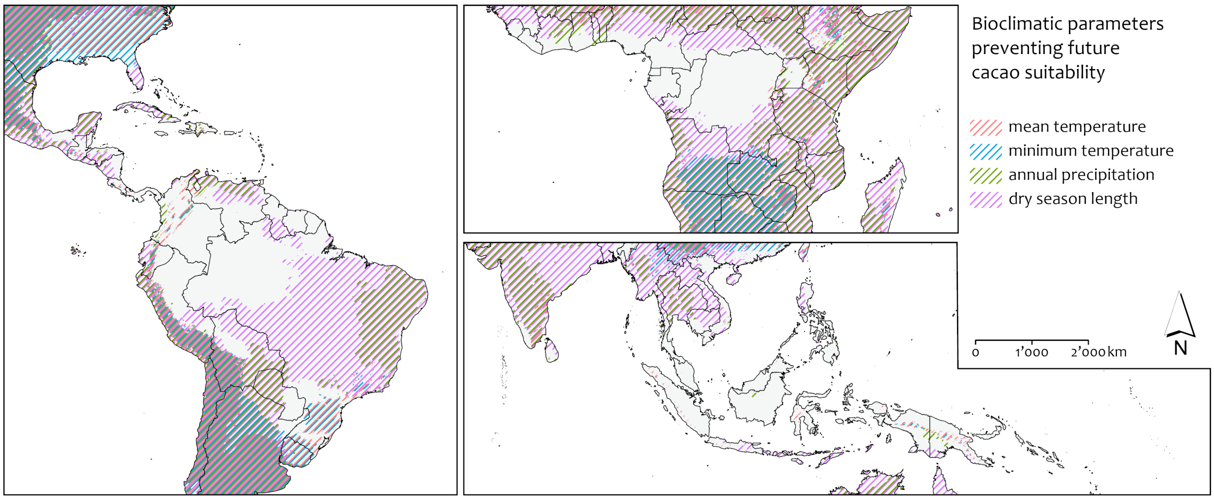

Figure 24: Bioclimatic parameters preventing future suitability for *T. cacao* cultivation.

3.2 Constant and changing suitability maps

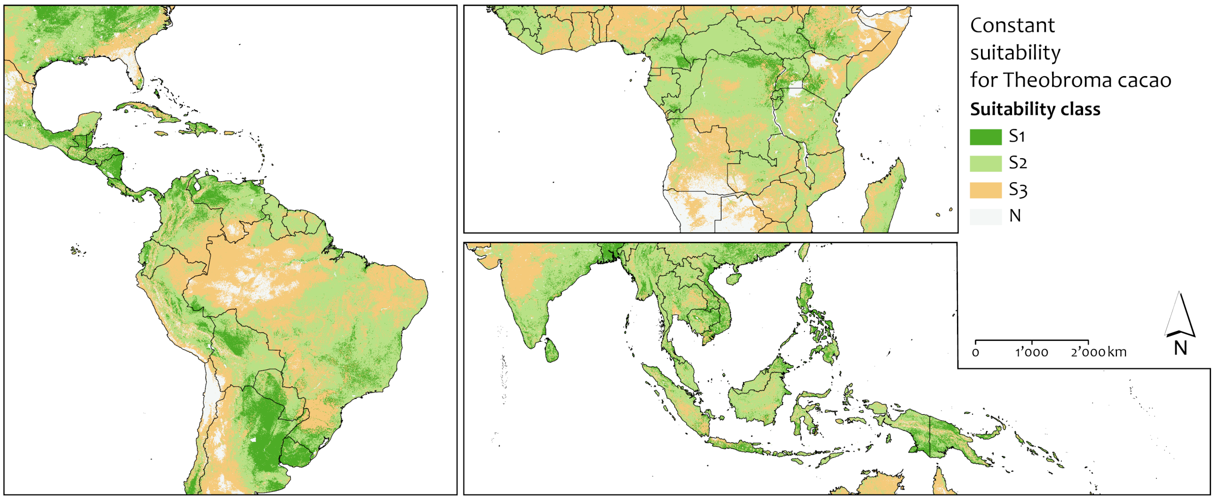

Figure 25: Constant suitability for *T. cacao* cultivation.

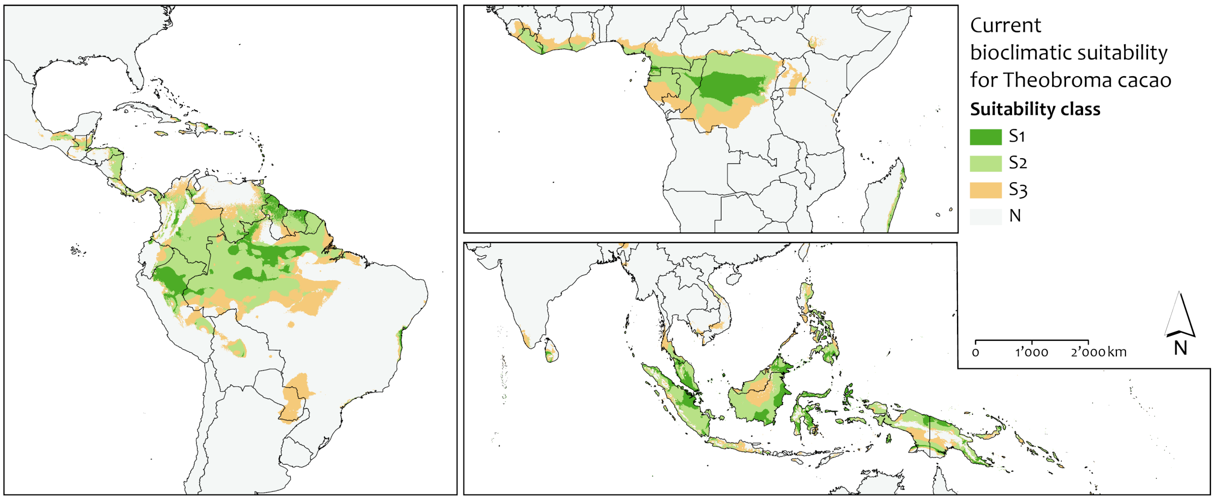

Figure 26: Current bioclimatic suitability for *T. cacao* cultivation.

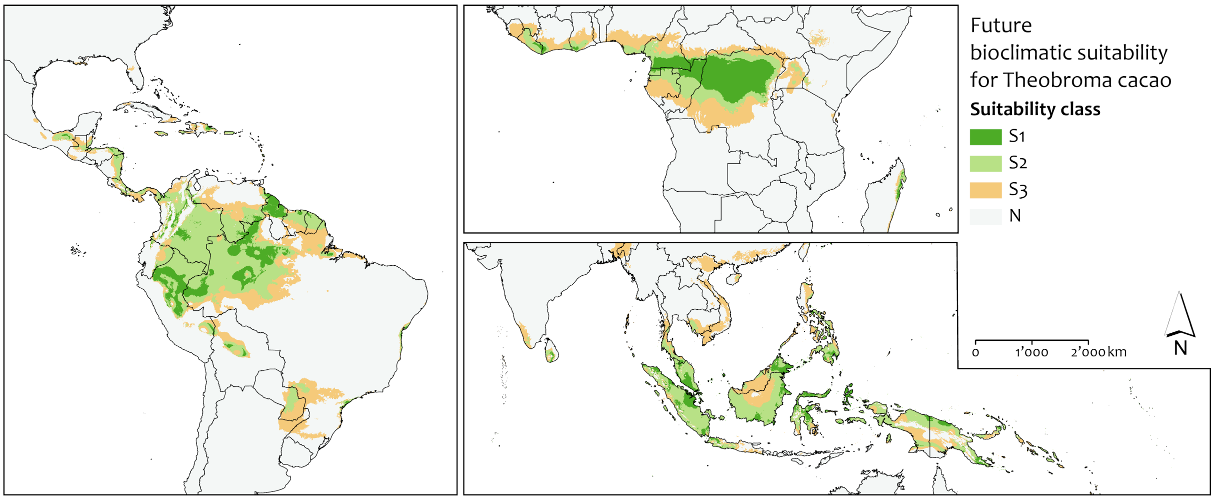

Figure 27: Future bioclimatic suitability for *T. cacao* cultivation.

4 Model validation

4.1 Validation of model results

The modelled current global suitable regions of cacao cover all major producing countries based on FAOSTAT (FAO, 2023) (Figure 28). In addition, within-country-concentration of suitable cacao area corresponds well with the MapSPAM interpolation of cacao areas (IFPRI, 2024) (Figure 29), one of the few spatially explicit global agricultural datasets available, showing total harvested area in ha with a resolution of 5 arcmin (10x10 km).

The only curious exception is Ghana, though for this country, my results compare well with studies reporting clustering of cacao areas to the South based on expert interviews (Ariza-Salamanca et al., 2023; Läderach et al., 2013; Schroth et al., 2016b), which lets me doubt the accuracy of MapSPAM data for this region.

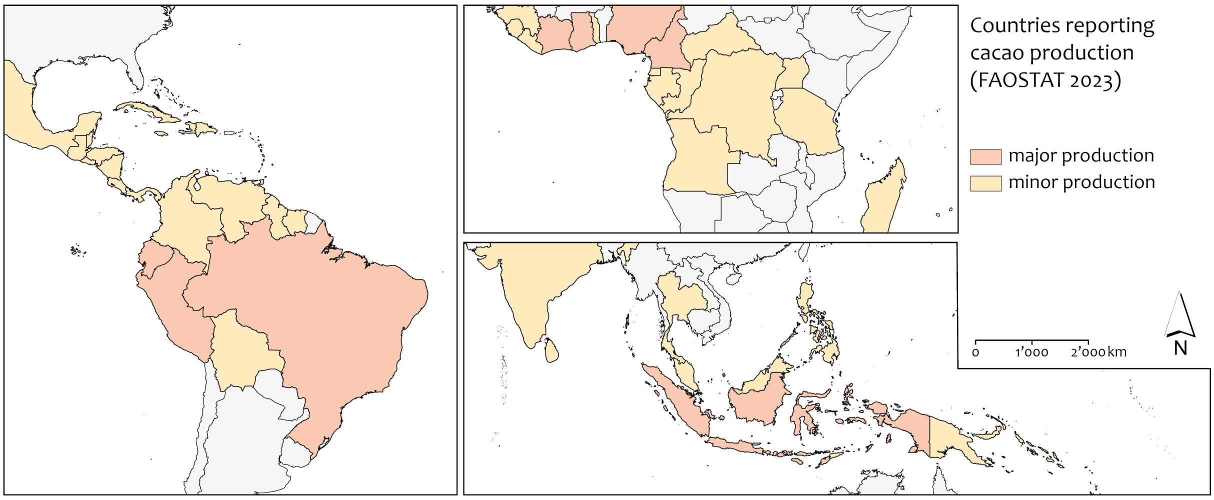

Figure 28: Cacao producing countries in Central and South America, West, Central and East Africa, South and Southeast Asia (according to FAOSTAT **(2023)**)

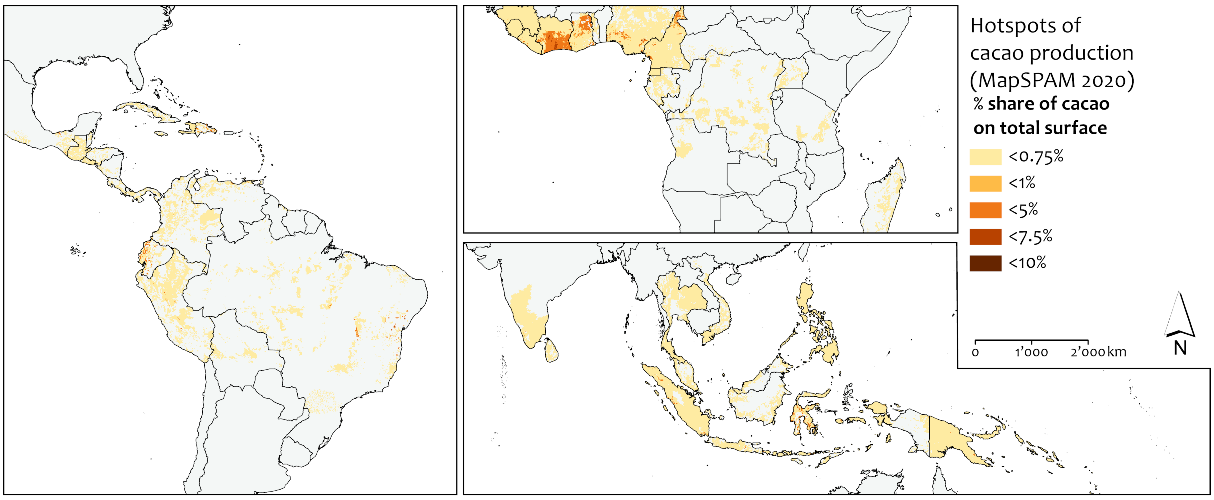

Figure 29: Intra-national distribution of cacao producing areas (MapSPAM data 2020) (IFPRI (2024))

My model also predicts large areas of good suitability for cacao in the western Amazon basin, coinciding with regions of high genetic variability in wild cacao stands in Peru, Ecuador, Bolivia, Colombia and Brazil (Nieves-Orduña et al., 2023; Thomas et al., 2012), where Theobroma cacao is native. Hence, the model can indeed predict the suitability of a region to produce cacao.

Global analysis investigating cacao suitability under climate change is scarce. At a global level, Bunn et al. (2017a) presented preliminary research results at a conference, but never followed up with a detailed peer-reviewed publication. And the research group, which recently developed CONSUS (Jaisli et al., 2019), a land suitability model, and published global coffee, avocado and cashew suitability maps (Grüter et al., 2022), adapted their model to cacao and published the results as web map (Grüter et al., 2023), but never in a peer-reviewed journal.

Thus, in the discussion section of the manuscript, the results of the model are compared primarily to studies on a regional scale for validation. Cacao suitability maps are available for larger regions: West Africa (Ariza-Salamanca et al., 2023; Black et al., 2020; Läderach et al., 2013; Schroth et al., 2016a), Central Africa (Kamath et al., 2024) and Central America (Bunn et al., 2019b; de Sousa et al., 2019); and individual countries Ecuador (Ceccarelli et al., 2024), Peru (Ceccarelli et al., 2021), Brazil (Heming et al., 2022; Igawa et al., 2022), Ghana (Bunn et al., 2019a), Nigeria (Omotayo et al., 2024), Papua New Guinea (Singh et al., 2021) and Indonesia (Bunn et al., 2017b; Nael and Papilaya, 2019; Nurfadila et al., 2020; Syahri et al., 2020).

4.2 Discussion of the model approach

The chosen model approach yielded sensible results for all objectives of this study. Nevertheless, it has some limitations, which should be considered.

The method applied in this study is based on the land evaluation approach (FAO, 1976) matching crop requirements with bioclimatic and soil data. This method greatly differs from other bioclimatic crop modelling approaches using species distribution models, such as maximum entropy or Random Forest modelling, that are dependent on current production locations as input. As Grüter et al. (2022) point out, this is a transparent approach, particularly well-suited for determining the constraints for profitable production. There are, however, distinct limitations associated with it.

The first difficulty was to define reasonable thresholds for cacao suitability classes. Often scientific literature and management handbooks either recommend very general conditions or focus on specific regions, exhibiting substantial variability in optimal growing conditions even for widely accepted crucial variables such as temperature and precipitation. Uncertainty associated with the definition of the classification thresholds was not analysed in this study.

The second major challenge is associated with data availability and the spatial scale chosen for analysis. Working with climate models always introduces some uncertainty to the analysis as they use interpolated climate data, which poses the risk of modelling errors especially in areas with sparse historical climate records (Fick and Hijmans, 2017). It is very fortunate that WorldClim (Fick and Hijmans, 2017) provides standardized datasets for a wide variety of present as well as future climate parameters on a global scale, as this eliminates the risk inherent in the integration of several data sources. Similarly for SoilGrids (Poggio et al., 2021) providing a wide variety of soil parameters at the same resolution and extent. For a global assessment, the resolution of 30 arc seconds (ca. 1 km^2) can be considered feasible, but fails to depict the variability of local characteristics. The possibility of small scale weather patterns and microclimates, leading to pockets of suitable or unsuitable conditions not detected at the chosen spatial resolution, has to be taken into account when interpreting the results. Only one future climate parameter (dry length season) could not be obtained through WorldClim and it was not easy to find a suitable dataset of similar quality, extent and resolution. The chosen Envidat dataset (Karger et al., 2020) for future precipitation used to calculate future dry season length, only includes simulations for 4 different climate models (WorldClim offers 13) and comes at a lower resolution of 0.049° (ca. 25 km^2). Resampling to a higher resolution, as was done for the present simulation, is generally not advised, but was considered acceptable in view of lacking alternatives, manageability of the dataset and the fact that the model is very conservative, as it aggregates suitability by the most limiting factor. In view of the emerging importance of dry season length as limiting parameter of the model in most of the current major production regions, the quality of the dataset should still be reviewed in case the model is developed further.

This exploratory study focuses on a few key biophysical requirements that need to be fulfilled for cacao to be growing in certain areas. The model does not take into account interdependencies between different parameters, for example between precipitation and soil parameters affecting drainage and water retention capacity, and does not allow weighting of variables to distinguish between hard and soft criteria and/or thresholds. Beside macroclimatic parameters, the effect of microclimatic conditions within cacao plantations are reported to have an equally important role in defining cacao suitability (Almeida and Valle, 2007), though to incorporate such effects in a global study would not be feasible. Neither does the model include adaptive management practices such as irrigation, liming or improved varieties which can broaden the climatic range for profitable cacao production. Important current production locations may therefore be classified as not suitable, or only marginally suitable. The model further disregards the importance of socio-economic, demographic, institutional, political and cultural context improving or hampering cacao suitability of an area. For example, factors such as political stability, rural infrastructure, government support have been identified as one of the main drivers in differences in cacao production between Cameroon in comparison to other countries in the Congo basin (Megevand et al., 2013). Such preconditions also determine the prospects of the producers to adapt to climate change and deal with changing cacao suitability (Dang et al., 2019; Schroth et al., 2016a; Yiridomoh et al., 2022). Especially when assessing risk for deforestation, it is advisable to take into account socio-economic and infrastructure parameters. It has been proven that the risk of deforestation is much higher when access is created (Ruf, 2001). However, including more parameters also adds uncertainty to the modelling approach and the added complexity would hamper results analysis.

Evaluation of the formal structure of the model shows some opportunities for improvement. Under the constraints of time, technical performance limits and prevailing cacao knowledge gaps, utilizing ArcGIS reclassification and map algebra tools made the most sense. Other methodologies could have been employed to provide more nuance by weighting variables or adding quantitative detail through zonal statistics.

Overall, the need for future research on impacts of climate change on cacao production, as well as future deforestation risk hotspots, is apparent. More specific studies using similar criteria at the local level are needed to make recommendations for on-the-ground interventions and adaptation measures. This study provides a starting point by allowing the broad prioritisation of focus areas.

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