Climate vulnerability and adaptation of the smallholder cocoa and coffee value chains in Liberia

Working Paper No. 134

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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Abstract

Liberia is one of the world's poorest countries. Efforts to rebuild its economy after several years of internal conflict were partially set back by the 2014–5 Ebola crisis. The country's lowland humid climate and land-use history suggest a potential to increase the production of cocoa (*Theobroma cacao*) and coffee (*Coffea* spp.) to generate income and employment for smallholder farmers, and these value chains are, therefore, the focus of projects funded by donors including the International Fund for Agricultural Development (IFAD) and the World Bank. This study analyzes the present and projected future climatic conditions of the country and compares them with conditions in other cocoa- and coffee-producing parts of Africa. Soil conditions, farming systems and supply chain characteristics are also briefly reviewed. On the basis of this information, a comprehensive strategy to reduce the vulnerability of the cocoa and coffee supply chains to climate change and ensure their future viability is proposed.

Keywords

Climate suitability modeling; climate vulnerability analysis; *Coffea arabica*; *Coffea canephora*; Maxent; *Theobroma cacao*; tree crop agriculture; West Africa.

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Contents

Tables

Figures

Acronyms and abbreviations

AEZ	Agro-ecological zones
ASAP	IFAD's Adaptation for Smallholder Agriculture Programme
CAAS	Comprehensive Assessment of the Agriculture Sector
CARI	Central Agricultural Research Institute
CIAT	International Center for Tropical Agriculture
CNRA	National Center for Agricultural Research, Côte d'Ivoire
CSSV	Cocoa Swollen Shoot Virus
DAPA	CIAT's Decision and Policy Analysis Research Area
ENSO	El Niño Southern Oscillation
ETP	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
IFAD	International Fund for Agricultural Development
IITA	International Institute of Tropical Agriculture
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
LASIP	Liberia Agriculture Sector Investment Program
LIGIS	Liberia Institute of Statistics and Geo-Information Services
m.a.s.l.	Meters above sea level
MOA	Ministry of Agriculture
NGO	Non-governmental organization
REDD+	United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
STCRSP	Smallholder Tree Crop Revitalization Support Project
TCEP	Tree Crops Extension Project
TEB	Total exchangeable bases
UNDAF	United Nations Development Assistance Framework

Part A – Introduction

In collaboration with the Government of Liberia, the International Fund for Agricultural Development (IFAD) has been supporting the tree crop sector of Liberia, specifically cocoa and coffee, since 2012 through the Smallholder Tree Crop Revitalization Support Project (STCRSP). The overall objective of the project is to develop a "viable and sustainable smallholder cocoa and coffee subsector in the country's main producing belt and where the potential for long-term income-generation for smallholder farmers is significant." The main cocoa- and coffee-producing belt of Liberia includes Lofa, Bong and Nimba Counties. In the design and implementation of this project, IFAD has identified "years of farm neglect, old trees, lack of agronomic knowledge (best practices), lack of access to credit for labour and seedlings, and climate change-induced impacts," including the effects of climate variability, as key obstacles to increasing cocoa and coffee yields and estimates that, through farm rehabilitation, a triplication of the current yield levels is possible. Accomplishments of the project during the first one and a half years include the rehabilitation of nearly 3,500 ha of smallholder farms, more than threefold increase of the cocoa and coffee exports of some of the participating cooperatives, and the development of an innovative approach to public-private partnership, involving the Ministry of Agriculture (MOA) and a private exporter.

IFAD is now complementing this existing project, whose focus is on Lofa County, through a new project – Tree Crops Extension Project (TCEP) – whose focus will be on Nimba County, while an ongoing project of the World Bank focuses on the cocoa sector of both Nimba and Bong Counties. A new aspect of TCEP is the involvement of the Adaptation for Smallholder Agriculture Programme (ASAP). ASAP is a "multi-year and multi-donor financing window targeted at mainstreaming adaptation to climate change into IFAD projects and programmes. ASAP aims at scaling-up successful tried and tested approaches and combine these with innovative processes and tools." This includes:

- A deeper risk assessment
- The replication of multiple-benefit approaches that increase productivity while reducing climate-related risk
- Enabling smallholder farmers to access climate finance.

Within this context, IFAD has sought the support of the International Center for Tropical Agriculture (CIAT) through its Decision and Policy Analysis (DAPA) Research Area, with the objectives of:

(i) Assessing the impact of climate change on the cocoa and coffee sectors and the climate-related risks for smallholder farms of cocoa and coffee in Liberia;

(ii) Highlighting the additional or different investment needs that will help both crops adapt to climate changes on the basis of the crops' vulnerability analysis.

This work was carried out by a team from CIAT between September 2014 and January 2015, and the reports delivered to IFAD provided an input into the project design process of TCEP. The subsequent participation of one of the team members in the design process, and notably the second design mission to Liberia in July 2015, provided an opportunity to discuss the findings and recommendations with a wider set of stakeholders from IFAD, several government agencies, especially the Ministry of Agriculture, members of the private sector and NGOs, as well as a small number of farmers. Although their input was invaluable and helped to validate the findings in consideration of the realities on the ground, the responsibility for opinions expressed in this report remains entirely with the authors. The original reports delivered to IFAD were revised and slightly updated for the present publication.

The objective of this publication is to provide a very brief overview of the cocoa and coffee supply chains in Liberia to analyze the key vulnerabilities to projected climate change up to the 2050s, and to lay out some elements of a climate change adaptation strategy for the smallholder cocoa and coffee sectors of the country. Following this Introduction, Part B of the report thus opens with an overview of the cocoa and coffee supply chains in Liberia, which also includes a tabular, conceptual review of the main elements of the supply chains and their respective vulnerabilities in the specific context of the country. Part C gives an overview of the soil conditions of Liberia, focusing on the main cocoa- and coffee-producing counties Lofa, Bong and Nimba, and discusses briefly their suitability for tree crop agriculture and interactions with climate conditions. The climate of the country, including recent climatic changes, is then discussed in Part D relative to the specific climatic requirements of the cocoa and coffee crops. This analysis also allows to identify key climate variables that are influencing climatic suitability for cocoa and coffee in Liberia now or could increasingly do so in the future. In Part E, the vulnerability of cocoa and coffee to present and future climate conditions in Liberia is then analyzed in more detail by comparing current and projected future conditions in Liberia with those in key cocoa- and coffee-producing regions elsewhere in Africa and/or the world. The underlying assumption here is that as long as conditions in Liberia are projected to remain within the bounds of the climatic conditions found in other, major cocoa- and coffee-producing areas, conditions would remain suitable for producing cocoa and coffee in the country. This section also employs a statistical model based on the Maxent algorithm to arrive at current and future maps of relative climatic suitability for cocoa and coffee in Liberia as compared to reference areas elsewhere in Africa. Based on the findings of this section, Part F proposes key elements of a climate change adaptation strategy for cocoa and coffee in Liberia. Many of these are also applicable to other countries of the region and to other tree crops. The strategy takes a medium-term view, as is appropriate in climate change adaptation, but also highlights immediate, no-regret options. Part G discusses general questions, including whether and by when the climate in Liberia could become unsuitable for growing cocoa and coffee, and concludes the report.

Photos: G. Schroth

Rehabilitated cocoa farms in Liberia's Nimba (above) and Bong (below) Counties.

Part B – Overview of the cocoa and coffee supply chains in Liberia

1. Country overview

Physical geography

Liberia's land area is 96,320 sq km, of which about half is classified as forest (42,000 sq km) (Figure B.1). The elevation ranges from 0–1380 m and is divided into four regions: coastal plains (up to 100 meters above sea level), interior hills (100–300 m), interior plateaux (300–600 m), and mountain areas (upward of 600 m) (Republic of Liberia 2010). Overall, the forest cover of the country is well conserved compared to other countries in West Africa. The most densely inhabited and most deforested area in the country is a broad strip of land reaching from the capital Monrovia on the coast along the country's central road axis into Bong and northern Nimba Counties, including part of the cocoa and coffee belt. The relatively high forest cover by West African standards indicates a need and potential to link tree crop development with forest conservation and climate change mitigation, thereby helping to distinguish Liberia's tree crop products on the international market. This opportunity will be discussed in more detail in a later part of this study.

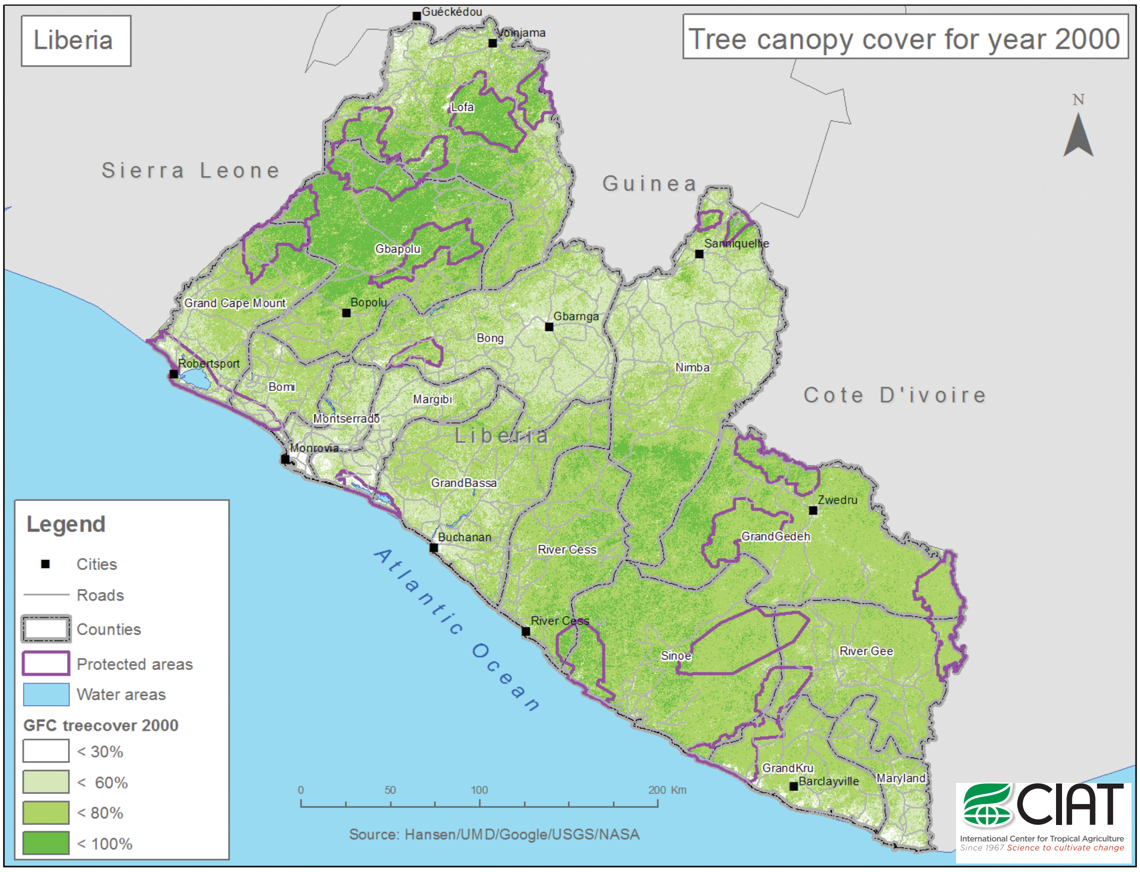

Figure B.1. Map of Liberia with percent tree cover.

The climate of the country is humid tropical. Average temperature is between 24–28 °C, while relative humidity ranges from 65–80%. Sunshine averages two to eight hours per day. Rainfall is unimodal with a rainy season from May–October and a dry season from November–April. Rainfall is more abundant in the southern regions, with 3,500–4,600 mm of annual rain, than in the northern regions with 1,500–2,500 mm. Most parts of Liberia have a water surplus for five to eight months each year. Wind conditions are described as generally mild. The *harmattan*, a dry Saharan wind, affects the climate during the dry season. These winds cause drought but also bring nutrient-rich dust from the savannah, which acts as a natural fertilizer to the West African forest zone. The climate conditions are thus favorable for the production of various tree crops.

Climatic suitabilities (which will be discussed in more detail in Part D) are modified through local soil conditions. The vast majority of soils in Liberia pose more or less severe restrictions to their agricultural use. The most wide-spread soil types are various forms of Ferralsols, which are mostly deep soils but have low chemical fertility. Soil conditions will be discussed in Part C.

Population

As of July 2014, the population of Liberia was about 4 million with an annual growth rate of 2.5% (CIA 2014). The majority of Liberia's population lives in Montserrado County, where the capital Monrovia is located. The next most populous counties are Nimba, Bong and Lofa, the Liberian cocoa and coffee belt (FAO 2012). The median age is 17.9 years, and the life expectancy at birth is 58 years. Access to modern health services is estimated at 41% (Republic of Liberia 2010). The 2014–5 Ebola crisis highlights the vulnerability of the health sector.

The urban population is 48.2% of the total, increasing by 3.43% per year, i.e., faster than the overall population growth, suggesting that people are moving from rural areas into the cities in search for better economic opportunities. This trend is also seen in other countries in West Africa and can influence agriculture in various ways. For example, young people leaving rural areas could restrict efforts at farm rehabilitation and intensification, while their return to rural areas after being for some time exposed to the urban environment might stimulate innovation in the farming communities (Ruf and Schroth 2015a).

Immigrants contribute 5.3% of the population (IOM 2014), which is low for West African conditions, compared for example to neighboring Côte d'Ivoire, where migrants from the savannah zone of the same and neighboring countries play a dominant role in cocoa and coffee farming, and some major coffee and cocoa production areas are predominantly populated by migrants.

During 2014–5, Liberia and its neighboring countries Sierra Leone and Guinea were affected by the Ebola crisis that, by September 2015, had caused in Liberia alone over 10,600 confirmed, probable and suspected infections (the second highest number of reported cases of any country) and over 4,800 deaths (the highest number of deaths of any country) (http://apps.who.int/ebola/). Although the crisis was essentially over in the country by mid-2015 (whereas new cases were still being reported in neighboring countries), it had caused major disruptions of economic activities and rural life, including in the cocoa and coffee sectors.

Roads and ports

The poor road and port infrastructure is regularly mentioned as a major cost factor in Liberia's cocoa and coffee value chains. It also restricts market access for the rural population. According to Republic of Liberia (2010), *"primary roads make up about 1,798 km, of which 561 km are paved. Secondary roads (2,504 km) and feeder roads (1,425 km) are unpaved. ... As a result of degradation during the last two decades of war and emergency, the paved roads are severely pot-holed and the rest of the road network is in a very poor state of repair (many feeder roads have reverted to jungle). Vehicular travel in rural areas is difficult in the dry season and impossible in many places during the rainy season. ... The consequence of poor roads and few transport services is high transport costs, particularly during the rainy season and especially on poor quality roads."* According to one informant, a truck transporting 10 tons of cocoa from Lofa County to Monrovia may take up to 2 days for the trip, so that transport costs add significantly to the cost of the commodity at the port. Considering the dependency of rural areas on unpaved roads, and the high susceptibility of unpaved roads to degradation under adverse weather conditions (e.g. high rainfall), the impacts of future climate change on the road network need consideration and monitoring (Figure B.2).

Figure B.2. Rural road in Lofa County in Liberia's cocoa and coffee belt during the rainy season.

The importance of a reliable road network for economic development of rural areas has been recognized by the Government and a number of donors. Since 2006, 1,000 miles of inland roads and 400 miles of feeder roads have been built in order to improve access to markets for farmers and small businesses. Improvement of feeder roads is also part of donor-funded cocoa and coffee projects. The maintenance of rehabilitated roads remains, however, a challenge. Work on increasing the capacity of ports is also underway for Monrovia, Bassa, Sinoe and Harper (UNDAF 2013).

2. Economic situation and the role of agriculture

Economic situation

Liberia's economy is still recovering from the civil war that lasted, with interruptions, from 1989 to 2003. Economic recovery has taken place since the inception of the new government in 2006. However, Liberia remains one of the world's poorest countries. According to Republic of Liberia (2015), Liberia's human development index ranked 175 out of 187 countries in the world in 2014. Average life expectancy is 60 years, and average school attendance is 4 years. According to World Bank data, 40% of men and 60% of women lacked employment by December 2014. Agriculture and forestry are the main employers. According to World Bank data, 83% of the population survives on less than US$1.25 a day, while 52% of the population live on less than half a US dollar a day. In 2015, 16% of the population were classified as food insecure (Republic of Liberia 2015). In this context, the Ebola crisis of 2014–5 was also a major setback for the development efforts in the country.

Agriculture

Liberia's natural resources include gold, diamonds, iron ore and hydropower (CIA 2014). However, with the collapse of the formal economy during the war, the share of agriculture and forestry of total Gross Domestic Product (GDP) has risen, and agriculture is now the primary livelihood of over 60% of Liberia's population and has been essential for economic recovery after the civil war. Large-scale plantations grow rubber and palm oil, with substantial interest from international companies in oil palm development. Liberia is home to the world's largest contiguous rubber plantation (32,100 ha) owned by Firestone. In comparison, cocoa contributed a modest 5.1% to Liberia's agriculture and forestry exports in 2005, while the contribution of coffee exports was negligible (CAAS 2007).

The United Nations Development Assistance Framework (UNDAF 2013) estimates the number of households engaged in smallholder agriculture at 330,000. Based on the 2012 agriculture and crop survey, the Liberia Institute of Statistics and Geo-Information Services (LISGIS, 2012) determines the number of rural households as 352,760 and the number of agricultural households as 305,820, of which 25.5% were headed by females. Rice is the main subsistence crop, cultivated by over 74% of farmers, followed by cassava, which is grown by 62% of the farmer population (CFSNS 2008). In 2008, rice and cassava – two staple crops – contributed 22% and 23% to agricultural GDP, respectively; while tree crops (rubber, cocoa and coffee) accounted for 34% of agricultural GDP in the same year (CBL 2009). These data suggest that cocoa and coffee will not only have to compete with other cash crops such as rubber for farmers' attention and farm space, but also with food crops whose production may be perceived by many farmers as less dependent on an evolving market environment compared to tree crops.

3. Cocoa and coffee production trends

The following sections draw strongly on a survey of cocoa and coffee farmers carried out by the Sustainable Tree Crops Project of the International Institute of Tropical Agriculture (IITA) (CAAS 2007) as well as the Liberia Agriculture Sector Investment Program (LASIP) Report of the Liberian Government (Republic of Liberia 2010).

Cocoa

According to the Comprehensive Assessment of the Agriculture Sector (CAAS) (CAAS 2007), about 40,000 households in Liberia are engaged in the production of cocoa, the country's second most important export crop after rubber. Based on the 2012 agriculture survey, the Government statistics agency LISGIS (2012) reported a slightly lower number with 38,350 households involved in cocoa growing, of which 13,470 were in Nimba County, 12,120 in Lofa County and 3,930 in Bong County. This means that 76.9% of all cocoa producing households were located in the three counties of the "cocoa and coffee belt," while most other counties host a small number of cocoa producers. Cocoa accounts for as much as 12.6% of total employment in the agriculture sector (Republic of Liberia 2010). Although cocoa is an important crop for many households in Liberia, the country is only a minor player in the global cocoa market, accounting for <1% of global sales (ranked 21st globally among cocoa exporters in 2012). The Netherlands, Spain and Germany were the top three markets for Liberian cocoa in 2012 (Republic of Liberia 2012).

Total cocoa production of Liberia is estimated at about 10,000 tons from about 30,000 ha. Until recently, only the smaller part of this production was officially exported through Liberian ports, with the remainder being informally exported via neighboring countries Guinea, Côte d'Ivoire and Sierra Leone. Average cocoa farm size is 1–3 ha, in the same range as many cocoa farms in Ghana, where small farm size is often seen as an obstacle to the adoption of more intensive and profitable practices. Already modest average yields of 400 kg/ha experienced in the 1980s have further declined, often to values as low as 100–200 kg/ha (Republic of Liberia 2010), or even less.

Coffee

Liberian coffee production is also concentrated in Bong, Nimba and Lofa Counties, and often coffee is grown on the same farms as cocoa. Compared to cocoa, coffee is less significant as a smallholder crop in Liberia. According to the 2012 agriculture survey (LISGIS 2012), a total of 24,390 households were engaged in coffee production, of which 13,710 were in Lofa County, 6,300 in Nimba County and 1,120 in Bong County. The three counties of the cocoa and coffee belt thus contributed 86.6% of the households involved in coffee growing in the country. According to several informants, most coffee in the country is Robusta with very little Arabica coffee (mostly in Lofa County) and very little Liberica coffee (Box B.1). The reduced importance of coffee compared to cocoa as a smallholder crop in Liberia is in spite of the fact that coffee was the first tree crop introduced as an export crop (together with sugarcane) in the mid-19th century. However, after experiencing a large expansion in area and production between the 1960s and the 1980s, reaching 21,310 ha and 8,250 tons, respectively, by the mid-to-late 1980s coffee export earnings fell sharply, and cocoa was replacing coffee as the dominant smallholder tree crop (CAAS 2007). This is in line with developments observed in neighboring Côte d'Ivoire, where coffee farmers have shown a tendency to switching from coffee to other, more profitable crops, such as cocoa and rubber over recent decades (Ruf and Schroth 2015a).

Box B.1. Liberica coffee (*Coffea liberica*)

Coffea liberica currently accounts for 1% of commercially grown coffee. Beans are generally larger than those of Robusta or Arabica coffee, but the strong shell around the flavorful interior inhibits widespread commercial production. *Coffea liberica* and *Coffea canephora* (Robusta) are closely related ecologically and grow well in the same habitat, although Liberica is more successful at cooler temperatures (18.3–26 °C) as opposed to Robusta (24–30 °C). Optimal rainfall for Liberica is 1,500–2,500 mm (Lim 2012).

Coffea liberica can tolerate 21–30 days of drought (FAO 2007), but cannot tolerate waterlogging. The tree is larger and hardier than other *Coffea* species. Yields decrease under high rainfall, as the tree begins to develop wood at the expense of flowers and fruits. *Coffea liberica* can be grown under little or full shade and prefers a humid environment (FAO 2007; Lim 2012). Coffee varieties are true to seed, so seeds can be used for propagation (www.tradewindsfruit.com, 2013). However, little other research exists on details of the cultivation and post-harvest processing of *Coffea liberica*.

Currently, Malaysia is the leading producer of *Coffea liberica*, where it is called "Kope Baraka." Malaysian yields of Liberica are low, with 670–900 kg/ha (as opposed to 1,500–3,000 kg/ha for Arabica and 2,300–4,000 kg/ha for Robusta). Malaysia does not export Liberica, as its local consumers prefer Liberica to Robusta. It is said to complement Robusta nicely and is usually blended. The caffeine content of Liberica is similar to that of Robusta with 1.6% (Lim 2012).

Whether there is potential for a local specialty coffee product line from Liberia based on *Coffea liberica* requires investigation. This would also need to consider the disease resistance of the trees since, in the 1950s, many Liberica trees succumbed to a disease outbreak (T. Leroy, CIRAD, pers. comm.).

While export quantities of coffee in Liberia averaged 7,600 tons in the 1980s, only 124 tons were reported to have been exported in 2008, perhaps due to cross-border trading and local consumption. In spite of extension programs under various agricultural development projects in the past, yields have remained low (Republic of Liberia 2010).

Cocoa or coffee?

At this point, cocoa seems to be the crop of greater economic importance and future potential for Liberian farmers compared to coffee. In the survey of 2007, cocoa was the third most frequently desired tree crop after rubber and oil palm for Liberian farmers, while coffee was rarely mentioned (CAAS 2007). While coffee could be seen as a diversification option for cocoa to reduce the vulnerability of households to shocks, including weather or climate-driven ones, other crops including food crops, rubber and oil palm would also be options for the same purpose.

State of cocoa and coffee farms

In Liberia, as elsewhere in West Africa, cocoa and coffee are mostly grown by smallholders, although some commercial plantations (e.g., of rubber) have also diversified into cocoa and coffee (CAAS 2007). Cocoa and coffee farms are mostly old, established with unimproved local planting material (although improved Trinitario trees are present in some cocoa farms), have often been neglected or abandoned for prolonged periods during the war resulting in mortality of many trees, and are thus in need of rehabilitation and/or replanting. Although improved germplasm had arrived in the country in the 1970s, it was not usually available to the farmers and much of it has been destroyed during the war (CAAS 2007). Recently, improved cocoa varieties have been introduced by the Central Agricultural Research Institute (CARI) for testing and multiplication, and various projects are importing hybrid cocoa seed from neighboring countries, notably Ghana and Sierra Leone. This will be discussed in more detail in later chapters of this report.

Like elsewhere in West Africa, smallholder tree crop farms in Liberia are commonly diversified. Cocoa is often intercropped with other crop species, with cola nut and plantain being particularly common. Lofa had the highest proportion of cocoa only tree crop farms, while farmers in Nimba were much more likely to have multiple tree crops, especially a combination of cocoa/rubber or cocoa/rubber/oil palm (CAAS 2007).

Coffee farms are also commonly 20–40 years old, with very few young coffee farms. The 2007 survey found that 40% of existing coffee farms had been abandoned to the bush (CAAS 2007), apparently for inability to find buyers. Similar to the situation in cocoa, almost all coffee farms were planted with unimproved local material (CAAS 2007). According to the same source, coffee is also usually grown together with other crops in Liberia. Avocados and plantains stand out as popular food crops to be associated with coffee.

Input use

Liberian farmers use essentially no agrochemical inputs on their cocoa and coffee (CAAS 2007). According to several informants, this has not changed much in the last years. The fertilizers available on the market are not specifically formulated for use in tree crops. Some of these are imported from neighboring countries by cross-border traders, as there is a limited number of agriculture supply stores in the country, especially in rural areas (Republic of Liberia 2010). Donor-funded projects for cocoa and coffee have initially focused on access to improved planting materials (hybrid seedlings) and the application of good agricultural practices without which the use of agrochemical inputs would not be cost effective. Once good management practices are being implemented, the use of agrochemical inputs, including fungicides to control diseases (especially black pod – *Phytophthora* spp. – of cocoa) as well as fertilizers, will however become more important.

Labor availability

According to the CAAS survey (2007), most cocoa farmers work their own farm. Sharecropping is not common in Liberia, different from the situation in Côte d'Ivoire and Ghana. This may be an advantage since it may reduce certain forms of conflict over land that can hamper investments in the long-term productivity and sustainability of farms. The same survey suggests that in Liberia cocoa farming is less dominated by old farmers than in these other countries, indicating that labor-related limitations to farm rehabilitation and innovation could be relatively less severe in Liberia.

On the other hand, similar to Ghana and especially Côte d'Ivoire, tree crop production in Liberia appears to be a relatively male-dominated enterprise, while women are traditionally tasked with tending food crops for household consumption and surplus sales. Beside increasing household food security, this is another argument in favor of promoting the cultivation of cocoa and coffee in association with food crops, such as plantain and oil palm.

The use of child labor in cocoa farms does not seem to be a problem in Liberia, although this question requires further study and continuous monitoring to avoid the problems marring the cocoa sector elsewhere in West Africa.

4. The cocoa and coffee supply chains

Liberian cocoa and coffee are mostly harvested between October and January, i.e., at the end of the rainy season and beginning of the dry season (CAAS 2007). Considering the need to dry the harvest and the difficult road conditions, this situation can be considered fortunate.

CAAS (2007) described the Liberian cocoa supply chain, including the then prevalent cross-border trading, as follows:

> *"Generally, farmers will sell (possibly) dried and fermented beans to any available buyer that comes along to the farmgate or head-carry the load to a nearby market. At the farmgate, buyers may be agents for a local/regional buyer who finances village-level sales but is located in the nearby local/regional buying center. Alternatively, the buyer may be an intermediate village-level buyer with limited personally financed capital. These small-scale buyers take advantage of a farmer's pressing cash constraint and offer same day cash-on-hand along with prices that are less than the prevailing farmgate price from buyer's agents. There are also village-level buyers, looking to collect enough cocoa to make a trip to the regional buying center or to Guinea worthwhile. If the farmer chooses to take the cocoa directly to the buyer, located in a buying center or in Guinea, they may receive a better than farmgate price or open access to credit through informal, but direct arrangements with the local/regional buyers in Liberia. Buying centers at the local level are assumed to transport any of their accumulated cocoa to the regional buying centers. Regional buying center buyers, on the other hand, can benefit from the economies of scale they have created through aggregation of smallholder cocoa and have access to motorized transport to evacuate the cocoa to either Monrovia or deeper into Guinea's territory, possibly to the Guinean regional buying center (Nzérekoré). If the cocoa has remained in Liberia, the regional buyer transports the cocoa to Monrovia to sell to an exporter ... Cocoa that has been traded in Guinea will have a somewhat similar path. Buyers in border towns likely transport the cocoa to the main regional buying/ conditioning center (Nzérekoré) for the cocoa to be sorted and repackaged. Then the cocoa is transported to the port city of Conakry and exported to the world market."*

The marketing system for coffee is very similar to that of cocoa.

According to CAAS (2007), the *"fermentation of cocoa in Liberia occurs in hanging banana leaf-covered baskets or in a pile wrapped in banana leaves on the ground. Farmers reported fermentation duration ranges from two days to a week. Drying times ranged from three days to* *a week. Drying usually occurs on a bamboo mat or a tarp, rarely on the road, on raised platforms, or over fire. ... Following the harvest, cocoa is sometimes stored in the house prior to being sold."* This suggests that cocoa fermentation techniques are not much different from what is common practice in other cocoa-producing countries in the region. However, the post-harvest practices necessary for good quality are often not implemented. English (2008) reported that Liberian cocoa carried an origin discount (price penalty) of USD 200 to 330 per ton on the global market owing to its low quality (and presumably the low quantity). However, according to several informants, cocoa quality has improved during recent years. For example, some farmer groups now use solar driers, apparently with good success. There is a price differential for quality providing an incentive to farmers and cooperatives to produce higher grades, but it is not clear whether this incentive is sufficient. The increasing competition among buyers for the cocoa improves the farmers' negotiation position in the supply chain and reduces the risk of inappropriate price discounts, but this may also allow farmers to avoid higher quality standards of some buyers. Several informants related that the marketing position of the producer cooperatives has improved significantly. Often, buyers have to pay significantly more than the quarterly guide price for cocoa set by the government to obtain the cocoa.

Until some years ago, Liberian farmgate prices did not encourage smallholders to improve yields or adopt better drying or fermentation methods. However, the situation has improved considerably. Relative prices paid to Liberian cocoa farmers have improved from around 30% of New York prices in 2008 to 60–65% of those prices now (ACDI-VOCA, pers. comm.). Therefore, the incentive to rehabilitate farms for increasing production and to produce cocoa of higher quality is now much greater than it was a few years ago.

Credit availability

According to CAAS (2007), *"another dimension of the cocoa markets that affects the price for cocoa is the accessibility of credit and its source. There are currently very few sources of credit or loans in Liberia. As such, a farmer's capital constraints becomes an opportunity for buyers to either offer lower prices at the time of sale to take advantage of the farmer's pressing needs or offer the farmer loans/credit that can be paid back in cocoa at harvest. Such loans help the buyer limit search costs as they typically only make loans to farmers whose production capacity is known, and this contractually, albeit informally, obligates the farmer to sell to that buyer to repay the loan. Loans are often made directly by the cocoa buyer in a regional buying center to the cocoa farmer. Buyer's agents may also have this capacity though on a small scale. These loans are usually given in the form of cash or food during the starvation months of the rainy season. Typically, the farmers will pay back loans in cocoa but it is currently unknown if these farmers receive lower than average farmgate prices (thereby paying interest on the loan). For* *the cocoa farmers surveyed, the average length of loan was 3.3 months. Loans were used primarily for farm cleaning and maintenance."*

Although this description of the credit sector is 8 years old, various informants confirmed that the availability of credit, although it has improved, is still a limiting factor in the development of the cocoa sector. Credit is still mostly provided by the trade, as is common in the cocoa and coffee sector elsewhere in West Africa. According to one trader, the farmers' discipline in repaying loans is relatively low, a complaint that can also be heard in other cocoa-producing countries in the region. He also claimed that farmers often did not invest credit in their farms but spent it on medication, food, school fees etc., or even invested it in other profitable activities such as gold mining.

5. Principal vulnerabilities of the cocoa and coffee supply chains to climate change

We conclude this chapter with an attempt to identify the most critical components of the cocoa and coffee supply chains in Liberia with regard to climate variability and change, and to identify the key questions that need to be addressed and steps that need to be taken in order to reduce these vulnerabilities and to make the supply chains resilient to expected climate changes. For this purpose, we have broken the cocoa and coffee supply chains (which between each other show many similarities) into discrete steps or components for which we identify the general (biophysical) sensitivity to climate change, the specific vulnerability of farmers and other stakeholders of these supply chains in Liberia, and an approach for quantifying the specific risks and developing adaptation actions (Table B.1). Important relationships among elements of the supply chains and the principal stakeholders involved are illustrated conceptually in Figure B.3. Subsequent chapters will build on this approach and address critical aspects of the cocoa and coffee supply chains in more detail.

Table B.1. Steps of the cocoa and coffee supply chains of Liberia and their specific sensitivities to climate change, as well as a methodological approach to analyzing and addressing them

Step in farming cycle and supply chain	Sensitivity to climate variability and change	Vulnerability of / relevance to target groups within the supply chains of Liberia	Approach for assessing vulnerability and developing adaptation strategy
Selection of farm site (new versus rehabilitated)	Under climate pressure (especially drought), farmers may prefer to occupy new farms in a protective forest environment, taking advantage of the "forest rent," rather than rehabilitating old, degraded farms, following a common historical pattern elsewhere in West Africa	Abandoned state of farms, high investments and limited support for rehabilitation, and large areas of forest may encourage farmers, especially those who were dislocated during the conflict and/or have no clear claims to land, to occupy new farms in forest land	Conduct stakeholder interviews to understand current trends of rural mobility and migration, land occupation, and policies towards farm expansion into forest areas
Selection of farm site (part of country)	Reinforced by climate pressure, the wide climatic range (e.g., rainfall, altitude) of the country may encourage farmers to move to areas that have a favorable climate and soils for their crop, leaving ecologically less favored areas in state of abandonment	Climatic drivers of internal migration and investment decisions are reinforced by poor infrastructure in remote parts of the country, encouraging farmers to migrate to and invest in farm sites with good market connection and benefiting from government and private sector support	Conduct stakeholder interviews to understand current trends of rural mobility and land occupation
Choice of main crop (cocoa versus coffee versus other)	If climate becomes hotter and/or drier, farmers may prefer more rustic crops such as food crops and rubber, especially on marginal soils (e.g., dry, shallow, sandy, low-nutrient status). Current models indicate higher maximum temperatures during the dry season, but a tendency for a shorter dry season in the future	Abandoned state, high investment needs and limited support for rehabilitating cocoa and coffee farms and poor market connection may reinforce any pedo-climatic drivers towards the selection of less demanding, locally consumed (food crops), and less perishable crops for which technology is readily available (rubber)	Identify main climate variables likely to drive change in suitability for cocoa and coffee under representative selection of climate change scenarios
Choice of main crop (species of coffee)	The predicted increase in average temperature can result in reduced quality (and thus price advantage) of Arabica coffee, as compared to the more heat-tolerant Robusta and Liberica coffees	Currently there seems to be little Arabica, no emphasis on quality, and no separate supply chains for Arabica and Robusta coffee. Climate change may further reduce the potential for a separate supply chain for higher quality Arabica coffee	Analyze conditions for producing quality Arabica coffee in highlands and their future development under climate change
Selection of planting material	Under changing climate, most suitable varieties or genotypes may be different in the future from present ones, e.g., more heat tolerant and either more tolerant to drought or to fungal diseases, depending on future rainfall conditions and part of the country	Planting material currently available to farmers is mostly local, unimproved material, multiplied through seed. New cocoa varieties brought in from outside have not yet been tested for climatic suitability and there is yet little capacity to do so and to make recommendations available to farmers. No recent selection work on coffee in Liberia but possibility to draw on work done in Côte d'Ivoire	Propose process and criteria leading to improved planting material for cocoa and coffee tracking climate change and being available to farmers

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Step in farming cycle and supply chain	Sensitivity to climate variability and change	Vulnerability of / relevance to target groups within the supply chains of Liberia	Approach for assessing vulnerability and developing adaptation strategy
Plant propagation strategy	Climate change (e.g., greater heat stress, changes in pest and disease pressures) may require adaptation of propagation methods (e.g., vegetative propagation of locally adapted genotypes instead of reliance on hybrid seeds selected and produced centrally and potentially under different climatic conditions)	Limited access to technical assistance for farmers to learn selection and propagation methods, but familiarity of many farmers with vegetative propagation methods and rationale from rubber	Develop recommendations for technical assistance program to support farmers in selecting and propagating planting material
General plant management	Higher temperatures especially during dry season will increase the water demand of tree crops, for which the water supply during the dry season is likely to be already a limiting factor in northern parts of the country	Due to the abandonment of most farms for prolonged periods, trees have grown very large and need large amounts of water. Management practices are traditionally extensive and this is reinforced by low profitability of farms, requiring a change of practice to keep trees small and water efficient	Develop recommendations for tree management for increased water-use efficiency, especially for drier parts of the country
Farming system / use of shade	Climate change, especially increased heat stress during the dry season, may require adaptation of traditional practices with regard to shade use	While the use of shade from useful companion tree species in cocoa and coffee is common in Liberia, in some areas little-shaded farms predominate. Lack of understanding of relationships between climate and shade and lack of technical assistance limit farmers' ability to adapt practices to changing climate	Develop recommendations for shade use dependent on climate conditions and scenarios
Farming system / diversification	Increased environmental and market risk under climate change requires resilient household strategies, including the diversification of farms with food crops and secondary cash crops, to cope with income fluctuations	Cocoa and coffee farms in Liberia are often but not always diversified with secondary cash crops (cola, avocado, etc.) and food crops (plantain, cassava, etc.). The rehabilitation and replanting of old and overgrown farms increase the need (income gap after rehabilitation and new planting) and provide opportunities for diversification with food and cash crops	Develop recommendations for farm diversification, especially in connection with rehabilitation and replanting
Pest and disease control	Climate change may lead to changes in pest and disease pressures, affecting especially extensively managed and neglected farms and requiring additional expenses in cash and labor for their control	Over-aged trees and neglected, overgrown state of many farms result in already high susceptibility to pests and diseases. Low farm profitability and lack of technical assistance limit ability to invest in effective pest and disease control. Risk of introduction of aggressive strains of cocoa swollen-shoot virus from Côte d'Ivoire through uncontrolled cross-border exchange	Develop general recommendations for farm set-up and management that reduces the susceptibility to most important pests and diseases

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Step in farming cycle and supply chain	Sensitivity to climate variability and change	Vulnerability of / relevance to target groups within the supply chains of Liberia	Approach for assessing vulnerability and developing adaptation strategy
Harvest	Higher temperatures could lead to shorter maturation of cocoa pods. Together with irregular weather and flowering, this could lead to more cocoa being harvested during the wet season when sun drying is difficult	Low productivity and small farm sizes make necessary frequent harvest rounds more expensive due to small volumes. In combination with higher volumes being harvested during the rainy season, this could lead to deterioration of quality	Analyze likelihood of climate change leading to changes in ripening patterns. Develop recommendations for managing and adapting harvest process
Post-harvest handling	Changes in the seasonality and predictability of rainfall and faster pod ripening due to higher temperature could make open sun drying more difficult	Small production volumes, low farm profitability and lack of credit make investments in post-harvest infrastructure (e.g., solar dryers) more difficult	Identify main risks to quality from climate change and propose mitigation actions
Transport and marketing	If rainfall increases or becomes more violent, road conditions may deteriorate further and reduce market access for perishable products	Most rural roads are unpaved and in poor condition, making rural populations highly susceptible to reduced market access for their produce and increasing transport costs to traders	Develop strategy for decentralized storage and improvement of rural roads, especially in areas dependent on the production of perishable goods
Climate monitoring and information	A changing and less predictable climate requires a denser system of agro-meteorological stations connected to capacities to operate and maintain them, collect and analyze data, and generate and distribute alerts and recommendations to farmers and the industry	Currently the availability of meteorological information from Liberia is extremely limited, making climate suitability assessments and predictions very difficult	Outline a system of meteorological stations collecting the minimum data required for agro-meteorological assessments and predictions
Agricultural research	Research results on crop varieties, management practices etc. obtained now may not hold in the future, or not in the same locations	There is still limited research capacity in the country, including for cocoa and coffee. Although there is a wide-spread awareness that climate has changed over recent decades, climate change seems low priority compared to demands perceived to be more urgent, such as providing more productive germplasm to farmers	With participation of key stakeholders, identify important research questions and approaches related to adapting crops and farming systems to climate change
Training and technical assistance	Changing environmental (and market) conditions and new land-use practices make adequate levels of training and technical assistance to farmers even more urgent	Few, if any, countries in West Africa possess a system of training and technical assistance reaching the majority of their farmers. In Liberia, the scarcity of technical staff in government and private sector makes establishing such a system even more complicated. Extension services provided by the private sector are likely to focus on immediate, production-related topics and specific cash crops and are only a partial substitute for public extension services, especially in so far as medium-term issues like climate change and crop diversification are concerned	Outline a system of farmer training and technical assistance identifying the roles for public and private players

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Step in farming cycle and supply chain	Sensitivity to climate variability and change	Vulnerability of / relevance to target groups within the supply chains of Liberia	Approach for assessing vulnerability and developing adaptation strategy
Credit and insurance	Under pressure to adapt to a changing climate, farmers depend even more on the availability of credit to invest in farm rehabilitation, adaptation of farm practices, and potentially crop change, as well as insurance to protect their farm investments against unpredictable weather	Credit availability to farmers is currently extremely limited. Short-term credit from commodity traders suffers from poor repayment discipline (not unique to Liberia), while longer term credit and insurance for farm rehabilitation and adaptation is not available. Extension services to provide advice on farm investments are also insufficient	Outline the needs for agricultural credit and innovative forms of risk mitigation and insurance
Landscape mosaic	Climate change may increase the risk of dry winds, drying out of water courses, low atmospheric humidity, excessive heat, and potentially wildfire during the dry season	As a consequence of Liberia's still relatively high forest cover and the abandonment of many farm areas during the war, opportunities for maintaining a landscape mosaic with high tree cover, protection of riparian buffer strips and other remnant forest vegetation are relatively good. On the other hand, there may be little awareness among farmers and extensionists of the need and ways to increase landscape resilience to climate change	Develop recommendations for maintaining forest cover and farm trees in strategic locations in the landscape to maintain a protective microclimate for tree crops
Risk of wildfire	Increasing temperatures in the dry season increase the risk of fire escaping from slash-and-burn areas and damaging tree crop farms and forest vegetation, especially in the drier parts of the country	The prevalence of slash-and-burn farming in Liberia in combination with the abandoned state of many farms make rural areas vulnerable to wildfires unless fire management practices are systematically applied	Develop recommendations for fire management practices and incorporate them into training programs
Climate change mitigation	The conservation of forest and trees in agricultural landscapes and the use of low-carbon footprint production practices can contribute to mitigating climate change and to distinguishing Liberian cocoa and coffee on the international market as "climate friendly"	Liberia's relatively intact forest cover, modest population pressure and relative absence of land tenure conflicts present comparatively favorable preconditions for national policies towards climate and biodiversity-friendly commodity production. Legislation and markets should facilitate the commercialization of native timber trees produced on their farms by farmers	Outline a strategy for climate and biodiversity-friendly cocoa and coffee production in Liberia

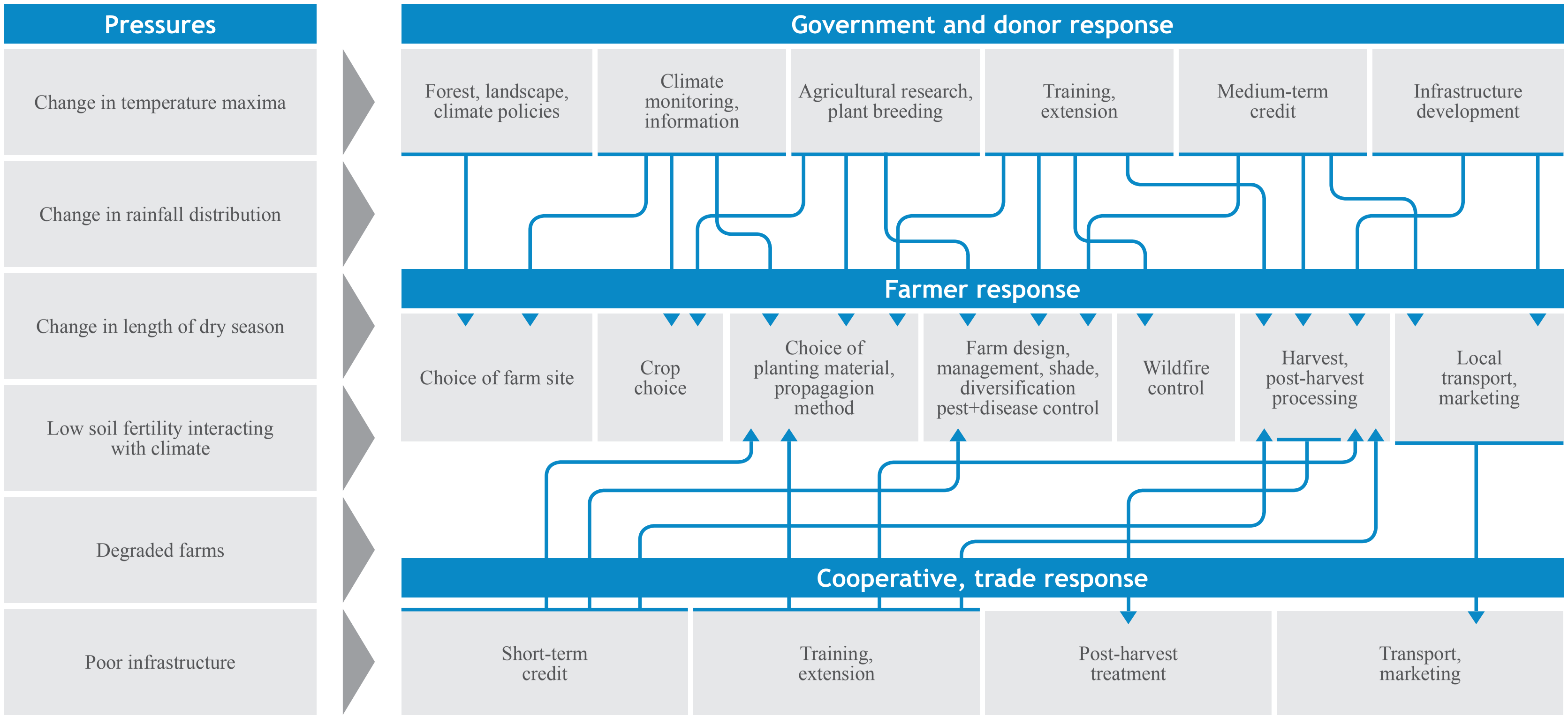

Figure B.3. Relationships between climate-relevant steps in the cocoa and coffee value chains and the main stakeholders, namely governments, farmers, cooperatives and trade.

The farmer is at the center of the graph since he or she is most exposed to climate pressures and has the greatest influence on climate vulnerability or adaptation. Governments and public service providers play key roles in influencing farmers' vulnerabilities and decision options. The trade also plays a significant role in influencing farmer options and in turn is influenced by these decisions, e.g. with regard to processing and transport. The blue arrows show schematically some main directions of influence of steps in the supply chain on farmers' activities and decisions with regard to climate change (see Table B.1 and text for further explanation).

Part C – Soil conditions and agro-ecological zones of Liberia

1. Agro-ecological zoning

Climate and soil conditions interact strongly in determining the agro-ecological suitability of a site for a given crop. By extension, soil conditions influence the way how climate change impacts a crop. For example, the effect of increasing length of the dry season would be reinforced in its effect on a crop by a shallow and physiologically dry soil, but would be of less consequence on a soil where the crop has access to a water table in the subsoil. Therefore, the analysis of soil conditions and an understanding of the ways how they interact with climate in determining the suitability of a site for a specific crop is of paramount importance for analyzing climate change vulnerabilities and developing adaptation strategies in agriculture. In this section of the report, we therefore provide an overview of the soil and agro-ecological conditions of Liberia.

Since the beginning of the 1980s, the Government of Liberia has worked to identify areas that have the most appropriate soil and environmental conditions for cocoa, coffee and other crops in the country (Hughes et al. 1989). This work can be usefully summarized with reference to the system of agro-ecological zones (AEZ) that was developed by the Food and Agriculture Organization of the United Nations (FAO) as a tool for making inventories and evaluating the biophysical land resource. The FAO-AEZ classification is based on key characteristics of climate, soils and topography. FAO (2012) identifies four main AEZ in Liberia (Table C.1). Cocoa and coffee can be found in all AEZ except the savannah.

Table C.1. Agro-ecological zones (AEZ) of Liberia with their main characteristics, locations and farming systems.

AEZ	Land coverage	Counties	Agro-Climate	Vegetation and Farming Systems
Coastal Plains	From sea level to a height of 30 m.a.s.l., reaching up to 25 km into the interior of the country	Bomi, Cape Mount, Grand Bassa, Margibi, River Cess	Very high rainfall (4450–4550 mm), high humidity (85–95%), long sunshine hours with high temperatures and wide temperature ranges	**Vegetation:** swampy along rivers and creeks, mangroves, scattered patches of both low and high bush and savannah woodland belt up to 25 km inland **Farming systems:** upland and lowland rice, cassava intercropped with vegetables and sugarcane; rubber, coffee and cocoa; grasslands are a potential pasture resource

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AEZ	Land coverage	Counties	Agro-Climate	Vegetation and Farming Systems
Upper Highland Tropical Forest	Plateau (tablelands) about 30 m.a.s.l. and mountain ranges (600 m) behind rolling hills	Upper Cape Mount, Lofa, Bomi, Margibi, Bong, Grand Bassa, River Cess and most of Nimba	Bi-modal rainfall (sub-divided by short dry spell of 2 weeks) more evenly spread from 1265 mm in Bong, 2900 mm in Lofa to Nimba, to 3200 mm (overall maximum); temperature variation is 5 °C	**Vegetation:** closed semi-deciduous forest and transition zone or secondary forest ("farmbush") **Farming system:** cocoa and coffee typical of Lofa, Bong and Nimba, as well as rubber, citrus and oil palm as main cash crops; food crops are upland and lowland rice, yams, cocoyam, plantains, potatoes and vegetables
Lower Tropical Forest	Mid-altitude rolling hills composed of valleys, hills and numerous water courses	Sinoe, Maryland, Grand Kru, Grand Gedeh and parts of Nimba County	Average rainfall from 3000 mm in Maryland to 4100 mm in Sinoe; long dry spell and two distinct peaks of rainy season	**Vegetation:** mostly evergreen rainforest in south-eastern part of the counties **Farming systems:** upland and lowland rice, yams, cocoyam, plantains, potatoes and vegetables; rubber, cocoa, coffee and sugarcane are the major cash crops
Northern Savannah		Northern Lofa and Northern Nimba	High elevation with average rainfall between 700 and 1750 mm	**Vegetation:** dense elephant grass (*Pennisetum purpureum*) of up to 1.5 m, scattered trees and patches of forest; it consists of the derived and Guinea savannahs, which in addition to the coastal savannah are the main pastoral resources

Source: FAO (2012).

2. Soils of Liberia

Most of the area of Liberia is covered by soils of low fertility. Haplic and Xanthic Ferralsols cover almost 70% of the territory (Figure C.1, Table C.2). Ferralsols are typically associated with tropical conditions, high rainfall and very old (Tertiary) land surfaces. As a consequence of intense weathering over prolonged time periods, they have lost nearly all of the weatherable minerals they had inherited from their parent rock and are now dominated by stable products such as aluminium oxides, iron oxides and kaolinite. Ferralsols are acidic and have low nutrient availability. Their ability to hold nutrients (e.g., from fertilizer or released from decomposing organic materials) is low and mostly tied to their organic matter. On the positive side, these soils are deep and have a favorable structure that poses few obstacles to water infiltration and root development (van Wambeke 1992).

The dominance of Ferralsols applies not only to Liberia as a whole, but also specifically to Lofa, Bong and Nimba Counties (Figure C.1). Part of Bong County also shows Plinthic Ferralsols as a soil type, a transition form to the Plinthosols. Plinthic Ferralsols and Plinthosols together cover 17% of Liberia. These soils possess different amounts of Plinthit, an iron-silica mixture that hardens irreversibly upon exposure, in their subsoils within reach of crop root systems. These soils are also commonly waterlogged at relatively shallow depth (van Wambeke 1992). The potential of these soils for growing tree crops is very low compared even to other Ferralsols, although they may be suitable for rice cultivation.

Part of Bong and small areas of Nimba County are also covered by Leptosols, shallow soils without agricultural potential and unsuitable for cocoa and coffee.

Cambisols are younger and more fertile soils than the dominant Ferralsols but cover only small areas in Nimba County.

More fertile soils with higher agricultural potential such as Nitisols, which can be found across the border in Guinea, only occur on very small areas in Lofa County.

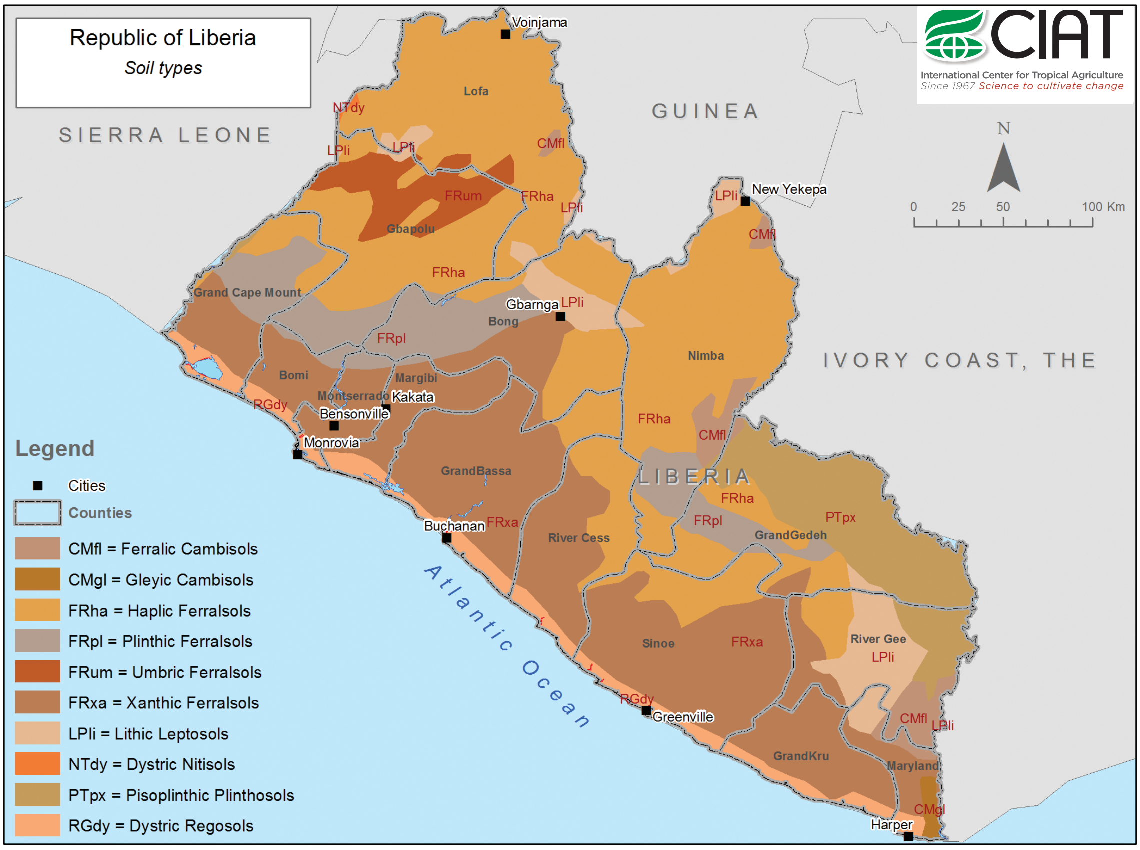

Figure C.1. Soils map of Liberia.

Source: Own elaboration with data from Jones et al. (2013).

Table C.2. Percentage of area covered by soil type in Liberia.

Legend	Soil types	%
Cmfl	Ferralic Cambisols	2.4
Cmgl	Gleyic Cambisols	0.3
Frha	Haplic Ferralsols	37.2
Frpl	Plinthic Ferralsols	8.7
Frum	Umbric Ferralsols	3.0
Frxa	Xanthic Ferralsols	30.8
Lpli	Lithic Leptosols	5.1
NTdy	Dystric Nitisols	0.1
PTpx	Pisoplinthic Plinthosols	8.1
RGdy	Dystric Regosols	4.1
No Data		**0.3**
Grand Total		**100.0**

3. Limiting factors in soils

Based on the overall characterization of soil types found in Liberia, we will now briefly discuss the principal limitations to agriculture presented by these soils. In Figure C.2, four limiting factors for agricultural suitability of Liberian soils are mapped based on the FAO Global Agro-ecological Zones Assessment for Agriculture (Fisher et al. 2008): nutrient availability, nutrient retention capacity, rooting conditions and oxygen availability.

Nutrient availability (SQ1)

This soil quality is decisive for successful low-level input farming and to some extent also for intermediate input levels. Diagnostics related to nutrient availability are manifold. Important soil characteristics of the topsoil (0–30 cm) are: texture/structure, organic carbon (OC), pH and total exchangeable bases (TEB). For the subsoil (30-100 cm), the most important characteristics considered are: texture/structure, pH and TEB.

Figure C.2 shows that most soils in Liberia, including its main cocoa- and coffee-producing counties, are classified as having between severe and very severe constraints with regard to nutrient availability. This classification reflects the dominance of acidic, highly weathered and leached Ferralsols. Only in the extreme north of Nimba County, where less weathered Cambisols predominate, are nutrient constraints less serious. This implies that for satisfactory yields of crops, such as cocoa and coffee, the application of fertilizer will usually be necessary. The use of shade in cocoa and coffee production, which dampens to some extent the nutrient requirements of these tree crops (Wood and Lass 2001), is recommended.

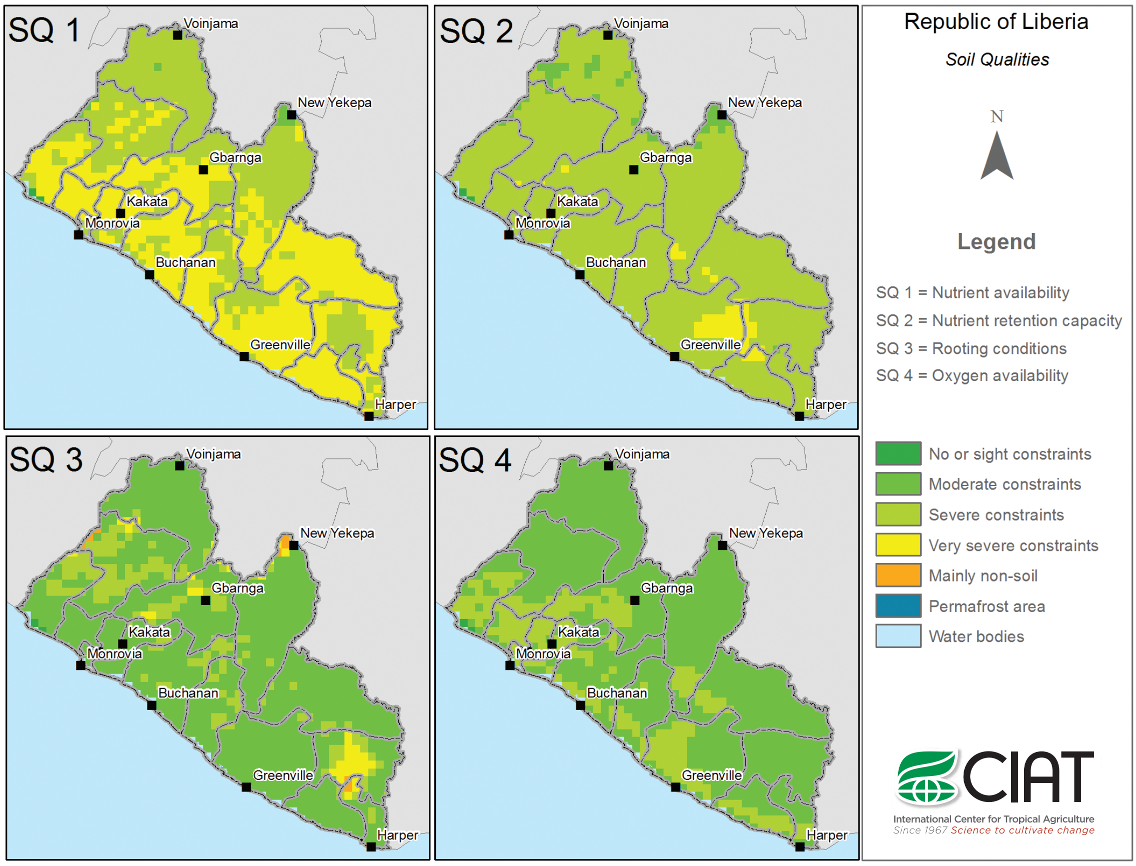

Figure C.2. Soil qualities of Liberia.

Source: Based on Fisher et al. (2008).

Nutrient retention capacity (SQ2)

Nutrient retention capacity is of particular importance for the effectiveness of fertilizer application and is, therefore, of special relevance for intermediate and high input level cropping conditions. Nutrient retention capacity refers to the capacity of the soil to retain added nutrients against losses caused by leaching. Plant nutrients are held in the soil on the exchange sites provided by the clay fraction and organic matter. Nutrient losses vary with the intensity of leaching, which is determined by the rate of drainage of soil moisture through the soil profile. Soil texture affects nutrient retention capacity in two ways, through its effects on available exchange sites on the clay minerals and by soil permeability. The soil characteristics used for topsoil are respectively: organic carbon (OC), soil texture (Text), base saturation (BS), cation exchange capacity of the soil (CECsoil), pH, and cation exchange capacity of the clay fraction (CECclay).

Figure C.2 shows again severe constraints with regard to this characteristic in most of Liberia, including the cocoa and coffee belt counties, reflecting the low nutrient retention characteristics and high infiltration rates typical for the dominant Ferralsols. For the cultivation of cocoa and coffee, this implies that fertilizer should be applied frequently in small doses and not during the maximum of the rainy season, in order to reduce nutrient losses from leaching.

Rooting conditions (SQ3)

Rooting conditions include the effective soil depth (cm) accessible to the roots of a plant and the effective soil volume (vol. %), which is the percentage of this soil volume that is not composed of gravel and stones. Rooting conditions can be affected by the presence of impenetrable subsoil layers, waterlogged conditions in the subsoil, shrinking and swelling properties of very clayey soils or any other condition that decreases the effective volume accessible for root penetration.

In Liberia, most soils show relatively little restrictions with regard to rooting depth, reflecting the deep Ferralsols that dominate the soil cover (Figure C.2). An important exception are the Leptosols (i.e., shallow soils), of which significant areas occur in Bong County. These are not suitable for cocoa or coffee.

Oxygen availability (SQ4)

Oxygen availability in soils is largely defined by drainage characteristics. The determination of soil drainage classes is based on procedures developed by FAO, taking into account soil type, soil texture, soil phases and slope.

In the coastal areas of Liberia, waterlogged soils are relatively common (Figure C.2). In Bong and Nimba Counties, the Plinthic Ferralsols, which occur in the western part of Bong and the south of Nimba, are waterlogged in the subsoil, which restricts their suitability for crops such as cocoa and coffee as well as many food crops (though not necessarily for rice). Among tree crops, oil palm is relatively tolerant to waterlogging.

4. Land suitability of the Mano River Union, northwestern Liberia

This study of land suitability was carried out in the 1970s but only covers the northwestern part of the country. Among the main cocoa- and coffee-producing counties, it includes Lofa but not Bong and Nimba (Figure C.3). It is based on aerial photographs and reconnaissance field checks in 1975/76. The objectives of the study included the evaluation of land suitability for cocoa and coffee among other crops, classifying a mapping unit as suitable if more than 50% of the land unit is suitable. The analysis took into account climate (annual rainfall and average annual temperature), altitude and vegetation data.

In the area, at the time of this study, smallholders commonly had some cash crop plots with coffee and (secondly) cocoa, as well as sugarcane for the production of cane juice, on terraces along streams with high embankments. These terraces are flooded occasionally, which is supported by cocoa if it is not too deep and not of too long duration. The groundwater level normally reaches a depth of 1 m during the rainy season, which is favorable for most crops including cocoa and coffee. The water availability is thus excellent. During the dry season, the groundwater table decreases to 2 m or more, but stays within reach of tree crops such as cocoa and coffee and also for sugarcane. Drought stress would thus not occur on such sites (Veldkamp 1980a). Such terrace sites benefiting from groundwater access would also be relatively secure under conditions of deteriorating rainfall, but would be vulnerable to conditions of increasing or more violent rainfall conditions that might lead to increased flooding.

The authors of this study considered the suitability of these sites for cocoa as poor to fair but never good because of the low chemical fertility of the soils. Also, the percentage of the total land area occupied by terraces that were considered suitable for cocoa is relatively low. In the interior of the country, where the dry season is more pronounced than near the coast, cocoa, coffee, oil palm and rubber can benefit on lower slopes from a lateral water flow. Here, the footslopes and deep gravel-free pockets are reserved for cocoa and coffee with the more demanding cocoa on the lower and more gravel-free sites (Veldkamp 1980b).

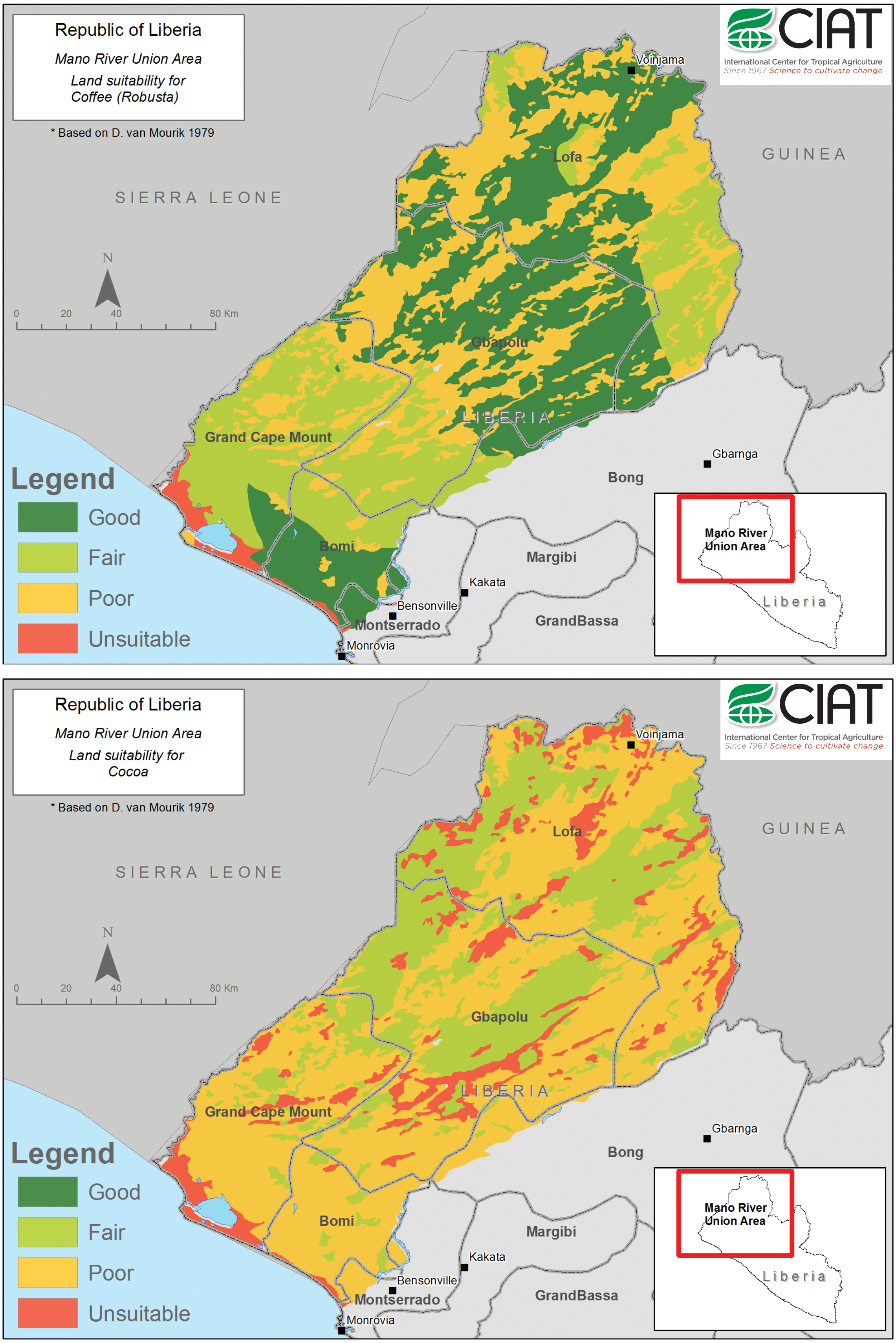

Figure C.3. Land suitability map of northwestern Liberia.

Source: Based on Van Mourik (1979).

Part D – The climate for cocoa and coffee in Liberia – an overview

1. Introduction

In this chapter, we (i) provide a description of the climate of Liberia, including its recent climate history, (ii) present briefly the climate requirements of cocoa, Arabica coffee and Robusta coffee, based on literature information, and (iii) compare suitable ranges of important climate variables of those crops with conditions in Liberia in order to identify those variables and parts of the country where climatic limitations for the production of these crops are to be expected. On the basis of this overview, the next chapter will then discuss current and projected future climatic suitability of Liberia for cocoa and coffee in more detail, with a focus on the northern counties where the production of these crops is currently concentrated.

2. Current and historic climate of Liberia

The climatic conditions of Liberia are humid tropical, with average temperatures of 24–28 °C, relative humidity of 65–80%, 2–8 hours per day of sunshine and mostly unimodal rainfall with a rainy season from May–October and a dry season from November–April. Figure D.1 shows the corresponding information for the three counties of the cocoa and coffee belt – Lofa, Bong and Nimba. All three counties match this general picture. The driest months are December, January and February, when also the highest maximum temperatures are reached. While the annual rainfall distribution is unimodal in Lofa County, Nimba County has a tendency towards a bi-modal distribution of annual rainfall, with a drier period in July–August that is also found in the forest belt of neighboring Côte d'Ivoire, the world's largest cocoa and a significant coffee producer.

The seasonal rainfall in the region varies considerably on inter-annual and inter-decadal timescales, due in part to variations in the movements and intensity of the Intertropical Convergence Zone (ITCZ), resulting in variations in timing and intensity of the West African Monsoon (McSweeney et al. 2012). The best documented cause of these variations is the El Niño Southern Oscillation (ENSO). El Niño events are associated with drier conditions in West Africa. Strong El Niño events in the 1970s and 1980s led to year-long droughts in the Sahel zone and strong yield decreases of cocoa and coffee, accompanied by bushfires, in the forest zone of West Africa (Ruf et al. 2015).

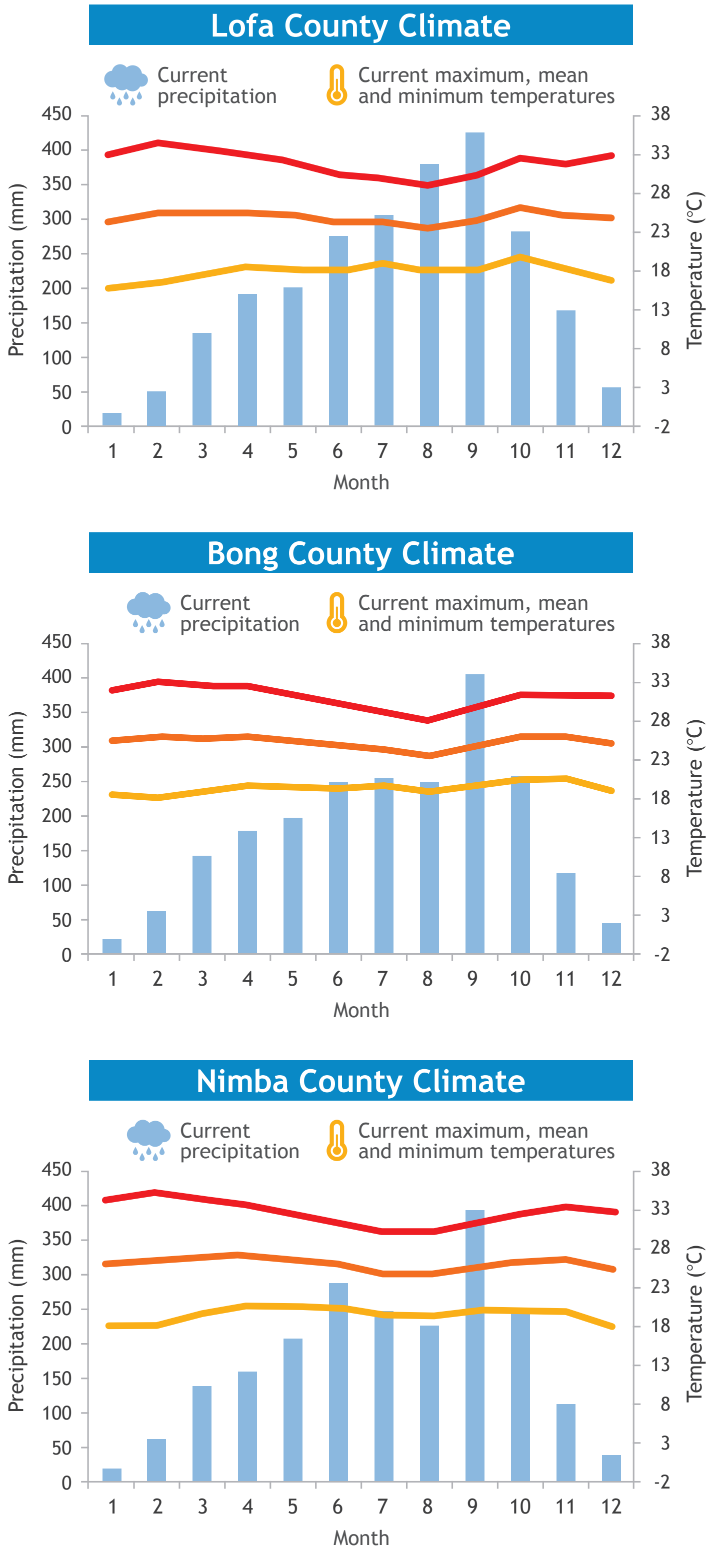

Figure D.1. Climate diagrams of Lofa, Bong and Nimba Counties, Liberia.

Source: WorldClim database.

As shown in Figure D.2, mean annual rainfall over Liberia has decreased since the 1960s, but it is difficult to determine whether this is part of a long-term trend because of the variable nature of rainfall in this region (McSweeney et al. 2012). The rainfall record shows a sequence of wetter and drier periods. The 1960s were particularly wet, while the early 1970s and 1980s were very dry. Similar patterns have been observed elsewhere in West Africa (Ruf et al. 2015). Rainfall in 2005 and 2006 has been very low in Liberia.

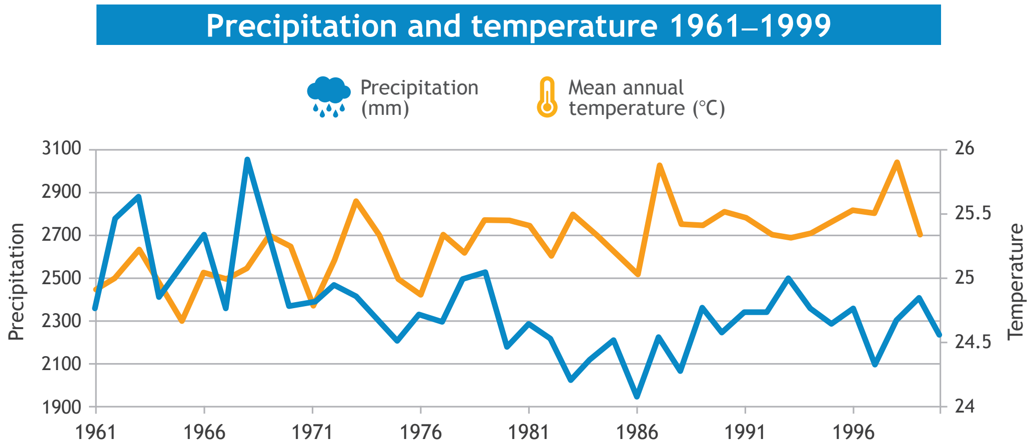

Figure D.2. Annual precipitation and mean annual temperature in Liberia, 1961–1999.

Source: Based on McSweeney et al. (2012).

The rainfall data by quartal in Figure D.3 suggest that the average rainfall during the first three months of the year (January–March), the driest quartal, has decreased from the 1960s to the 1980s. In the 1990s, monthly rainfall during this quartal has been highly variable. These data seem to corroborate the feeling in the country that the dry season has become longer (or at least more intense; D. Parker, ACDI-VOCA, pers. comm.).

Mean annual temperature has increased by 0.8 °C between 1960 and 2006, at an average rate of 0.18 °C per decade (Figure D.2). There are insufficient daily data available to determine trends in daily temperature extremes for all seasons. Available data, however, indicate that despite the observed increases in mean temperature, there was no significant increase in the frequency of particularly hot days. Data do, however, indicate a significant increase in the frequency of relatively hot nights by 15.7% between 1960 and 2003, while the average number of relatively cold nights per year has decreased by 4.8% in the same interval.

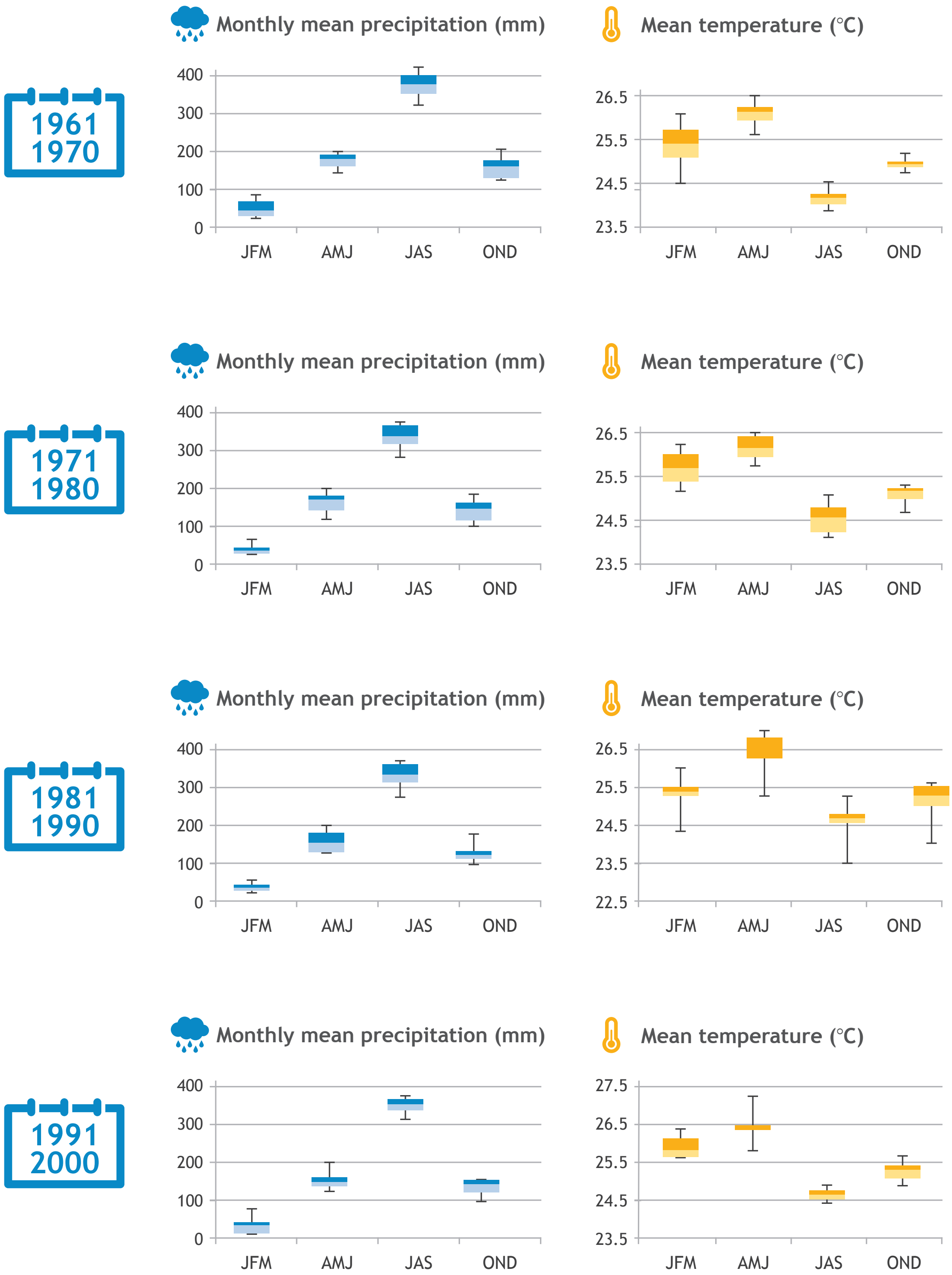

Figure D.3. Mean precipitation and temperature per trimester and per decade from the 1960s to the 1990s.

Source: Based on McSweeney et al. (2012).

Spatial variation of the climate in Liberia

For a more detailed description of the spatial variation of climate variables within Liberia, we use data from the WorldClim global climate database at 0.5" arcmin resolution (Hijmans et al. 2005).[1] For Liberia, 37 data stations are included in the WorldClim dataset, plus stations from surrounding countries by interpolation. Of these stations, 33 provide data for monthly precipitation, 26 for monthly temperature averages and 7 for monthly mean maximum and minimum temperatures. Stations are distributed between 3 and 659 m.a.s.l. Climate stations for the higher elevations of the country (up to 1380 m) are missing. Data for such locations are interpolated using the known temperature gradient with altitude as covariate. From these data, the climate surfaces in Figure D.4 were created.

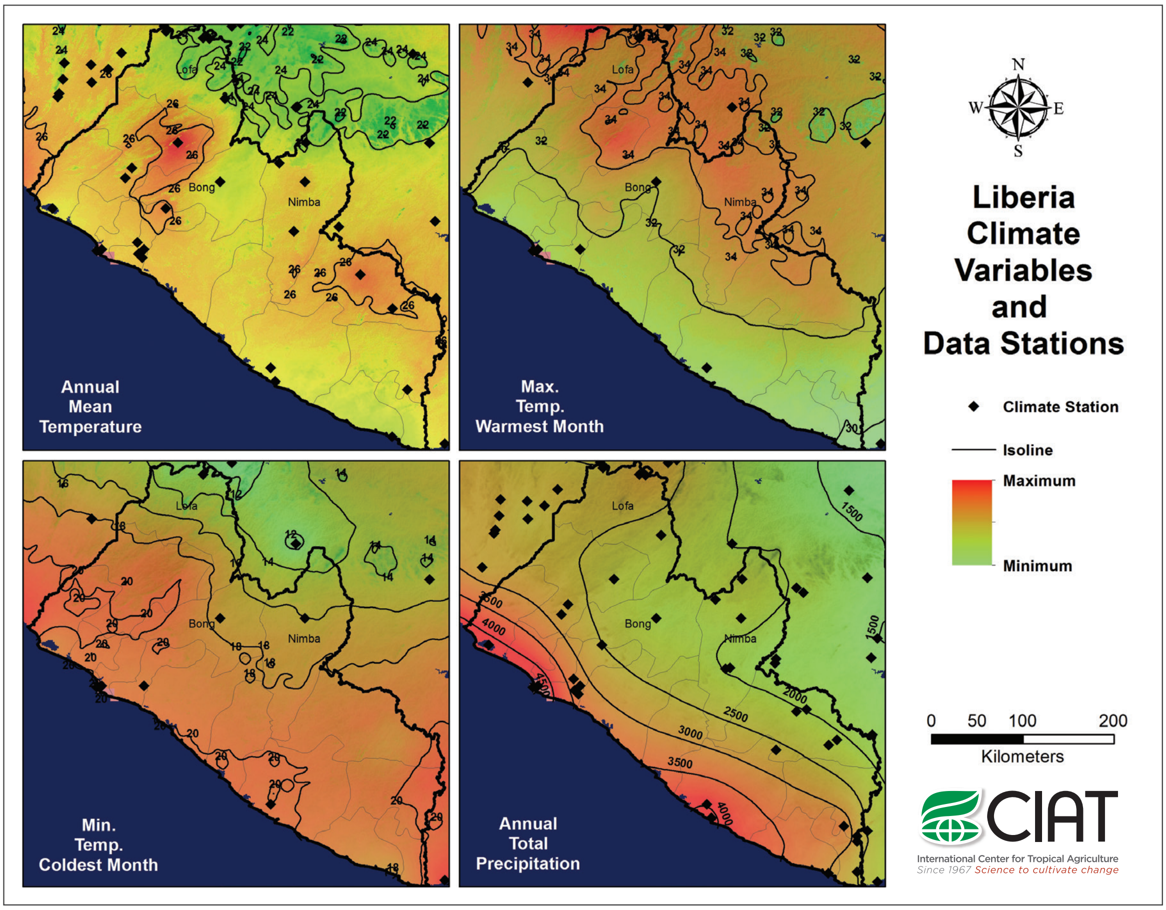

Figure D.4. Distribution of climate variables and underlying weather stations in Liberia.

Source: Based on Hijmans et al. 2005.

[1] For this database, interpolated climate surfaces of monthly precipitation and mean, minimum and maximum temperature for global land areas have been generated from a comprehensive set of climate data sources. The database is based on precipitation records from 47,554 locations, mean temperature data from 24,542 locations, and minimum and maximum temperatures from 14,835 locations with uneven geographic distribution. Especially regions with low population density, such as Liberia, are underrepresented in the station data. It has been criticized that uncertainties of precipitation data are often relatively high at high altitudes, but this is not very relevant for West Africa. Also, mean deviations for precipitation in tropical regions are often higher than 10 mm/month, which can be relevant for models focusing on the length and intensity of the dry season.

In Liberia, annual mean temperature does not follow latitudinal variation but is mostly influenced by the altitudinal gradient (Figure D.4). It is lowest in the northern mountain ranges of Nimba and Lofa Counties. Also, in south-eastern coastal areas, the annual mean temperatures are relatively low due to the proximity of the sea. Mean temperatures are highest around one station in the Gbapolu District, possibly a data error. The value of the highest temperature of the warmest month follows a gradient perpendicular to Liberia's coast line, with increasing maximum temperatures as the temperature moderating effect of the sea decreases. This indicates that especially young tree crops may need or benefit from shade in the interior as protection from high dry season temperatures. Exceptions are high altitudes. The mean minimum temperature of the coldest month is fairly uniform in the entire country with a median value of 19.5 °C. Colder temperatures can only be found at the higher altitudes.

Annual total precipitation is generally high. The mean across the country is 2700 mm. The distribution follows a similar gradient as the mean maximum temperature of the warmest month. Coastal areas receive very high rainfall; the interior of the country is slightly drier but most of the cocoa and coffee belt of Lofa, Bong and Nimba Counties receives between 2000 and 2500 mm annual rainfall (Figure D.4).

Figure D.5 shows that the length and severity of the dry season increase from south to north. While the south does not experience months with less than 100 mm rainfall per month, parts of Nimba and Bong have a severe dry season with less than 40 mm rainfall per month during two consecutive months of the year. In most parts of the country, three consecutive months have less than 80 mm of monthly precipitation.

3. Climatic requirements of cocoa and coffee

Cocoa, Robusta coffee and Arabica coffee have all relatively specific climatic requirements for optimal productivity and a relatively narrow genetic base (Anthony et al. 2001; Wood and Lass 2001). This makes these crops susceptible to climate change (DaMatta 2004). The threat of climate change is further aggravated by the long lead time of adaptation measures such as breeding for stress tolerance, which may take decades (Eskes and Leroy 2008), reinforced by the insufficient resources of national breeding programs.

The cocoa tree is originally from the wet forests of South America, very close to the equator. In its natural habitat, rainfall is heavy and the temperature is relatively uniform. However, in its major production regions in West Africa, production systems have been adapted to a climate with one long and usually a short dry season per year. In general, for optimal conditions

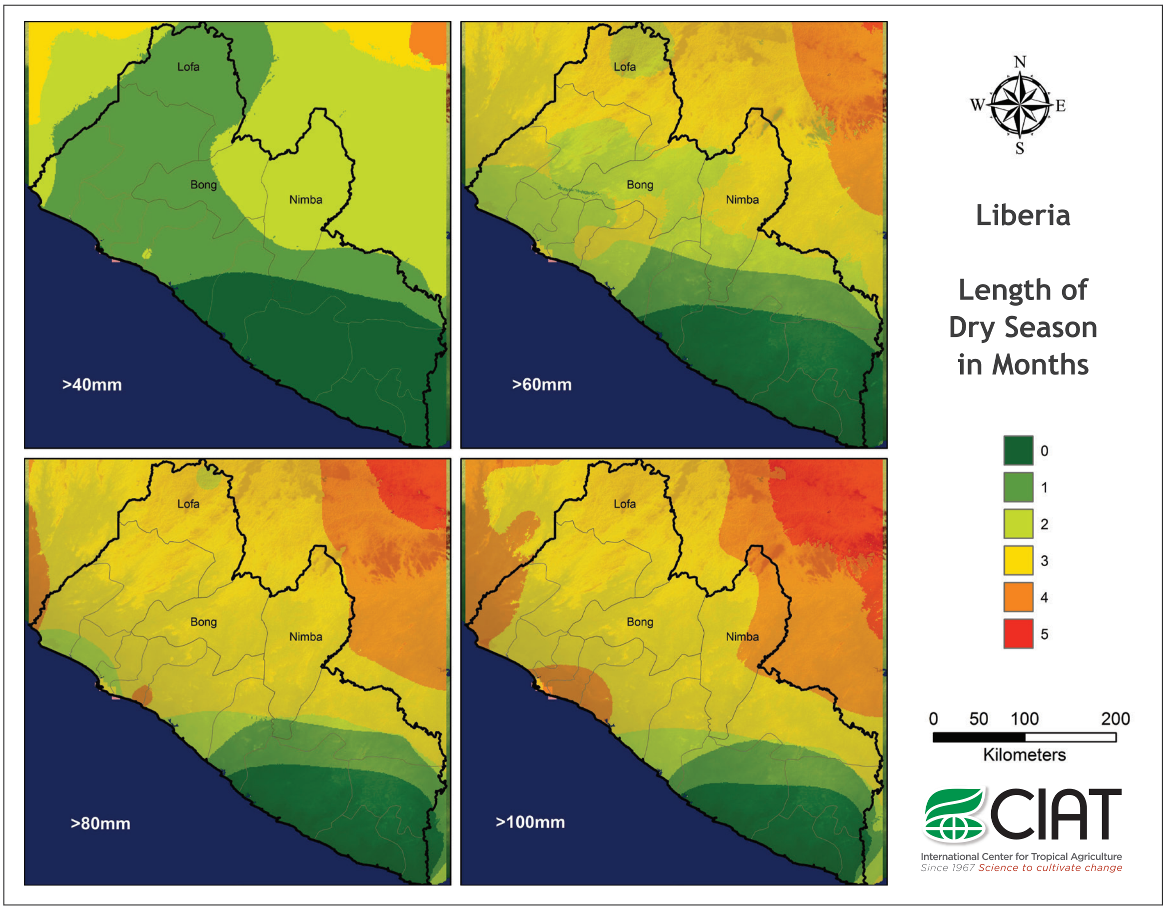

Figure D.5. Length and severity of dry season in Liberia.

Source: Based on WorldClim data.

maximum temperatures should not exceed 32 °C and not drop below 18 °C. Temperatures below 10 °C can be lethal. The cocoa crop requires high precipitation of about 1500–2000 mm during the year. Months with less than 100 mm are considered dry months (Wood and Lass 2001). Dry months are more detrimental to cocoa where the soils are shallow, sandy or very clayey (i.e., have a low available water holding capacity) within the upper 2.5 m or so that can be reached by the taproot of the tree. Conversely, dry months affect the trees less on deep, loamy soils with high water storage capacity or even where they have access to a groundwater table (see example in Part C). While a dry season induces uniform flowering, overall yields are higher without such a period. The plant drops its leaves during prolonged drought. After the rains start, the plant then needs to first develop new foliage before flowering. Fruits require about 120 to 150 days to maturity, depending on growing season average temperatures. Peak harvest can be expected about 5 to 6 months after the onset of the rainy season. With increasing temperature, the time to maturation of the pods decreases.

The main species that are used for coffee production globally are *Coffea arabica* and *C. canephora* var. Robusta (the species *C. liberica* is currently of little importance; see Part B).

Arabica originates from Ethiopian high plateau areas and is naturally found between 1300 and 2000 m altitude. Robusta's natural habitats are found below 1000 m in tropical Africa. Arabica coffee is grown in tropical countries along the equator between 22 °N and 26 °S. Robusta is cultivated closer to the equator within a 13° belt. It takes approximately three years from germination to first fruit production. The shrubs then remain productive for up to 80 years, though the economic lifespan is 30 years maximum (Wintgens 2008). The key environmental factors that influence coffee productivity are temperature, water availability, sunshine intensity, wind, type of soil and topography. The optimal mean temperature for Arabica is considered to be 18 °C during the night and 22 °C during daytime. Extremes should not exceed 15 °C during the night and 25–30 °C at daytime. Reduced photosynthesis at temperatures above 25 °C and a loss of flowers or fruit degeneration at temperatures above 30 °C compromise productivity. Robusta is generally more tolerant of high temperatures but the tree may die at 4–5 °C. Arabica requires about 1400 to 2000 mm (min. 800–1000 mm) of annual rainfall, Robusta between 2000 and 2500 mm (min. 1200 mm). Values lower than the minimum are potentially damaging for production. Excessive rainfall is mostly a problem because of topsoil erosion and the low fertility of the highly leached soils that are typical for very high rainfall areas. A dry season of up to 3 months is considered beneficial to the productivity of Arabica (Wintgens 2008). Robusta also requires a dry season to induce flowering, but the fruits require more time to mature than in Arabica. For Robusta, the tolerated length of the dry season depends on the genotype – shorter for varieties from the Congo Basin and longer for varieties originating from the Atlantic coast of Africa (Montagnon and Leroy 1993).

Data about the crops' climatic requirements can be found in FAO's EcoCrop database (FAO 2007). This database summarizes abiotic factors that determine crop performance. We use this database as a starting point to assess the suitability of the climate in Liberia for cocoa and coffee. The EcoCrop data are supplemented with values for annual mean temperatures that are widely used to describe suitability for cocoa and coffee in the literature. Table D.1 lists the values of environmental variables that define optimal and marginal ranges of suitability for each crop.

If we now compare these crop climatic requirements with the climate data of Liberia, we see that most of the country is too warm for Arabica coffee, with only few locations in the northern mountain areas showing annual mean temperatures within the range commonly accepted for this crop (Figure D.6). The suitable area appears to be even smaller when regarding the minimum and maximum temperatures within the physiological limits of Arabica, reflecting maximum temperatures during the dry season that are too high for quality Arabica production. In contrast, most of Liberia shows annual mean temperatures suitable for Robusta production.

Table D.1. Environmental limits of Arabica coffee, Robusta coffee and cocoa.

Variable		Arabica	Robusta	Cocoa	Unit
Annual mean temperature	Optimal	18–22	22–26	22–25	°C
	Tolerance	16–24	20–28	20–27	
Annual precipitation	Optimal	1400–2300	1700–3000	1200–3000	mm/year
	Tolerance	750–4200	900–4000	900–7600	
Dry months	Optimal	1	1	0	Consecutive months
	Tolerance	0.2–3	0–2	1–3	
Min/max range	Optimal	14–28	20–30	21–32	°C
	Tolerance	8–32	12–36	10–38	

Source: FAO (2007).

Also, minimum and maximum temperatures across the country are within tolerable ranges for Robusta although, in most of the interior of the country, Robusta may suffer from heat stress during the maximum of the dry season, suggesting that it should be grown under shade (Figure D.6).

Liberia has similarly suitable temperatures for cocoa (Figure D.6). High maximum temperatures suggest again that, in the interior of the country, unshaded cocoa trees may suffer from heat stress during the maximum of the dry season. Fortunately, current cocoa cultivation practices in Liberia usually use shade, which reduces temperature extremes by 2 °C to 4.5 °C, thereby reducing heat stress (Almeida and Valle 2007). The adoption in Liberia of (almost) zero-shade

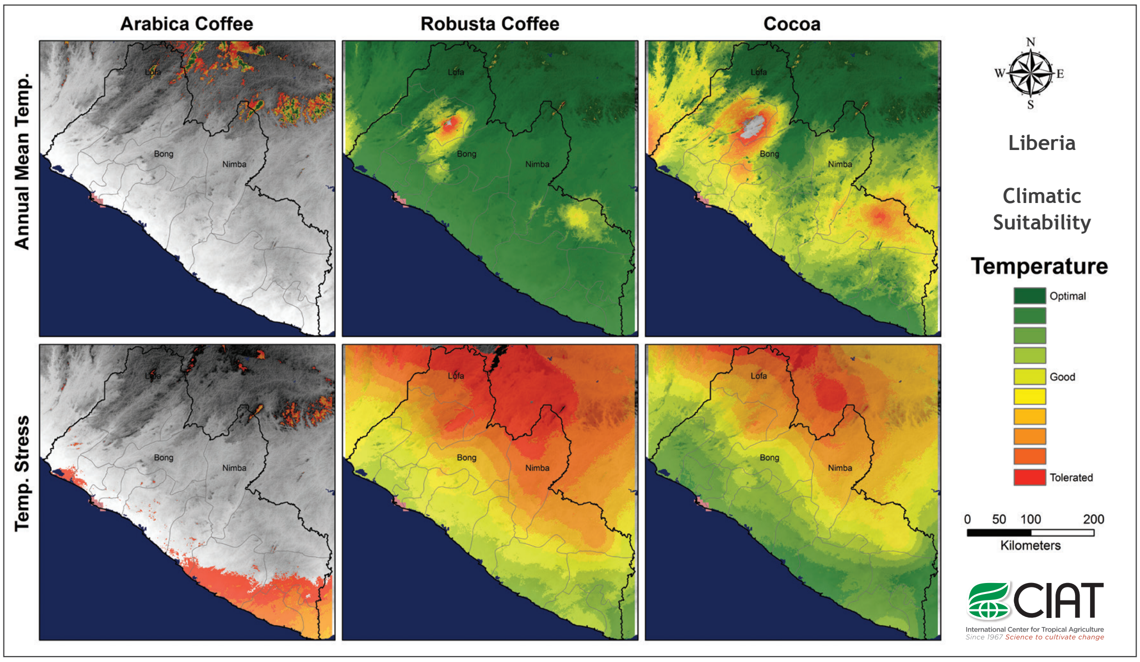

Figure D.6. Distribution of temperature variables in Liberia. Shading indicates altitude.

Source: Based on WorldClim data.

practices that are typical for parts of southwestern Côte d'Ivoire and Ghana would, therefore, be problematic and reduce the resilience of cocoa to expected future temperature increases. This will be discussed in more detail later in this report.

Precipitation is generally favorable to the three crops throughout the country (Figure D.7). An exception are coastal areas where annual precipitation values of more than 4000 mm/year create excessive humidity and would increase the pressure from fungal diseases, the need for artificial drying of the yield, and quick leaching of nutrients, including mineral fertilizer from the soil. On the other hand, the duration of the dry season is mostly within optimal or tolerable limits for cocoa and coffee. The classification of the precipitation regime of northern Liberia as "sub-optimal" for both crops in Figure D.7 indicates that seasonal drought needs to be managed, for example, through selection of appropriately deep soils with sufficient water holding capacity as well as the use of shade.

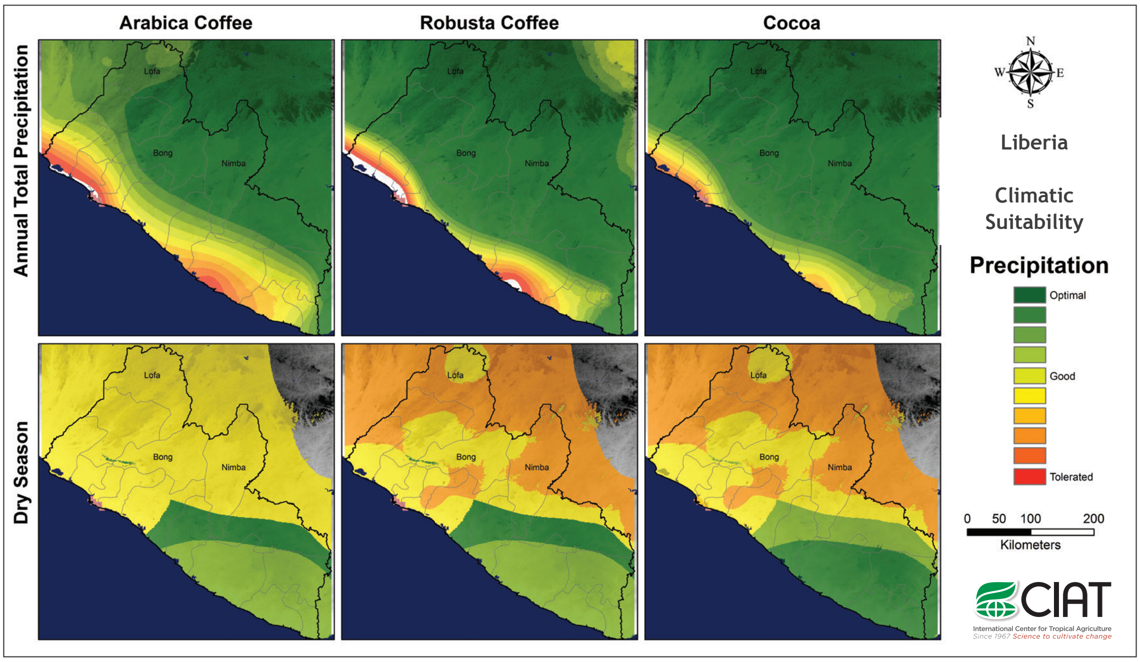

Figure D.7: Distribution of precipitation variables in Liberia. Shading indicates altitude.

Note: Dry season is defined here as months with less than 60 mm rainfall.

Source: Based on WorldClim data.

Our preliminary analysis of climate variables thus shows that under current conditions the climate in Liberia is suitable for cocoa and Robusta (but not Arabica) coffee production, but also highlights the importance of the length of the dry season and maximum temperatures during the dry season as critical variables influencing yield potential and requiring specific management strategies. These variables will be discussed in more detail in the next chapter, also in the context of future climate projections.

Part E – Climate change vulnerability of cocoa and coffee in Liberia

1. Introduction

To obtain a more detailed, quantitative understanding of the vulnerability of cocoa and coffee in Liberia to future climate change, we will in this chapter put the climate of Liberia into the context of the climates in West and Central Africa where these crops are currently grown. We will consider a set of climate variables, identified in part in the previous chapter, that are likely to influence the growth and yield of cocoa and coffee, and will also consider integrated measures of relative climatic suitability for those crops. Relative climatic suitability will be calculated through statistical computer models, using the climatic conditions of current cocoa and coffee production zones as a reference. The methodology will be explained in more detail below.

But first, we want to mention some caveats of the approach. By comparing projected future climatic conditions in an area of interest with those prevailing today in cocoa- or coffee-growing areas, we implicitly assume that in the future, farmers will find it profitable to grow cocoa or coffee at a site if the conditions there are similar to those found now in cocoa- and coffee-growing areas, and unprofitable to grow these crops if climatic conditions are outside the range of conditions found now in cocoa- and coffee-growing areas. This is the best assumption we can make but it may not always be correct, including because these decisions are influenced by future prices of the crops we are interested in as well as future prices of alternative crops. For example, if prices of a crop go up for reasons that may or may not be related to climate change, then farmers may decide to grow this crop under conditions under which they would not consider this crop profitable enough, relative to other crop options, under current conditions. There are now expectations that cocoa prices may increase in the near future and this may encourage farmers to grow this crop even under sub-optimal or even risky environmental conditions under which they would prefer alternative crops now. On the other hand, a further decrease of coffee prices may induce coffee farmers to look for alternative crops (including cocoa) even at sites that they currently consider suitable enough for this crop. However, it is not possible to know how prices will be some decades from now or to predict how farmers would respond to these price changes in their decisions whether or not to grow a certain cash crop. The important point here is that, when we analyze climatic vulnerability of crops and cropping systems, we can indicate probable future trends, but we cannot accurately predict farmers' future behavior and decisions, since these will be influenced by many other factors besides climate.

Of course there are also eco-physiological limits for where a certain crop can grow and produce a harvest. These may include maximum temperature and length of the dry season, as will be discussed below. In practice, however, for market crops such as cocoa and coffee, which are grown for income and not for the farmers' own subsistence, the impacts of such eco-physiological limits on crop choices will usually be economically mediated. For example, increasing maximum temperatures during the dry season may influence the frequency of years with particularly hot weather when crop yields may be reduced and perhaps some trees die, and this will influence the economics of the cropping system relative to other crop options. The same is true for the risk of drought, or – under other climatic conditions and with other crops – for the risk of winter frost, hail, high rainfall damaging the crop, etc. The more profitable a crop relative to its alternatives, the more frequent "bad years" will be accepted, and the less profitable it is relative to its alternatives, the quicker an increased risk of such "bad years" will trigger decisions to diversify and switch to other crops. This means that even a discussion of absolute climatic limits for growing a cash crop such as cocoa or coffee is ultimately not only about crop eco-physiology, but about how increasing environmental pressures on a crop translate into lower profitability and income security relative to other crop options, and thus into farmers' land-use decisions.

> *Relative climatic suitability for a given crop should thus not be interpreted in a deterministic way, but rather be seen as one among several factors that will influence farmers' decisions whether or not to grow a certain crop at a given site in the future.*

Based on the preliminary analysis of Liberia's climate in Part D, we will now compare the climatic factors that are likely to be most limiting for cocoa and coffee between Liberia and the main cocoa- and coffee-producing areas in West and Central Africa for the current and projected future (2050s) climate. Of course, Liberia's climate might become more favorable for cocoa or coffee according to one climate variable (say, water availability) and less suitable according to another (say, temperature). Therefore, in a subsequent step we will provide a more integrative, multi-factor comparison of the current and future climatic suitability of Liberia compared to the region as a whole.

As "region as a whole" – or reference region – we use either West Africa or all of Africa, or even the entire tropics. For cocoa, our reference region is the West African cocoa belt between Sierra Leone and Cameroon because this is where about 65% of the world's cocoa is grown, despite the fact that part of this region has a relatively long and intensive dry season for cocoa (Wood and Lass 2001). There are cocoa-producing regions elsewhere in Africa with different climates, including parts of the Congo basin (de Beule et al. 2014), but we assume that these are less informative for the decisions and crop choices Liberian farmers are going to make over the next few decades than conditions in main cocoa-producing countries. For Robusta coffee, we also use West Africa as the most important reference base, but also compare conditions in Liberia with those in other Robusta-producing regions in Africa, where the plant is native and has a wide distribution. Finally, for Arabica coffee, West Africa is not a globally significant producer and therefore not a good reference. We opted here for including major Arabica-producing regions outside Africa in our comparison. We explain this in more detail in the respective crop sections.

2. Cocoa

Climate conditions in Liberia as compared to West Africa

In Part D, we have pointed out that the climatic factors that are most likely to directly affect cocoa in Liberia are maximum temperatures, which are highest during the dry season, and water availability during the dry season. Many other climate factors may affect cocoa indirectly. For example, cocoa pests and diseases may respond to a range of climate factors and their interactions in a complex pattern and are difficult to predict. Such complex climate effects are partly captured by the integrative, multi-variable analysis using a climate model that is provided in the next section.

We now compare climatic conditions in Liberia with those in other cocoa-producing areas in the West African cocoa belt.[2] Figure E.1 shows a regional map of maximum temperatures of the warmest month. Green colors signal relatively low maximum temperatures (lower 30s) along the coast, in mountain areas and in the less seasonal, equatorial climate of Cameroon, while orange and red colors signal savannah climates with their higher dry season temperatures (upper 30s and 40s). Maximum temperatures in cocoa climates generally range from 30–35 °C, with the higher values at the northern limits of the cocoa belt, close to the forest-savannah boundary. Maximum temperatures >35 °C are rare in the cocoa belt. In Liberia, maximum dry season temperatures reach from the lower 30s near the coast to around 35 °C in northern Nimba and

[2] The location of cocoa-producing areas in West Africa was taken from the Atlas on Regional Integration in West Africa (ECOWAS 2007). These distribution maps were updated for Nigeria with a map of cocoa-producing districts from the 2007 national cocoa production survey (CRIN 2008). We included all of Liberia as cocoa-producing area because a recent survey shows some cocoa production for essentially every part of the country (CAAS 2007). We also included in the cocoa area the wet, southwestern parts of Côte d'Ivoire and Ghana where cocoa farming has expanded relatively recently (Ruf et al. 2015). Spatial climate data were obtained from the WorldClim database (Hijmans et al. 2005, www.worldclim.org). These data were generated at a 30 arc-second spatial resolution (1 km) through an interpolation algorithm using long-term average monthly climate data of the 1950–2000 period that we refer to here as "current" or "present" climate. Only stations for which there were more than 10 years of data were included. WorldClim provides bioclimatic variables derived from temperature and rainfall measurements of 751 climate stations within the cocoa belt of West Africa. Following the method used by Läderach et al. (2013), we augmented these bioclimatic variables by nine further variables reflecting potential evapotranspiration as well as the length of the dry season measured as the number of consecutive months with less than 100 mm of rainfall. For a complete list of the variables see Table E.1.

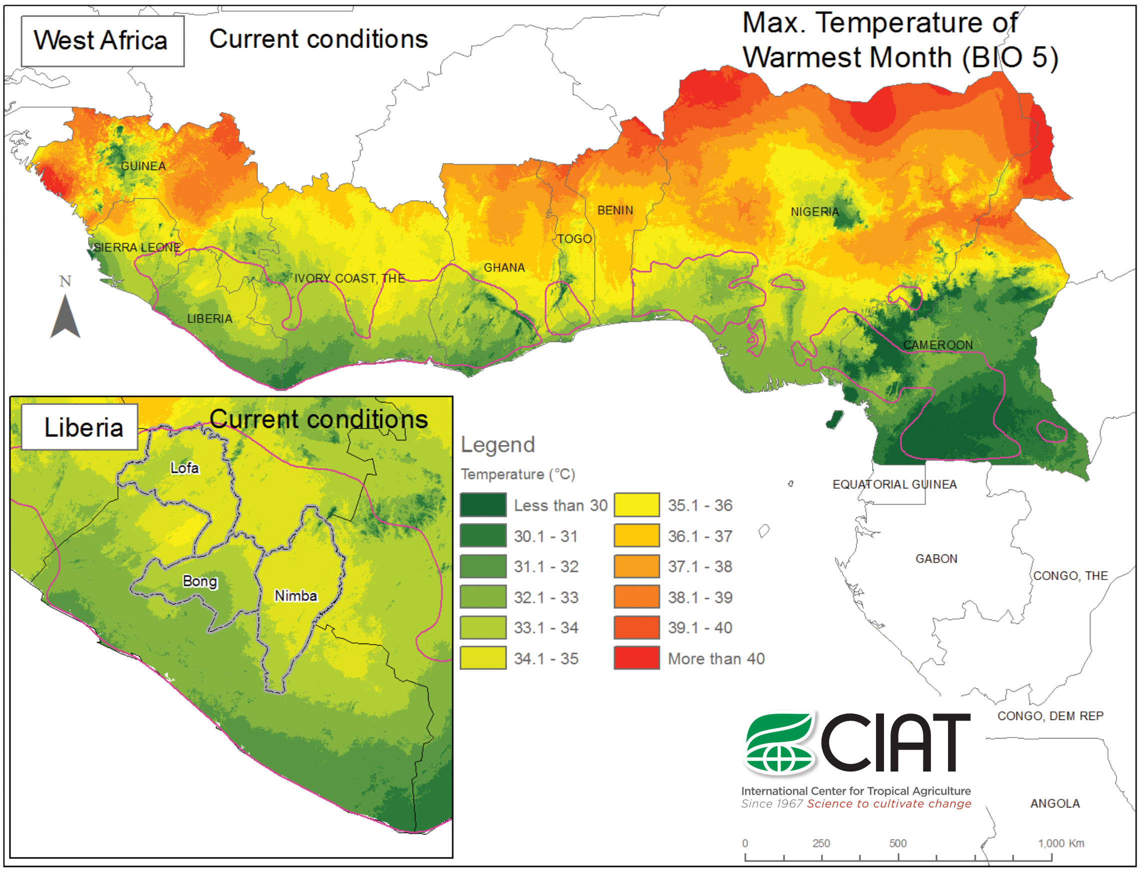

Figure E.1. Maximum temperature of the warmest month (BIO 5, in °C) in Liberia and the West African cocoa belt for current climate conditions.

Note: The red lines delimit current cocoa-producing areas.

Lofa Counties, with a locally higher value in Gbapolu that could be due to a data error. The highest values found are in the same range as maximum values found in other cocoa-producing countries in the region. The orange and red colors characteristic of non-cocoa, savannah climates do not occur in Liberia.

Under present climate conditions, northern Nimba and Lofa Counties are the most vulnerable areas to high dry season temperatures in Liberia. The maximum temperatures here are however within the range also found in other parts of the West African cocoa belt. Bong County, the southern part of Nimba and counties further to the south are less vulnerable to high dry season temperatures.

We now look at the hydrological conditions during the dry season, which is the other potential source of climatic vulnerability of cocoa in West Africa (see Part D). Figures E.2 and E.3 show two indicators of the intensity of the dry season for Liberia as compared to other parts of the West African cocoa belt: the number of consecutive months with less than 100 mm of rainfall (often used to measure the length of the dry season for cocoa); and precipitation during the driest quarter (BIO 17). The length of the dry season in Bong, Lofa and almost all of Nimba Counties is 2–3 months, similar to the southern parts of Côte d'Ivoire, Ghana and Cameroon. The northern parts of the cocoa belts of Côte d'Ivoire and Ghana have 3–4 months of dry season, and cocoa-growing areas in western Nigeria have even 4–5 months. In comparison to the rest of the West African cocoa belt, the length of the dry season in the main cocoa-producing areas of Liberia is thus relatively short.

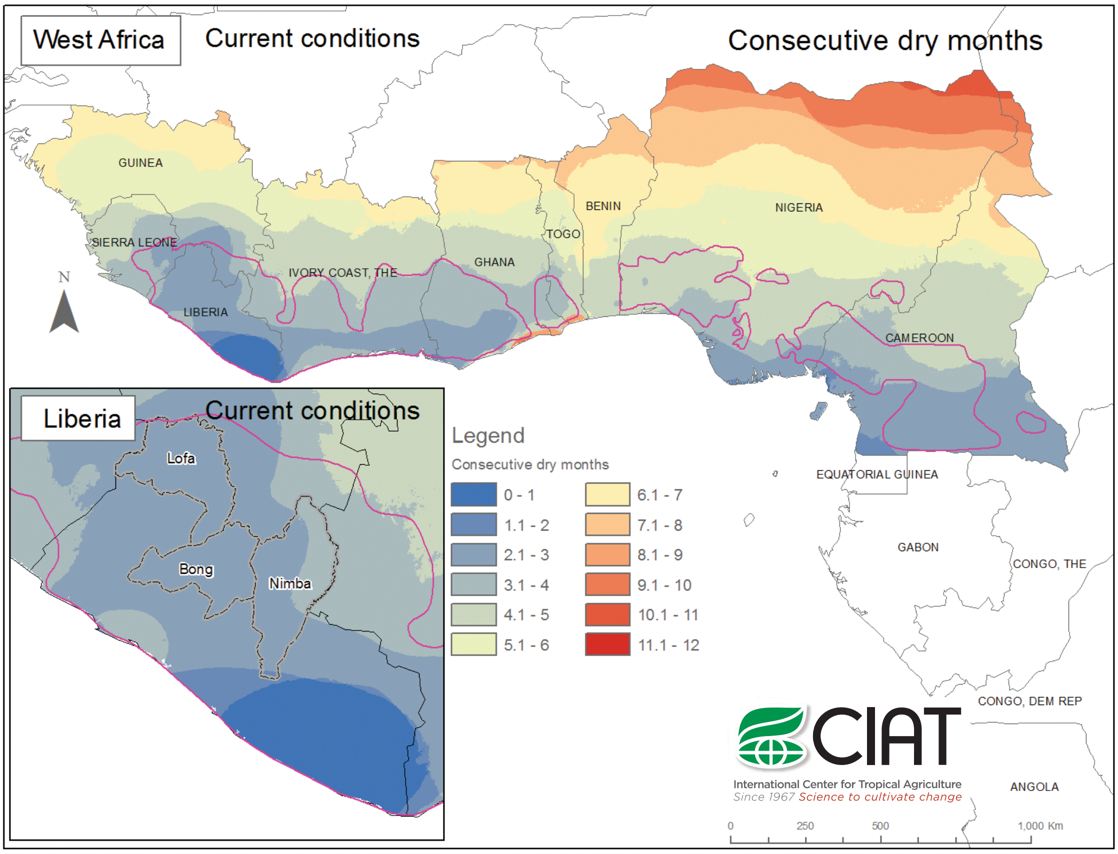

Figure E.2. Number of consecutive months with <100 mm rainfall in Liberia and the West African cocoa belt for current climate conditions.

Note: The red lines delimit current cocoa-producing areas.

For precipitation during the driest quarter (BIO17), Liberia's cocoa belt also falls into the same class as the southern, coastal parts of the cocoa belts of Côte d'Ivoire, Ghana and southern Cameroon, that is, the least drought-prone parts of the West African cocoa belt. Values comparable to the drought-prone northeast of the Ivorian cocoa belt or large parts of the relatively dry cocoa area of western Nigeria do not occur in Liberia.

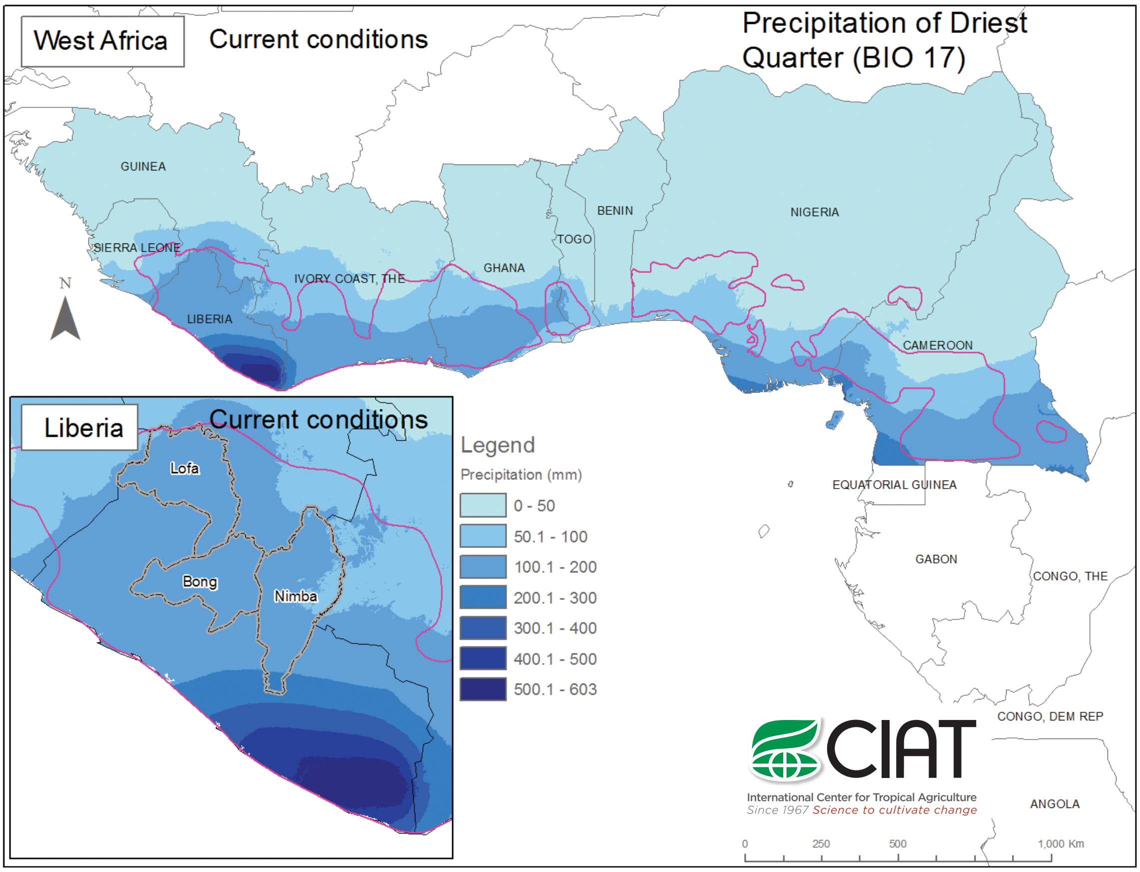

Figure E.3. Precipitation of the driest quarter (BIO17, in mm) in Liberia and the West African cocoa belt for current climate conditions.

Note: The red lines delimit current cocoa-producing areas.

> *Under current climate conditions, dry season rainfall in Bong, Nimba and Lofa Counties is thus comparable to that in large parts of the cocoa belt of West Africa, not including its driest parts. These areas are subject to occasional drought stress especially during particularly dry years. Liberia may also have the option of expanding cocoa production in already deforested areas in the wetter parts of the country, where the dry season is very short or non-existent, although the fungal disease pressure would also be higher, and the problems of drying cocoa would be more challenging.*

However, the potential for water stress during the dry season is not only determined by rainfall conditions (water supply) but also by potential evapotranspiration (ETP, water demand), which in turn is influenced by temperature, radiation, atmospheric humidity and wind speed (Läderach et al. 2013). As indicator of potential drought stress, we use the difference between rainfall and ETP during the dry season which is indicative of the degree to which rainfall in a particular month is able to meet crop water demand. Figure E.4 suggests that ETP is higher in northern Nimba and Lofa Counties than in most other cocoa-producing areas in the region, as indicated by orange colors that elsewhere are typical for the savannah. ETP values in southern Nimba and Bong are lower and more typical of conditions elsewhere in the cocoa belt. The higher water demand in northern Nimba and Lofa compared to other parts of the West African cocoa belt is apparently influenced by the hot and dry conditions in the nearby savannah of Guinea from where dry winds (locally known as *harmattan*) reach northern Liberia during the dry season.

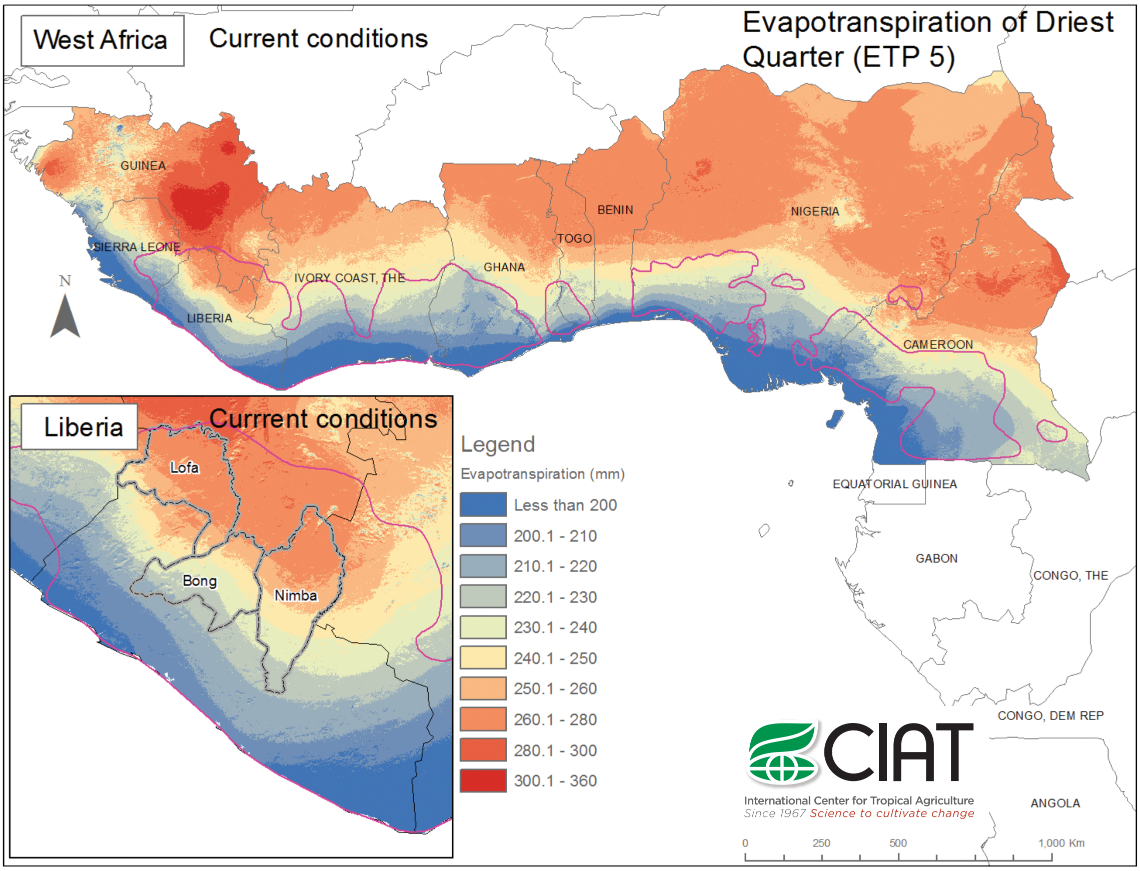

Figure E.4. Potential evapotranspiration during the driest quarter (ETP 5, in mm) in Liberia and the West African cocoa belt for current climate conditions.

Note: The red lines delimit current cocoa-producing areas.

The excess of rainfall over potential evapotranspiration (Figure E.5) reflects this and shows for northern Nimba County values similar to those found in the dry parts of the cocoa belts of Côte d'Ivoire, Ghana and Nigeria, near the forest-savannah transition zone, where the risk of drought stress during the dry season is significant. In southern Nimba, Bong and Lofa, the balance of dry season rainfall and ETP is more favorable. In its southern parts, where little cocoa is now grown, Liberia has the lowest drought risk of all of West Africa according to this indicator.

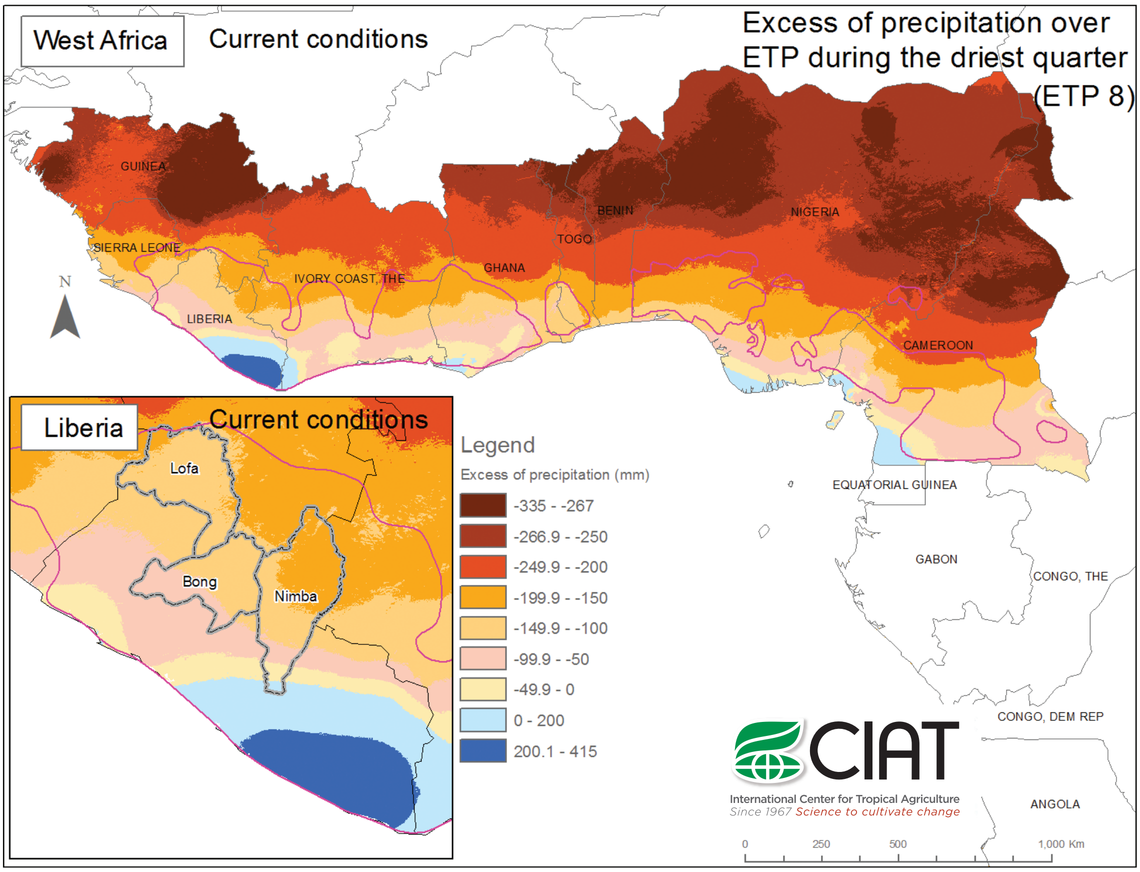

Figure E.5. Excess of precipitation over potential evapotranspiration during the driest quarter (ETP 8, in mm) in Liberia and the West African cocoa belt for current climate conditions.

Note: The red lines delimit current cocoa-producing areas.

In summary, the comparison of potentially critical climate variables in the cocoa belt of Liberia, focusing on Nimba, Lofa and Bong Counties, with the rest of the West African cocoa belt suggests that under current conditions, all of Liberia has a climate suitable for growing cocoa. However, the available climate record suggests unusually (for the cocoa belt) high maximum temperatures in the northern part of Nimba County, apparently influenced by the nearby savannah of Guinea. In combination with the relatively large distance to the sea and prevailing wind directions during the dry season, this results in a relatively unfavorable balance between ETP and precipitation during the driest quarter of the year, and consequently a risk of drought stress that could affect cocoa yields especially during unusually dry years. In this regard, conditions in the area are comparable to those in the northern parts of the cocoa belts of other countries in the region. In southern Nimba, Bong and Lofa Counties, the drought risk is lower than further to the north.

Compared to other cocoa-producing countries in the region, Liberia has the great advantage of significant areas with much wetter conditions in the southern half of the country, to which cocoa (and coffee) might progressively expand on existing farmland, although the risk of causing deforestation directly or indirectly through such a southward expansion of the Liberian cocoa and coffee belt would need to be carefully monitored.

Relative climatic suitability

While the analysis of individual climate variables has the advantage that specific climate risks can be pin-pointed, its disadvantage is that important interactions among climate variables can be missed and that there is no straight-forward way of assigning a weight to one factor (say, maximum temperature) relative to others (say, dry season ETP). Furthermore, complex climate effects, such as changes in pest and disease pressures as a result of various climate factors, might not be captured when looking at individual climate variables only. Therefore, we will now consider an integrated measure of climate suitability of Liberia relative to other cocoa-producing countries in West Africa, using the Maxent algorithm. We create an integrated measure of climatic suitability for Liberia from a set of climatic variables reflecting temperature, rainfall, ETP and dry season length that was derived from data in the WorldClim database.[3] The complete set of variables is listed in Table E.1.

Most of Liberia is classified by the model as suitable for cocoa, which is in line with observation (Figure E.6). Blue colors signal areas of medium to high climatic suitability for cocoa, while yellow colors are typical for forest-savannah transition zones but also occur in patches throughout the cocoa belt, and areas shown in orange are marginal. For Liberia, the mix of blue and yellow colors is about similar to adjacent areas in western Côte d'Ivoire and the Western Region of Ghana, two of the world's largest cocoa-producing regions. However, there are patches where climatic suitability was classified by the model as marginal near the border to Guinea, particularly in Lofa County. In part, this may reflect small-scale spatial heterogeneity in the available climate data, whose quality has declined in West Africa since the 1970s (Agnew and Woodhouse 2011), and partly it reflects the influence of the nearby savannah.

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[3] For calibrating the climate model, 720 points were generated systematically covering the cocoa production areas in West Africa with a 0.3 degree grid, generating 558 evenly spaced sampling points that were used as calibration points. In addition, a random background ("pseudo absence") sample at a 5:1 ratio of background to calibration points was drawn from the area of the countries of the cocoa belt excluding points of known cocoa presence to characterize the general environment. Spatial climate data were obtained from the WorldClim database and augmented by potential evapotranspiration (ETP) and length of dry season as explained previously. The climate model was then refined through various iterations. The model was run with all variables in Table E.1 and those climate variables making the largest contributions to explaining the variability between more or less suitable areas were identified. For each of these variables, an expert judgment was made of whether it was meaningful as a differentiating factor of climatic suitability for cocoa for this specific area, and if this was not the case then the variable was eliminated and the model was re-run until the variables that made the greatest contributions to the model outcome did no longer include any variables that we considered not meaningful in this specific context. This process resulted in the exclusion from the initial model of the variables for ETP of the wettest month (ETP2), ETP of the wettest quarter (ETP4), precipitation of the coldest quarter (BIO 19) and ETP of the coldest quarter (ETP7) on the grounds that in a humid tropical forest area during the wet season (which includes the coldest quarter), water supply is normally abundant, and a difference in rainfall or ETP would not be expected to make a critical difference for the crop.

Table E.1. Climatic variables used in the integrative modeling of relative climate suitability of Liberia compared to the West African cocoa belt.

Bioclimatic	ETP	
BIO1 = Annual Mean Temperature	Cons_mths =	Consecutive dry months
BIO2 = Mean Diurnal Range (Mean of monthly max temp - min temp)	ETP1 =	Annual Evapotranspiration
BIO3 = Isothermality (BIO2/BIO7) (*100)	ETP2 =	Evapotranspiration of Wettest Month
BIO4 = Temperature Seasonality (standard deviation *100)	ETP3 =	Evapotranspiration of Driest Month
BIO5 = Max Temperature of Warmest Month	ETP4 =	Evapotranspiration of Wettest Quarter
BIO6 = Min Temperature of Coldest Month	ETP5 =	Evapotranspiration of Driest Quarter
BIO7 = Temperature Annual Range (BIO5-BIO6)	ETP6 =	Evapotranspiration of Warmest Quarter
BIO8 = Mean Temperature of Wettest Quarter	ETP7 =	Evapotranspiration of Coldest Quarter
BIO9 = Mean Temperature of Driest Quarter	ETP8 =	Excess of precipitation over ETP during the driest quarter (ETP8=BIO17-ETP5)
BIO10 = Mean Temperature of Warmest Quarter		
BIO11 = Mean Temperature of Coldest Quarter		
BIO12 = Annual Precipitation		
BIO13 = Precipitation of Wettest Month		
BIO14 = Precipitation of Driest Month		
BIO15 = Precipitation Seasonality (Coefficient of Variation)		
BIO16 = Precipitation of Wettest Quarter		
BIO17 = Precipitation of Driest Quarter		
BIO18 = Precipitation of Warmest Quarter		
BIO19 = Precipitation of Coldest Quarter		

It is not meaningful to interpret these modeled suitability data at a high spatial resolution but rather to use them as indicator of relatively large-scale spatial trends. These confirm that the northern counties of Liberia are currently suitable for cocoa farming, but that climatic suitability falls off relatively sharply at the northern border.

Climatic suitability of Liberia for cocoa in the 2050s by variable

In this section, we will look at individual climate variables of known importance to cocoa, and compare the climatic situation projected for Liberia for the 2050s[4] with the current situation in other parts of the West African cocoa belt. Our assumption is that if the most important climatic variables in Liberia in the 2050s are projected to be within the climatic range currently found within the cocoa belt of West Africa, then the projected climate of Liberia in the 2050s will still

[4] The climate data for the 2050s are the average of 19 internationally recognized global circulation models (GCMs) from the 2013 Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; www.ipcc-data.org.ch). We used the intermediate emissions scenario RCP 6.0 (Moss et al. 2010; van Vuuren et al. 2011) for the 30-year period 2040 to 2069, centered on 2055 and referred to here as “2050s.” The spatial resolution of the GCM results is too coarse for agricultural applications; therefore, we used data statistically downscaled with the Delta method to produce 1-km resolution surfaces (Ramírez-Villegas and Jarvis 2010), similar to the method used for current climate surfaces.

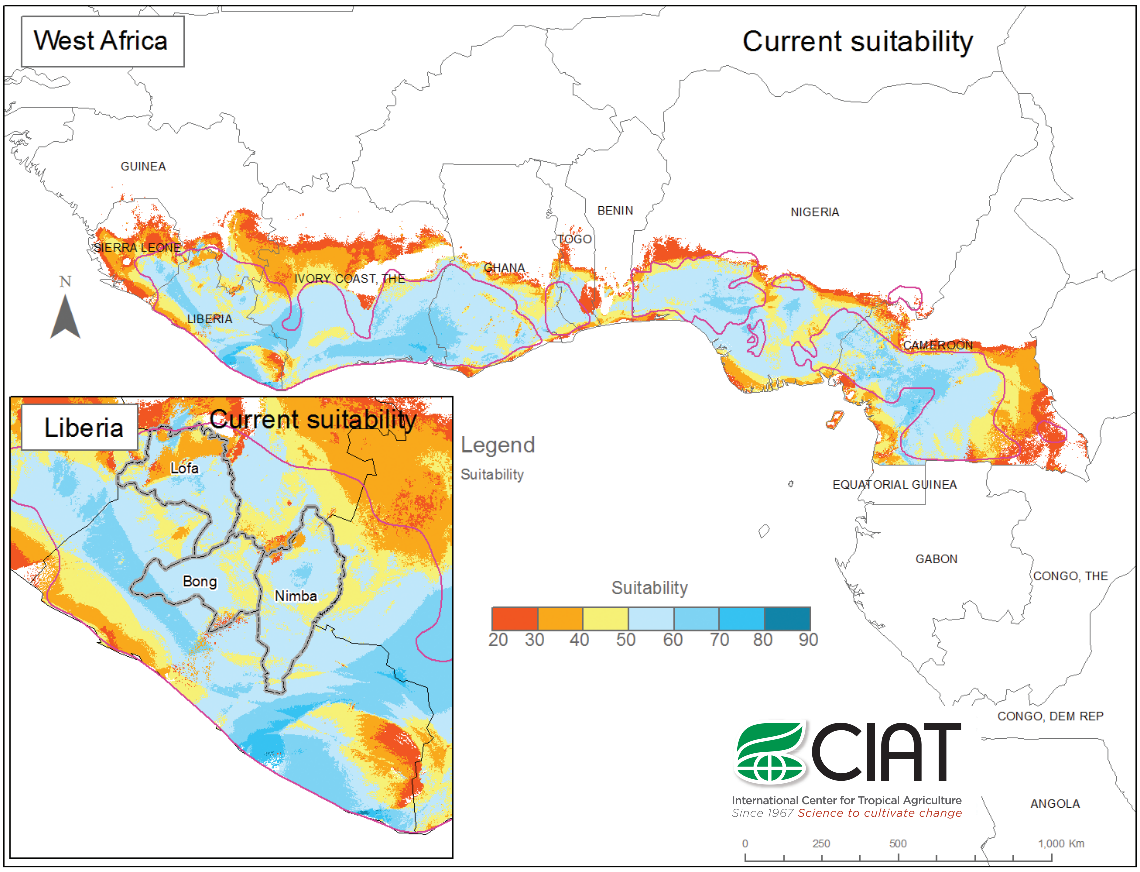

Figure E.6. Relative climatic suitability (percent) for cocoa of Liberia and the West African cocoa belt for current climate conditions.

Note: The red lines delimit current cocoa-producing areas.

be suitable for growing cocoa, just as the climate in the current cocoa belt is suitable for growing cocoa now. On the other hand, should critical climate variables in Liberia in the 2050s lie well outside the range of climates found within the cocoa belt now, then this could indicate a future climatic vulnerability.

We begin again with the maximum temperature during the height of the dry season, which we had identified as a potentially critical factor for cocoa in Part D, although one that could be managed through standard agronomic practices such as the use of shade (Lin 2007). Figure E.7 compares the projected maximum temperatures in Liberia in the 2050s with those of the rest of the cocoa belt of West Africa under current conditions. According to FAO (2007), the ideal temperature range for cocoa is 21–32 °C but temperatures up to 38 °C are tolerated. Currently, such high maximum temperatures occur only in the savannah, outside the cocoa belt. In the 2050s, temperatures in Liberia (as globally) are projected to be warmer than now and in parts of Lofa County and potentially in Nimba County, extreme temperatures in excess of 36 °C are expected to be reached. In the current climate, such high temperatures do not occur in the West

African cocoa belt. These are maximum temperatures in an average year, and it is possible that in particularly hot years, the maximum temperatures might get close to or even exceed the tolerance limit of cocoa.

> *Protecting cocoa from extreme temperatures during the dry season through shade trees will thus be a constant and increasing need in Nimba and Lofa Counties and, to a lesser extent, in Bong County. Growing cocoa without shade, as is now quite common in the western parts of both Côte d'Ivoire and Ghana, is not recommended in northern Liberia because it may result in heat stress for the cocoa trees during the dry season, resulting in leaf loss and a delay in growth, flowering and fruit set at the onset of the rainy season, while the cocoa trees need to build new foliage.*

With increasing proximity to the coast, maximum temperatures are projected to decrease in Liberia's 2050s climate, although temperatures will be higher than they are now. Therefore, as a prophylactic measure, the recommendation of shade use should be extended to the whole country.

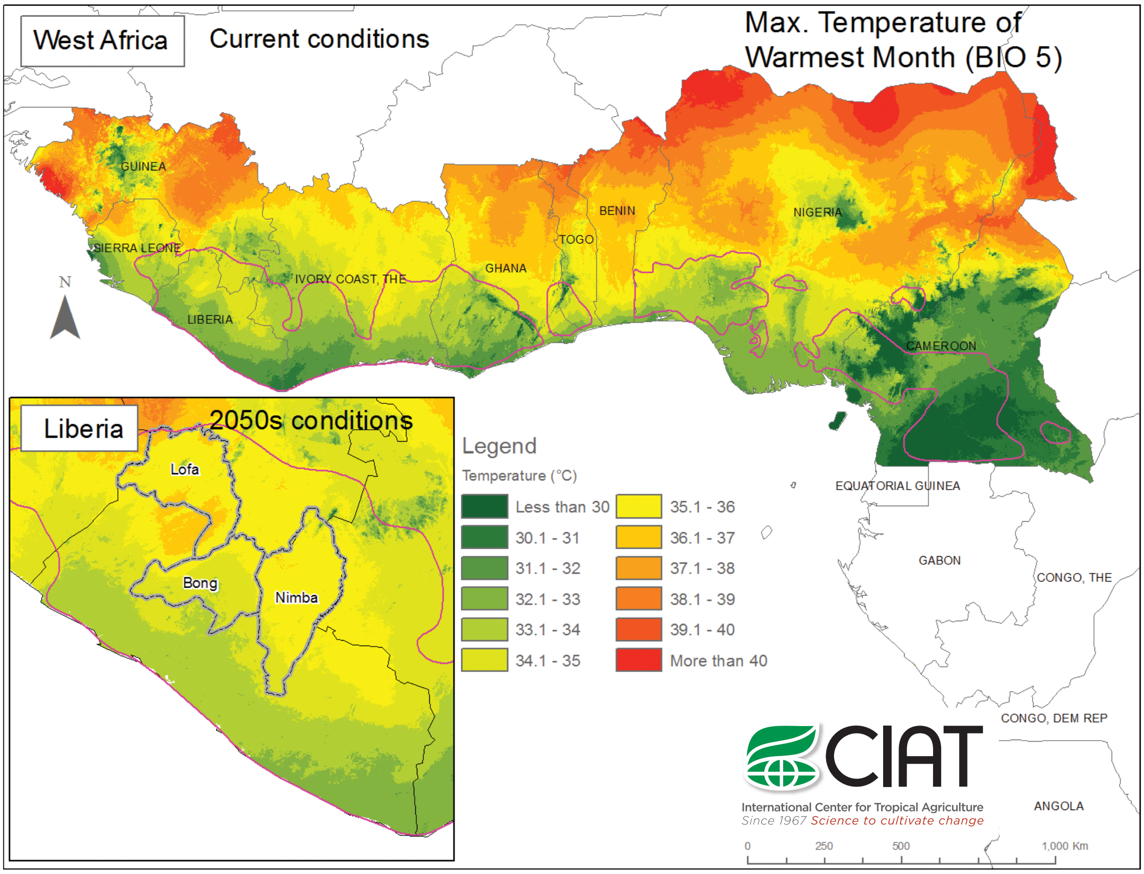

Figure E.7. Comparing maximum temperature of the driest month (BIO 5) for the projected 2050s climate in Liberia with current climatic conditions in the West African cocoa belt.

Note: The red lines delimit current cocoa-producing areas.

Figures E.8 and E.9 compare the projected length of the dry season and rainfall during the driest quarter between Liberia in the 2050s and the current climate of the West African cocoa belt. The length of the dry season is projected to become shorter in West Africa by the 2050s than it is now, as a result of a more even distribution of rainfall during the year with little change in total annual rainfall. By the 2050s, the main cocoa-producing counties of Liberia are projected to have a dry season of 1–2 months, instead of 2–3 months now. Large parts of the West African cocoa belt now have a dry season of >3 months.

By the 2050s, the dry season in most of the Liberian cocoa belt is projected to be shorter than it is almost anywhere in the West African cocoa belt now.

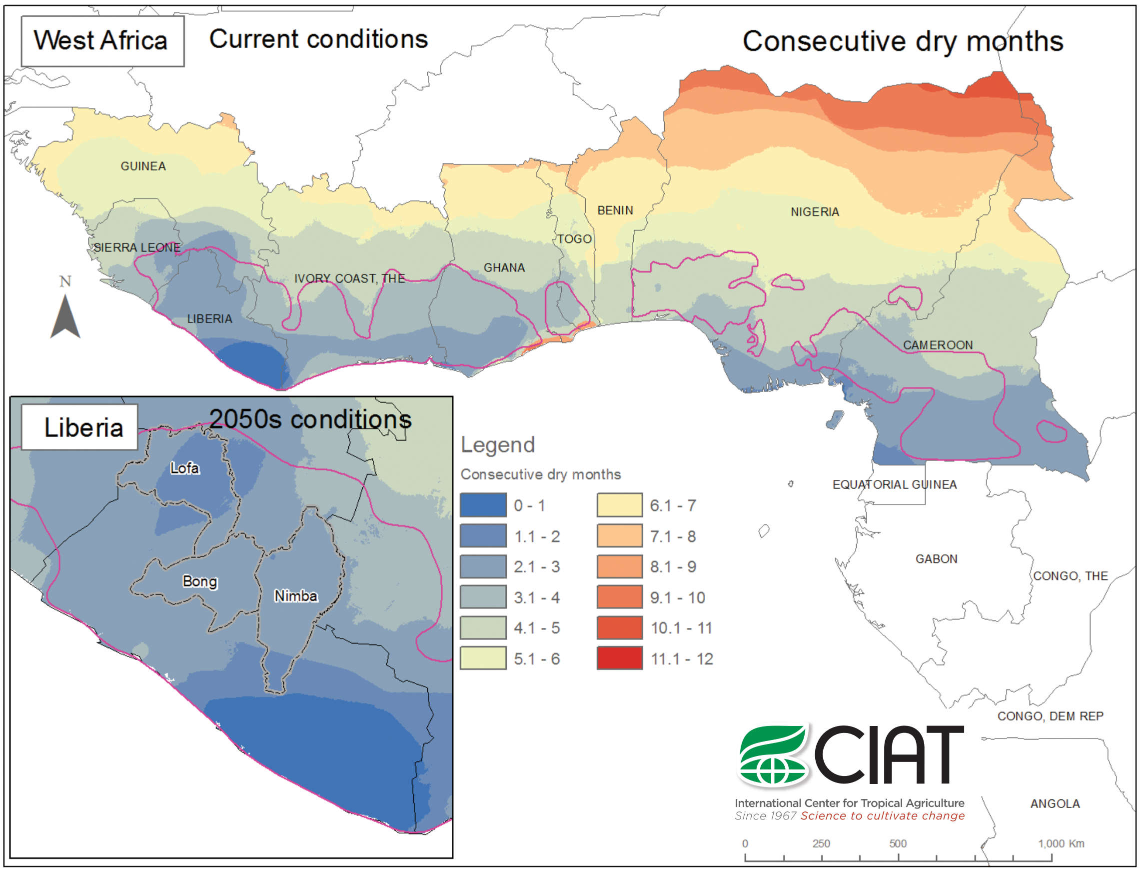

Figure E.8. Comparing length of the dry season measured as number of consecutive months with less than 100 mm rainfall for the projected 2050s climate in Liberia with current conditions in the West African cocoa belt.

Note: The red lines delimit current cocoa-producing areas.

For rainfall during the driest quarter, little change is projected for Liberia between present and 2050s conditions, which are again projected to be comparable to those of the wetter parts of the West African cocoa belt. The conditions in Nimba, Bong and Lofa Counties are projected to be comparable in the 2050s to those in the wetter parts of Côte d'Ivoire and Ghana now.

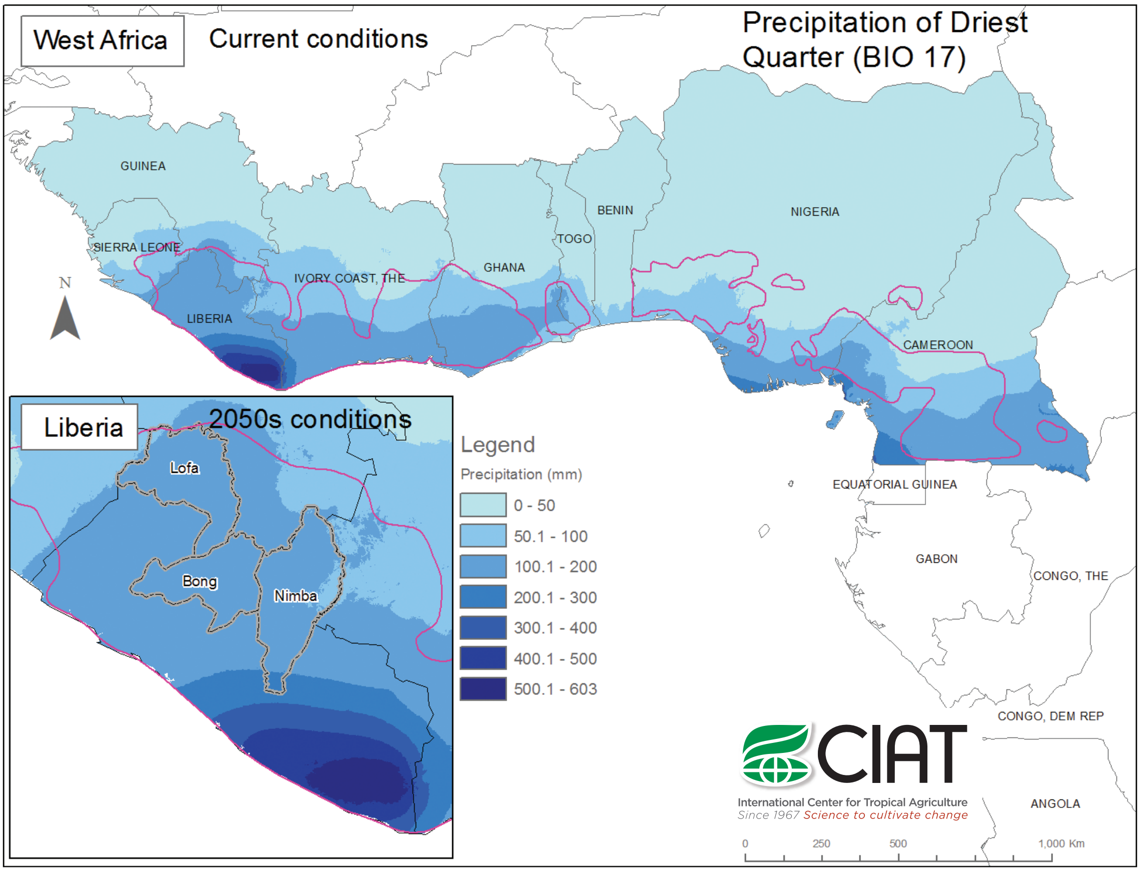

Figure E.9. Comparing precipitation of driest quarter (BIO 17, in mm) for the projected 2050s climate in Liberia with current conditions in the West African cocoa belt.

Note: The red lines delimit current cocoa-producing areas.

However, along with the overall higher temperatures, the water demand of the plants is also projected to increase (Figure E.10). ETP in northern Nimba and most of Lofa Counties in the 2050s are projected to be comparable to values currently found in the savannah climates of northern Ghana and Côte d'Ivoire, but not in current cocoa-growing areas. The influence of the proximity of the savannah of Guinea is again visible. Projected ETP values for the 2050s for southern Nimba and central Bong Counties are comparable to values currently found in the forest-savannah transition zone of West Africa, that is, the driest parts of the current cocoa belt.

To what extent this increased plant water demand in the 2050s can be met by dry season rainfall in Liberia is indicated by the difference between dry season rainfall and ETP shown in Figure E.11. In the 2050s, the driest conditions according to this indicator are projected to be found in northern Nimba and the east and west of Lofa County. The conditions there are projected to be comparable to those currently found in the northern parts of the cocoa belts of Côte d'Ivoire, Ghana and Cameroon and the western cocoa area of Nigeria. In this area, drought stress during the dry season is a distinct possibility, and this needs to be taken into account in

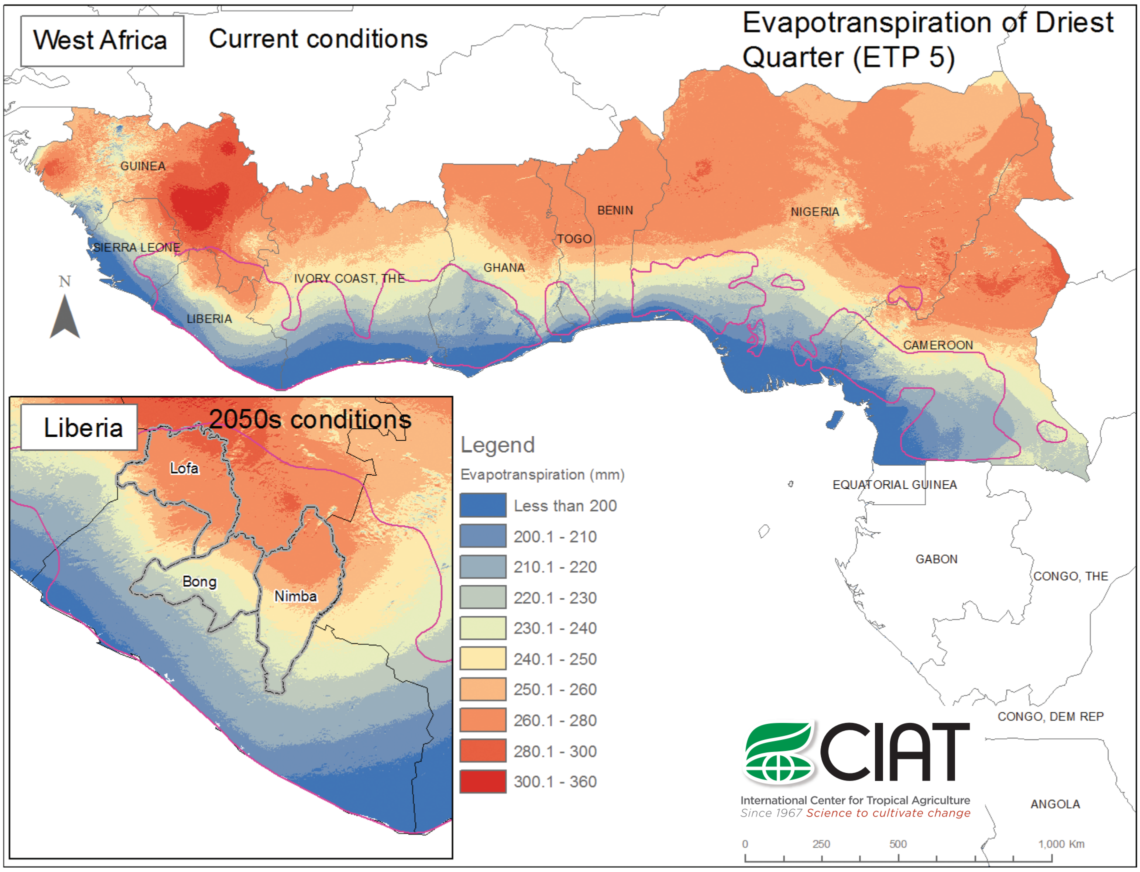

Figure E.10. Comparing evapotranspiration of the driest quarter (ETP 5, in mm) for the projected 2050s climate in Liberia with current conditions in the West African cocoa belt.

Note: The red lines delimit current cocoa-producing areas.

site selection for cocoa growing (deep soils with sufficient water holding capacity and not posing obstacles to taproot development of the cocoa trees), as discussed previously.

> *If these basic rules in site selection are respected, the most drought-prone parts of Liberia should have enough water for growing cocoa in the 2050s, subject to periodic drought stress and yield reductions during dry years, similar to the current situation in the more drought-prone parts of the West African cocoa belt.*

In southern Nimba and Bong Counties, water availability during the dry season in the 2050s is projected to be more favorable than further to the north and comparable to conditions currently found in the central parts of the cocoa belt of Côte d'Ivoire and Ghana. Southern Liberia, currently not a major cocoa-producing area, is projected to still have a more favorable water supply during the dry season in the 2050s than any other part of the West African forest belt has now.

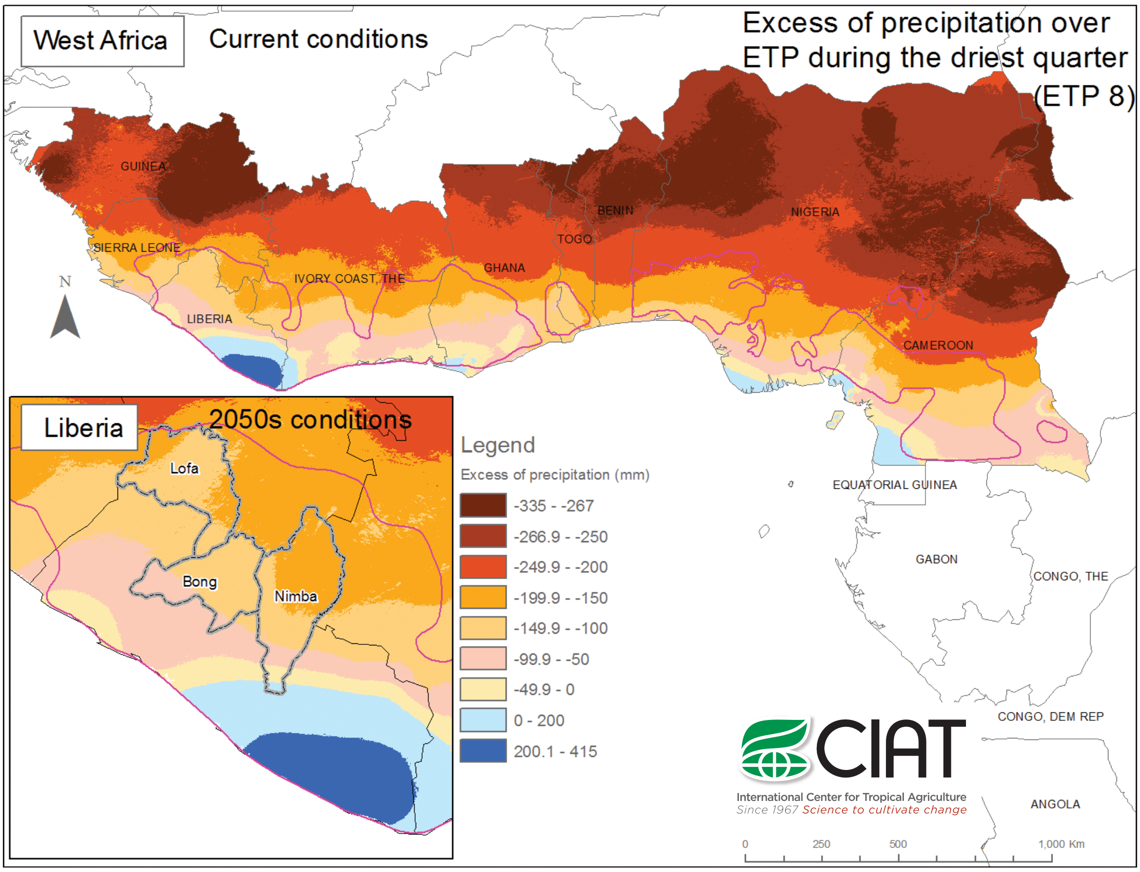

Figure E.11. Comparing the difference between rainfall and evapotranspiration of the driest quarter (ETP 8, in mm) for the projected 2050s climate in Liberia with current conditions in the West African cocoa belt.

Note: The red lines delimit current cocoa-producing areas.

Integrative climate model – 2050s suitability

We now take a final look at the integrative evaluation of relative climatic suitability of Liberia for growing cocoa in the 2050s, using the same model as in Figure E.6, but comparing now projected 2050s climatic conditions in Liberia with conditions found elsewhere in the West African cocoa belt now. In Figure E.12, projected climate conditions for northern Nimba and Lofa Counties for the 2050s appear in colors ranging from yellow to red, indicative of conditions that are in the current climate characteristic for the forest-savannah transition zones (yellow) to conditions that are found now mostly outside the cocoa production zones (orange to red). The small-scale variation in suitability is again substantial, suggesting data variability and should not be over-interpreted.

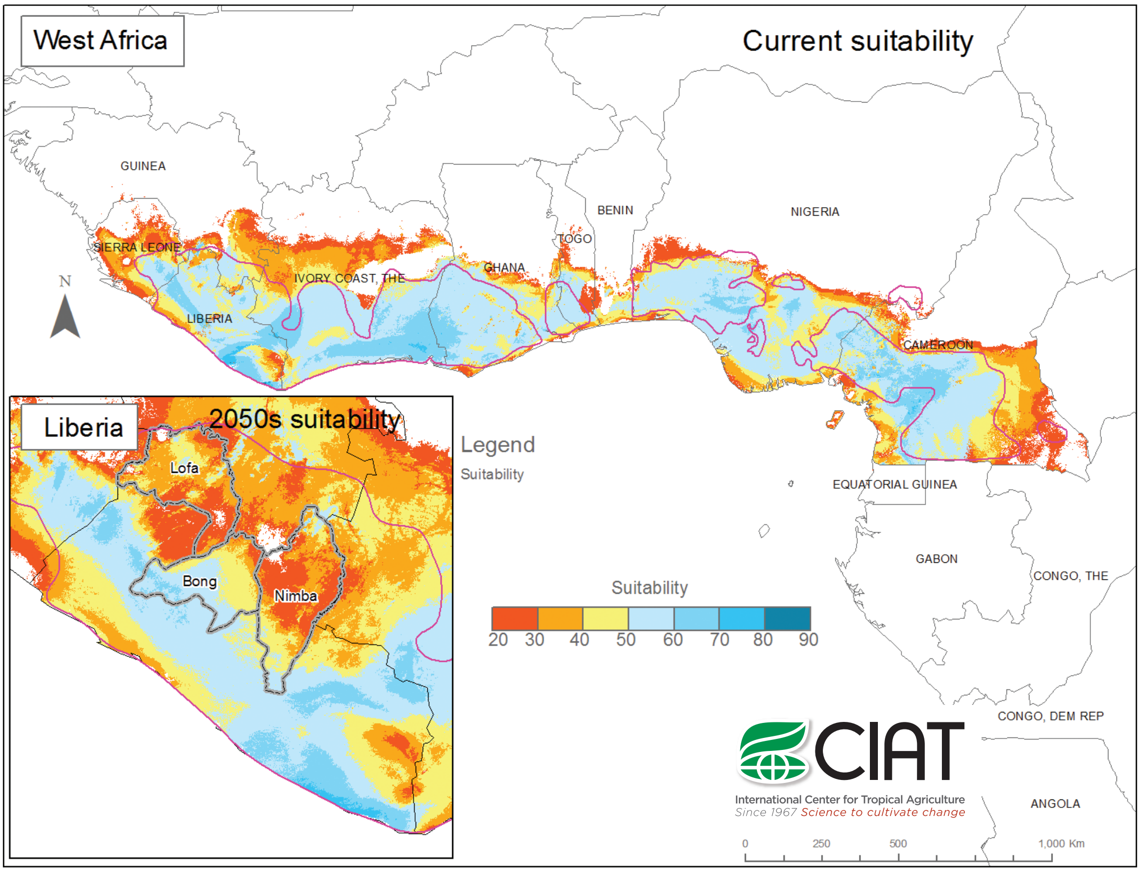

Figure E.12. Comparing climatic suitability (percent) for the projected 2050s climate in Liberia with current conditions in the West African cocoa belt.

Note: The red lines delimit current cocoa-producing areas.

The model thus indicates a pronounced decline in climatic suitability for cocoa in northern Nimba and Lofa Counties, which according to the previous discussion can mostly be ascribed to the increase in maximum temperatures, while hydrological conditions are projected to remain adequate for cocoa farming, though subject to periodic drought. This reinforces once more the need to grow cocoa under shade especially in these northern parts of the Liberian cocoa belt. Low-shade cocoa farming practices that are becoming increasingly common in parts of Côte d'Ivoire and Ghana are not suitable for northern Liberia since they would expose cocoa there to increasing heat stress during the dry season. In southern Bong County and the central part of Liberia, conditions for cocoa farming remain highly favorable, suggesting once more an opportunity to expand the cocoa production zone further southwards from the current main production areas in Nimba, Lofa and Bong Counties through a planned, monitored process that carefully avoids encroachment into forest areas and direct or indirect deforestation through the expansion of the cocoa production area.

Some key climate values

To conclude, we show some key climate values for the three counties of the Liberian cocoa belt (Nimba, Bong and Lofa) for the current climate and projections for the 2030s and the 2050s in comparison to the Western Region of Ghana, the main cocoa-producing region of that country (Table E.2). On average, the Liberian cocoa belt is now a little colder than the Western Region of Ghana. While temperatures are projected to increase everywhere, this is projected to remain the case in the 2030s and the 2050s. By the 2030s, the Liberian cocoa belt is projected to be 0.9 °C warmer than today, and by the 2050s it is projected to be 1.4 °C warmer than today. This average temperature increase will not be ecologically or agronomically very significant since these higher temperatures are tolerated by the cocoa tree, as indicated by the higher current temperatures in Ghana (and even higher temperatures in some other cocoa-growing areas such as Malaysia [Wood and Lass 2001]).

Agro-ecologically more significant than the increase in average temperature is that maximum temperatures reached during the dry season in Liberia are higher than in the Western Region of Ghana, apparently due to the proximity of the hot and dry savannah of Guinea. This is projected to remain the case, with highest temperatures reached in the 2030s and the 2050s in Lofa and the north of Nimba County where shade use will be particularly important.

Average annual precipitation is now higher in the Liberian cocoa belt than in the Western Region of Ghana. Current climate predictions show on average a slight increase by the 2050s, but this change is not very significant and subject to error. More important is precipitation during the driest quarter, which is currently lower in the Liberian cocoa belt than in the Western Region of Ghana, and this is expected to still be the case in the 2050s.

Because of the lower precipitation during the dry season and the higher dry season temperatures, the difference between precipitation and ETP during the driest quarter is more negative in the Liberian cocoa belt than in the Western Region of Ghana, with the most negative values in northern Nimba followed by Lofa County. This situation is projected to change little by the 2030s and the 2050s. Besides managing high dry season temperatures through shade, managing the risk of dry season drought stress through site selection, avoiding sandy and shallow soils, thus is and will remain key to successful cocoa growing in the Liberian cocoa belt.

Table E.2. Some key climate values for Nimba, Bong and Lofa Counties, Liberia, in comparison to the Western Region of Ghana for the present and projected 2030s and 2050s climates.

County or region	Annual mean temperature (°C)	Maximum temperature of warmest month (°C)	Annual precipitation (mm)	Precipitation of driest quarter (mm)	Precipitation minus ETP of driest quarter (mm)
PRESENT					
Bong	25.6	33.4	2188	128	-108
Lofa	25.0	34.3	2490	127	-137
Nimba (all)	25.7	34.2	2078	123	-123
Nimba (north)	24.9	34.3	2107	109	-158
Western Region of Ghana	26.3	32.5	1619	150	-52
2030s					
Bong	26.6	34.1	2243	129	-111
Lofa	26.2	35.3	2536	125	-146
Nimba (all)	26.2	34.4	2140	125	-125
Nimba (north)	26.4	34.8	2060	108	-150
Western Region of Ghana	27.6	34.0	1614	144	-65
Projected change[a]	+0.9	+0.6	+54	0	-5
2050s					
Bong	27.0	34.6	2262	127	-112
Lofa	26.7	35.9	2546	122	-148
Nimba (all)	26.7	34.9	2171	124	-128
Nimba (north)	26.9	35.4	2095	107	-153
Western Region of Ghana	28.0	34.3	1637	144	-65
Projected change[a]	+1.4	+1.2	+74	-1	-7

[a] In Nimba, Bong and Lofa Counties, compared to current climate.

Note: The 2030s and 2050s values are averages of 15 and 19 Global Circulation Models, respectively.

Summary for cocoa

Liberia, including its Nimba, Bong and Lofa Counties, has a suitable climate for growing cocoa, as indicated by comparison of the climatic conditions of the country with other parts of the West African cocoa belt through an integrative climate model and the analysis of individual climate variables considered the most critical for cocoa in this region. These are specifically the maximum temperatures during the dry season and the length and intensity of the dry season. Due to the proximity of the hot savannah of Guinea, the northern part of Nimba and Lofa are relatively hot during this part of the year, although the maximum temperatures reached are within the range found in other parts of the West African cocoa belt. Maximum temperatures are projected to further increase through global climate change. Protecting cocoa from excessive heat during the dry season through shade trees will thus be a constant and increasing need in Nimba and Lofa Counties and, to a lesser extent, in Bong County. Growing cocoa without shade, as is now common in the western parts of both Côte d'Ivoire and Ghana, is not recommended in the northern parts of Liberia because it may result in increasing heat stress for the cocoa trees during the dry season, resulting in leaf loss and a delay in growth, flowering and fruit set at the onset of the rainy season, while the cocoa trees need to rebuild their foliage. As a prophylactic measure, shade use in cocoa is also recommended further to the south where maximum temperatures are and will remain lower.

Rainfall conditions are relatively favorable in the Liberian cocoa counties, comparable to those found in the southern parts of the cocoa belts of Côte d'Ivoire and Ghana. Moreover, current climate models project on average a decrease in the length of the dry season through a more even distribution of rainfall throughout the year. However, plant water demand is also projected to increase as a result of the increasing temperatures. By the 2050s, the driest conditions are projected to be found in northern Nimba and the east and west of Lofa Counties, where water availability is projected to be comparable to conditions currently found in the drought-prone northern parts of the cocoa belts of Côte d'Ivoire and Ghana and the western cocoa area of Nigeria. To reduce the risk of drought stress, especially during particularly dry years, the selection of suitable sites with deep soils with sufficient water holding capacity and not posing obstacles to taproot development of the cocoa trees is important. If these rules in site selection are respected, the most drought-prone parts of Liberia will remain suitable for growing cocoa in the 2050s, subject to periodic drought stress and yield reductions during dry years, similar to the situation in the more drought-prone parts of the current West African cocoa belt.

What distinguishes Liberia from some other cocoa-producing countries in West Africa is the possibility of a controlled expansion of cocoa production further to the South, where maximum temperatures are lower and rainfall is higher than in the current cocoa counties. Here, the risk of heat stress and drought during particularly hot and dry years would be lower than elsewhere in West Africa, although fungal disease pressure would also be higher and the problems of drying cocoa would be more challenging.

3. Robusta coffee

Comparing climate variables among African Robusta coffee origins

Following a similar general methodology as for cocoa, we will now compare the present and projected 2050s climate[5] in Liberia with the present climate in other Robusta coffee origins across the African continent. Robusta coffee, which is native to Africa, is grown over much larger areas on the continent than is the case for cocoa. In addition to West Africa, where Robusta is often grown in association with cocoa but tends to expand into drier climates, Robusta is also present over large areas in the Congo basin and south into Angola. In East Africa, Uganda is a major producer of Robusta (whereas other East African countries are important Arabica producers). Furthermore, Robusta is grown in the wetter eastern parts of Madagascar and in northern Mozambique (Figure E.13).[6]

Maximum temperatures vary considerably over this huge area (Figure E.13). The highest temperatures are reached in Robusta-growing areas in West Africa on the boundary to the savannah, especially in Nigeria, with values in the mid and exceptionally in the upper 30s. Maximum temperatures in Cameroon, the Congo basin, Uganda and Madagascar are much lower. In the current climate of Liberia, maximum temperatures in northern Nimba and Lofa Counties do not exceed 35 °C. This is warmer than temperatures found in adjacent areas of Côte d'Ivoire, reflecting again the apparent influence of the hot savannah of Guinea, but lower than maximum temperatures reached elsewhere in West Africa. In Bong and southern Nimba, maximum temperatures are below 34 °C. In the projected 2030s climate, maximum temperatures are projected to increase to about 36 °C and to increase further by the 2050s to reach 35 to 36 °C in Bong and southern Nimba and 36 to 37 °C in northern Nimba and Lofa Counties (Figure E.13). These temperatures are at the limit of what is experienced currently anywhere in the Robusta producing areas of West Africa, especially at the forest-savannah transition in Nigeria. According to FAO (2007), Robusta coffee tolerates maximum temperatures up to 36 °C, and this limit is in line with its current distribution.

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5 For coffee, 2050s climate projections are based on a selection of five Global Circulation Models from the IPCC's Fifth Assessment Report (2013), representative of the range of GCM projections.

6 For the delimitation of Robusta coffee-growing areas in Africa and Madagascar, we use again the respective maps in the Atlas on Regional Integration in West Africa (ECOWAS 2007).

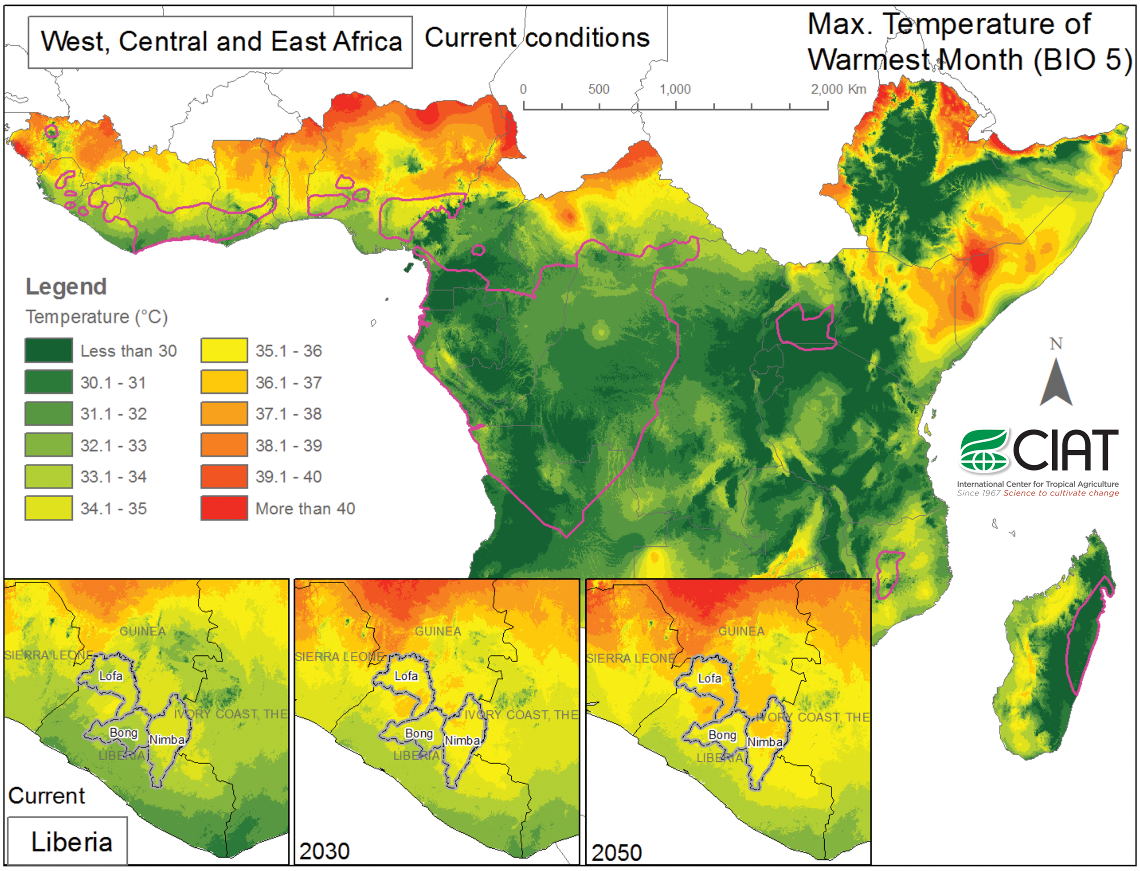

Figure E.13. Comparing maximum temperatures (BIO 5) for Liberia's current and projected 2030s and 2050s climate with current climatic conditions in other Robusta origins of Africa and Madagascar, indicated by the red lines.

> *This suggests that by the 2050s, maximum temperatures during the dry season could become a limiting factor for Robusta coffee production in Lofa and northern Nimba Counties, as well as in the neighboring Guinée Forestière. This trend is projected to be already visible by the 2030s. Bong and southern Nimba will remain slightly cooler. Shading is urgently recommended to make maximum temperatures tolerable for coffee, especially in northern Nimba and Lofa Counties, but also as a preventive measure in southern Nimba and Bong.*

The length of the dry season, measured as number of consecutive months with <100 mm rainfall, also varies considerably across the Robusta production areas in Africa, with 4–5 months in the northernmost growing areas in Nigeria to less than 1 month in the heart of the Congo basin (Figure E.14). Even drier areas shown to produce Robusta on the map might rely on irrigation or specific microsites where the coffee trees have access to groundwater. Liberia occupies a middle position on this range with 2–3 dry months in most of Bong, Lofa and Nimba Counties, comparable to southern Côte d'Ivoire and the Western Region of Ghana. Northern

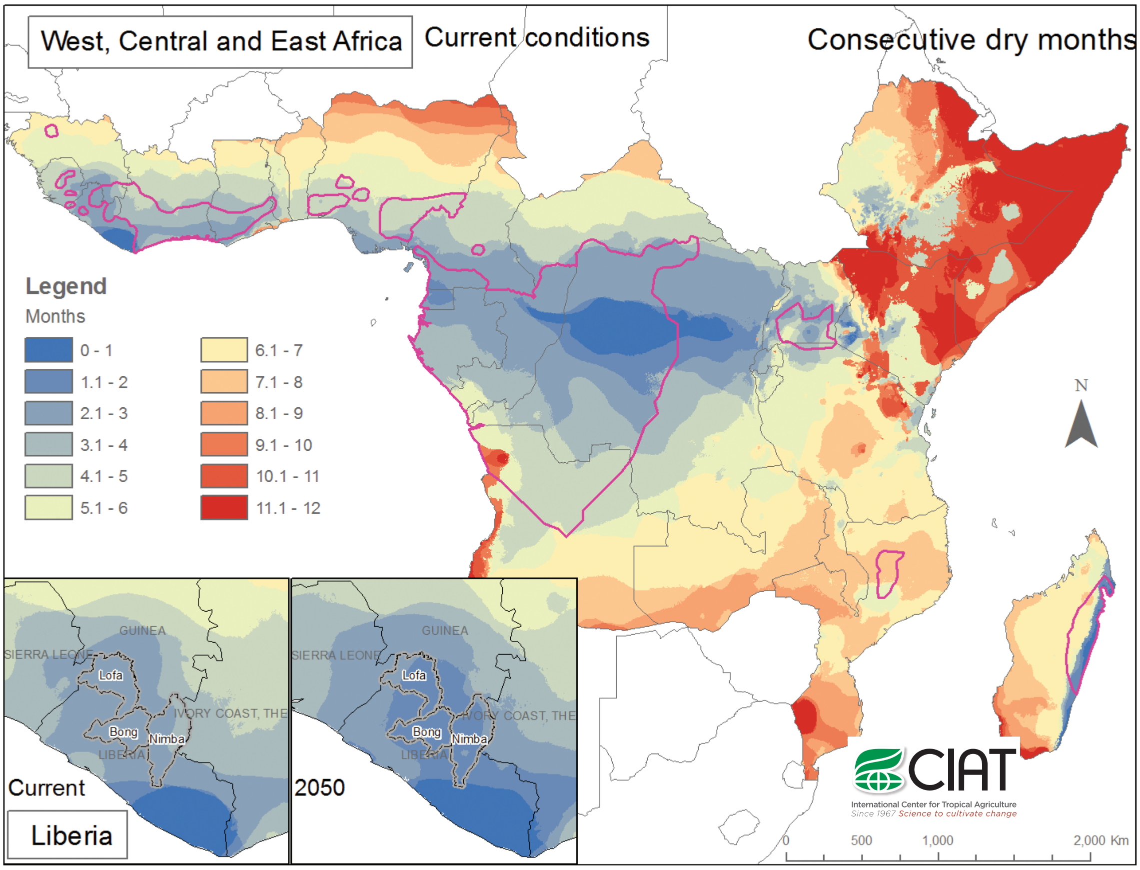

Figure E.14. Comparing length of the dry season (number of consecutive months with <100 mm rainfall) for Liberia's current and projected 2050s climate with current climatic conditions in other Robusta origins of Africa and Madagascar, indicated by the red lines.

Nimba has 3–4 dry months, similar to adjacent Robusta-producing areas in Côte d'Ivoire and *Guinée Forestière*. By the 2050s, the dry season is projected to be overall about one month shorter, that is 2–3 months in northern Nimba near the border to Côte d'Ivoire and Lofa near the borders to Guinea and Sierra Leone, and 1–2 months in the remainder of the Liberian coffee belt, as previously discussed for cocoa.

The relatively short dry season in Liberia compared to other Robusta origins in West Africa and its projected further shortening by the 2050s is also confirmed by the values for rainfall during the driest quarter of the year (Figure E.15). Currently, almost all of the Liberian cocoa and coffee belt receives 100–150 mm of rainfall during the driest quarter, comparable to values in much of southern Côte d'Ivoire and Ghana without their respective wettest southwestern parts. In comparison, the northernmost coffee-producing areas in Côte d'Ivoire, almost the entire coffee-producing area of Nigeria and large Robusta-producing areas in the southern Congo basin receive less than 100 mm during the driest quarter. By the 2050s, rainfall during the driest quarter is projected to increase slightly, so that then all of the Liberian coffee belt is projected to

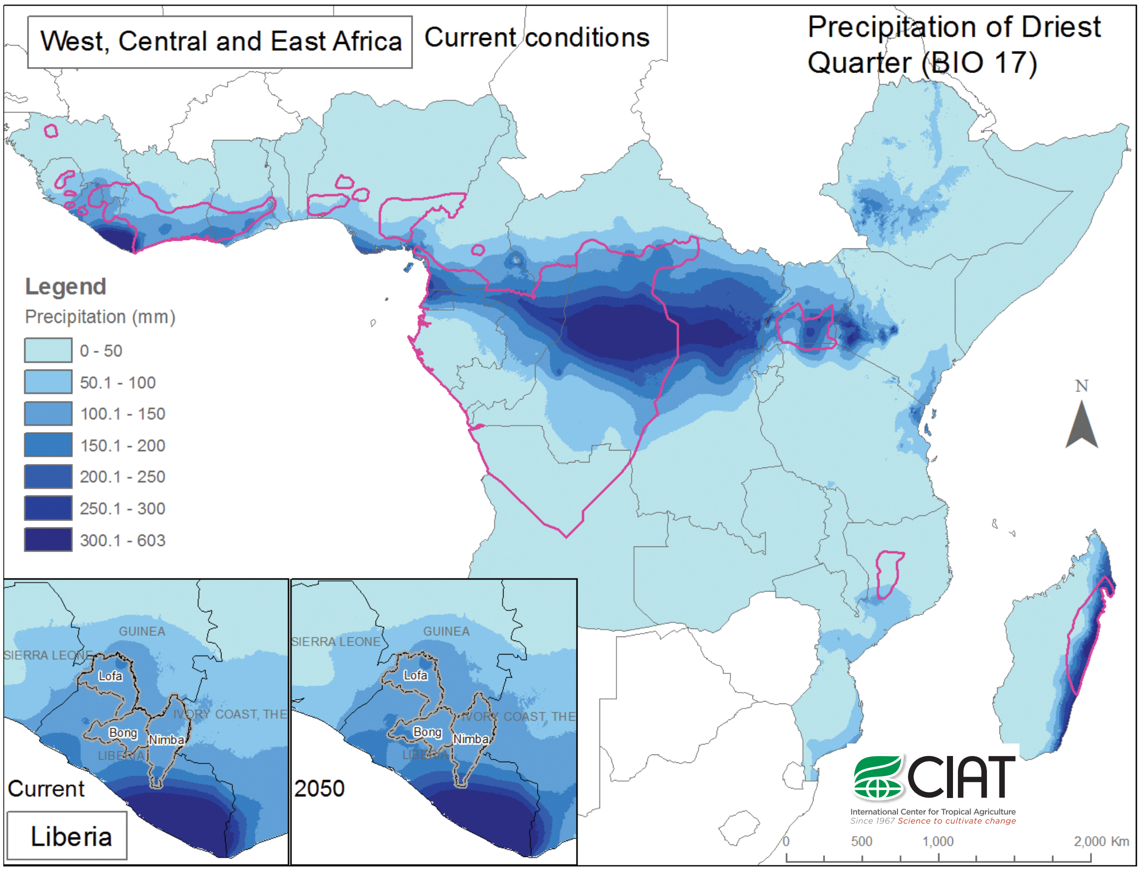

Figure E.15. Comparing rainfall during the driest quarter (BIO 17, in mm) for Liberia's current and projected 2050s climate with current climatic conditions in other Robusta origins of Africa and Madagascar, indicated by the red lines.

fall into the 100–150 mm bracket, with higher dry season rainfall in the southernmost parts of Bong and Nimba Counties.

The slightly increased rainfall during the dry season and overall reduced length of the dry season are expected to be partly compensated by an increase in ETP as a result of the projected temperature increase by the 2050s. Still, the balance between rainfall and ETP during the driest quarter (indicative of the water balance during the dry season) is projected to become slightly more favorable between now and the 2050s (Figure E.16). For Lofa, Bong and southern Nimba, this indicator shows values for the current climate comparable to those in the central cocoa and coffee belts of Côte d'Ivoire and Ghana, without their wettest coastal parts. In northern Nimba, this indicator of dry season water balance is comparable to the driest, northern coffee-producing areas in Côte d'Ivoire, while some coffee-producing areas in Nigeria are significantly drier. By the 2050s, this indicator of dry season water balance is projected to become only slightly more favorable.

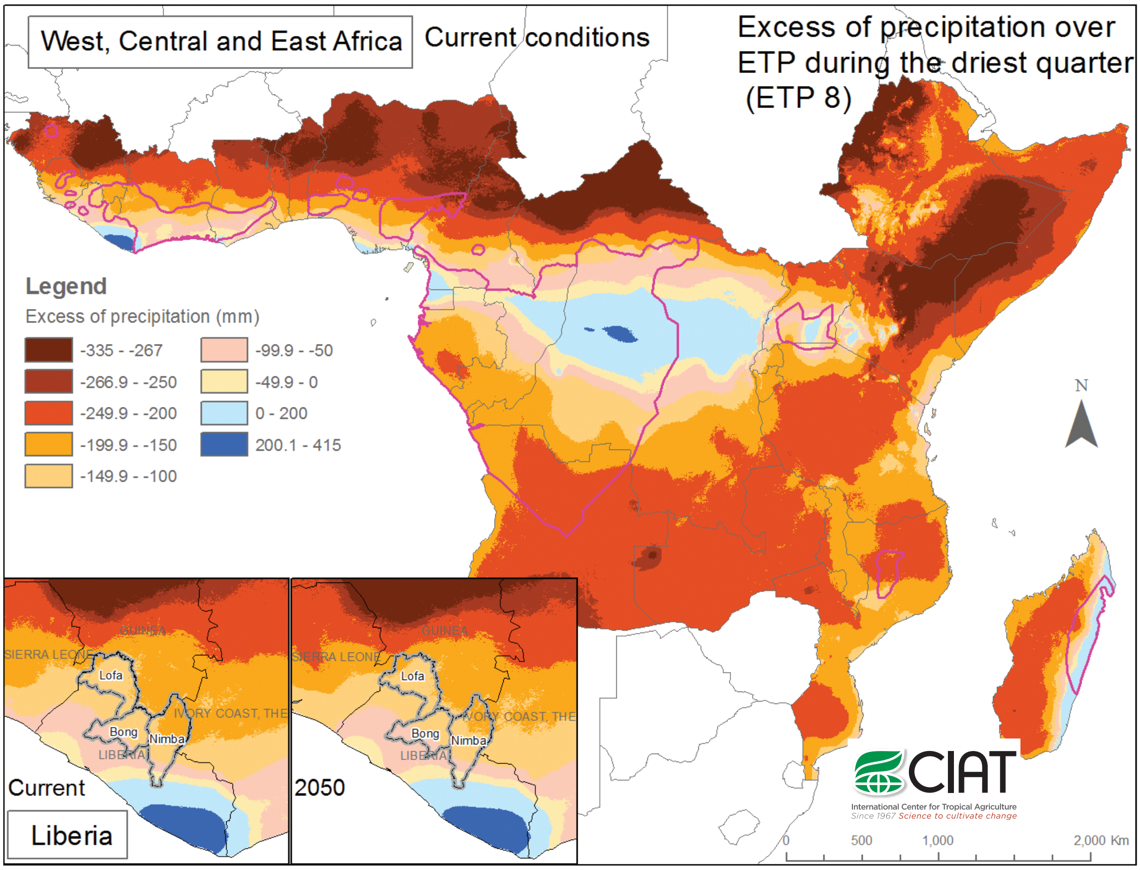

Figure E.16. Comparing the difference between rainfall and ETP during the driest quarter (ETP 8, in mm) for Liberia's current and projected 2050s climate with current climatic conditions in other Robusta origins of Africa and Madagascar, indicated by the red lines.

These results suggest that northern Nimba is and will remain subject to seasonal drought, especially during dry years, similar to what is currently experienced by coffee farms in the driest coffee-producing areas in Côte d'Ivoire, and this is projected to remain the case in the warmer future climate. Significantly drier conditions are tolerated by coffee in Nigeria, suggesting that the climate will overall remain suitable for Robusta coffee production even in the drier parts of the Liberian cocoa and coffee belt. This is not surprising, since we have already reached the same conclusion for cocoa which is more drought sensitive than Robusta coffee. In Lofa, Bong and southern Nimba Counties, the dry season water balance is projected to remain about similar to what is currently found in large parts of the cocoa and coffee belts of Côte d'Ivoire and Ghana.

Integrative climate suitability for Robusta now, in the 2030s and 2050s

The Maxent climate model was adjusted to the Robusta coffee distribution in West Africa in the same way as we did for cocoa. The Congo basin and other parts of Africa and Madagascar producing Robusta coffee where not included in the calibration of the model, because tests with different variations of the model showed that inclusion of the vast Congo basin with its cooler and, for a large part, less seasonal rainfall compared to the West African forest belt tended to downgrade the climatic suitability of the hotter and drier parts of West Africa including the cocoa and coffee belt of Liberia. In part, this reflects the fact that for different parts of Africa where Robusta coffee is grown, different varieties of the crop are more suitable, with varieties from the Congo basin being more adapted to climates with a short rainy season and higher fungal disease pressure and varieties from West Africa being more appropriate for climates with a more pronounced dry season and lower disease pressure (Montagnon and Leroy 1993). Our decision to calibrate the crop suitability model only on the Robusta-growing areas in West Africa implies a focus on the more drought-prone climates of West Africa as the basis of comparison for the current and future Liberian climates. We included all of Liberia in the calibration of the model in line with the recent production of at least small quantities of Robusta coffee in essentially all parts of the country (CAAS 2007).[7]

The model correctly shows a large belt of suitable climates for Robusta coffee along the Guinea coast of West Africa from Sierra Leone and Guinea to Cameroon, interrupted by the Dahomey gap as we have previously seen for cocoa (Figure E.17). The polygons where Robusta coffee is currently grown are correctly shown as suitable, with the exception of some outlying areas with a different climate that are not captured by the climate model. Similarly, almost all of Liberia is shown as suitable; only some coastal areas are shown as areas of low climatic suitability, reflecting the extremely high annual rainfall levels there (3–4000 mm) that are not typical for Robusta-growing areas in West Africa. Beyond the northern limits of the Robusta-growing areas in West Africa, modeled suitability levels fall off sharply, reflecting the transition into the drier and hotter savannah climate.

[7] We used the same iterative procedure for optimizing the model, starting with the complete set of climate variables in Table E.1 and progressively eliminated variables that had a strong influence on the model result but did not seem to be meaningful from an eco-physiological and agronomic point of view for determining climatic suitability for Robusta in this specific environment. For the final model, the variables ETP of the wettest month (ETP2), ETP of the wettest quarter (ETP4) and precipitation of the wettest month (BIO 13) were eliminated because all of these refer to the water cycle during the rainy season when water should not be a limiting factor for the crop.

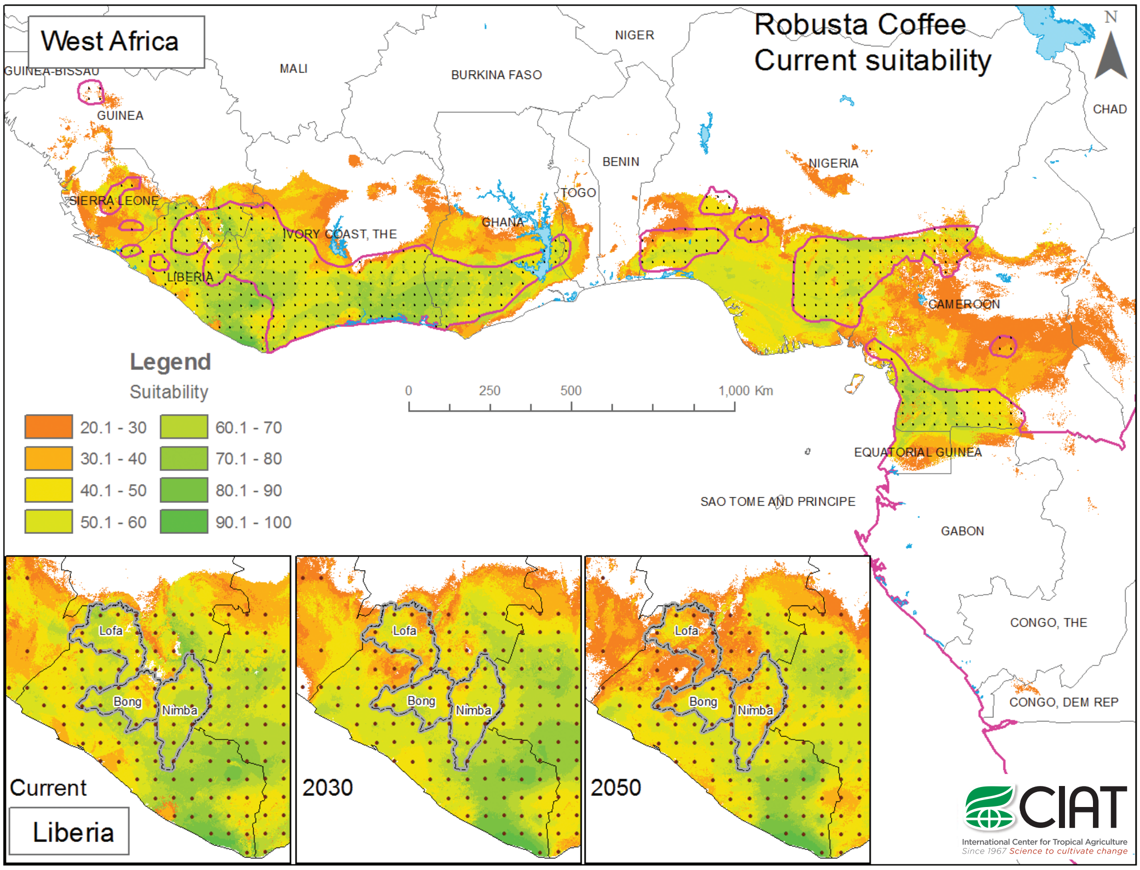

Figure E.17. Comparing the integrative climatic suitability as modeled with Maxent for Liberia and other Robusta origins of West Africa, indicated by the red lines, for current and projected 2030s and 2050s climates.

Note: The dots show the area used as presence locations for the model calibration.

For the current climate, the model shows medium to high suitability levels for Nimba, Bong and Lofa Counties in the Liberian cocoa and coffee belt, and also for adjacent counties in Liberia and neighboring areas in Côte d'Ivoire (Figure E.17). For the projected 2030s and 2050s climates, modeled levels of climatic suitability for Nimba County decrease as a result of the increasing temperatures, but remain within the range of suitabilities found now in coffee-producing areas of Côte d'Ivoire and Ghana, and especially further to the East in Nigeria and Cameroon. For Bong County, projected changes in climatic suitability are minor. For Lofa County and adjacent areas in Guinea, climatic suitability is projected by the model to decrease somewhat by the 2030s but then significantly by the 2050s, for which the increase in maximum temperatures is again the obvious driver. According to the model, some areas in Lofa and *Guinée Forestière* would effectively become unsuitable for Robusta coffee by the 2050s, though not by the 2030s. Maximum temperatures can be reduced by shade trees in the coffee farms, as discussed previously; therefore, this projection should not be seen as an absolute limit to the production of coffee in these areas beyond the 2030s, but rather as an indication of the urgency to grow coffee under shade lest high maximum temperatures may become a limiting factor for coffee. The area in Gbapolu County modeled to become unsuitable for Robusta coffee by the 2050s reflects once more a presumably erroneous high temperature record of one climate station. The higher rainfall areas in southern Liberia are projected to remain highly suitable for Robusta coffee throughout the period considered. Overall, the model thus confirms the declining climatic suitability of the northern part of Liberia, especially Lofa and northern Nimba Counties, caused by the increasingly high maximum temperatures that are projected to approach the limit of physiological tolerance of the crop.

Summary for Robusta coffee

Differently from cocoa, Robusta coffee is a relatively “robust” crop also with regard to its climatic requirements, and this is partly reflected by the huge geographic and climatic range over which it is grown in Africa. Currently, all of Nimba, Bong and Lofa Counties have a suitable climate for Robusta, and this is projected to remain the case through the 2030s. Northern Nimba is, however, subject to seasonal drought, similar to the drier parts of the coffee belt of West Africa. By the 2050s, maximum temperatures during the dry season in northern Nimba and Lofa Counties are projected to be higher than in almost all parts of Robusta’s current climatic range in Africa and close to or even above those reported in the literature as the limit of tolerance of the crop (FAO 2007). This is reflected in the modeled decrease in climatic suitability of Nimba and especially Lofa Counties. Some parts of Lofa are projected by our model to become unsuitable (too hot) for Robusta coffee between the 2030s and the 2050s. To prevent maximum temperatures from becoming a limiting factor for Robusta coffee in Lofa and northern Nimba, the use of shade in Robusta farms is required. This applies equally for a shorter time horizon (2030s), considering that the adjustment and optimization of shade practices across a country takes time, especially if shade trees have been removed and need to be reestablished. Fortunately, most coffee farmers in Nimba and Lofa Counties already use shade (CAAS 2007). While southern Nimba and Bong Counties are projected to remain a little cooler than northern Nimba and Lofa, shade is also recommended here as a prophylactic measure to reduce the vulnerability of coffee farms and as a means of income diversification.

Differently from temperature, water availability is projected to change relatively little over the period considered and to remain broadly adequate for Robusta coffee throughout the three coffee counties of Liberia and the remainder of the country. By the 2050s, the dry season is projected to be shorter in the Liberian cocoa and coffee belt than it is now, comparable to the situation in southern Côte d’Ivoire and the Western Region of Ghana. However, temperature and water demand are also projected to increase, and this will partly compensate for the shortening of the dry season. The differences between rainfall and ETP during the driest quarter, our indicator of water availability during the dry season, in northern Nimba and Lofa Counties are projected to be comparable to those experienced today in the northern (drier) parts of the coffee belt of Côte d'Ivoire. Even drier conditions are tolerated by Robusta coffee in some parts of Nigeria, suggesting that from a hydrological point of view, the conditions in Liberia will remain suitable for the crop. However, drought stress will be a possibility especially in particularly dry years, as it is now. Site selection for coffee should therefore always take local conditions into account, avoiding soils with low water holding capacity and posing restrictions to the root development of the coffee plants. This is similar to the recommendations for cocoa.

4. Arabica coffee

Differently from Robusta coffee, Arabica coffee is a crop that evolved in a mountain environment (Ethiopia) and is adapted to cool tropical climates (see Part D). While rainfall conditions in much of Liberia are favorable for Arabica, there are only very small areas in northern Nimba and Lofa Counties whose average temperatures fall within the range that is considered beneficial for the crop (Figure D.6).

Figure E.18 shows even more clearly that, within the African context, West Africa as a whole and especially Liberia have very unfavorable conditions for producing a cool-climate crop such as Arabica coffee. The main Arabica origins in Africa are centered on the highlands of Eastern and Southern Africa (Ethiopia, Rift Valley, Kenya, Tanzania, Madagascar, etc.), where dark blue colors indicate annual mean temperatures in the lower 20s that are favorable for producing high-quality Arabica coffees. Such conditions are also found around Mount Cameroon but only very locally further to the West. Moreover, climate projections suggest that by the mid of the century the small areas in northern Nimba and Lofa Counties that still have suitable conditions for Arabica coffee production will essentially disappear. By then, projected mean temperatures are above 26 °C almost anywhere in the country. Since the quality of Arabica coffee is very sensitive to higher temperatures, this implies a progressive decline in the quality of the coffee that could be produced in Liberia. Moreover, it has been observed in other Arabica-producing regions that increasing temperatures have tended to increase pest and disease pressures in Arabica coffee (Jaramillo et al. 2009).

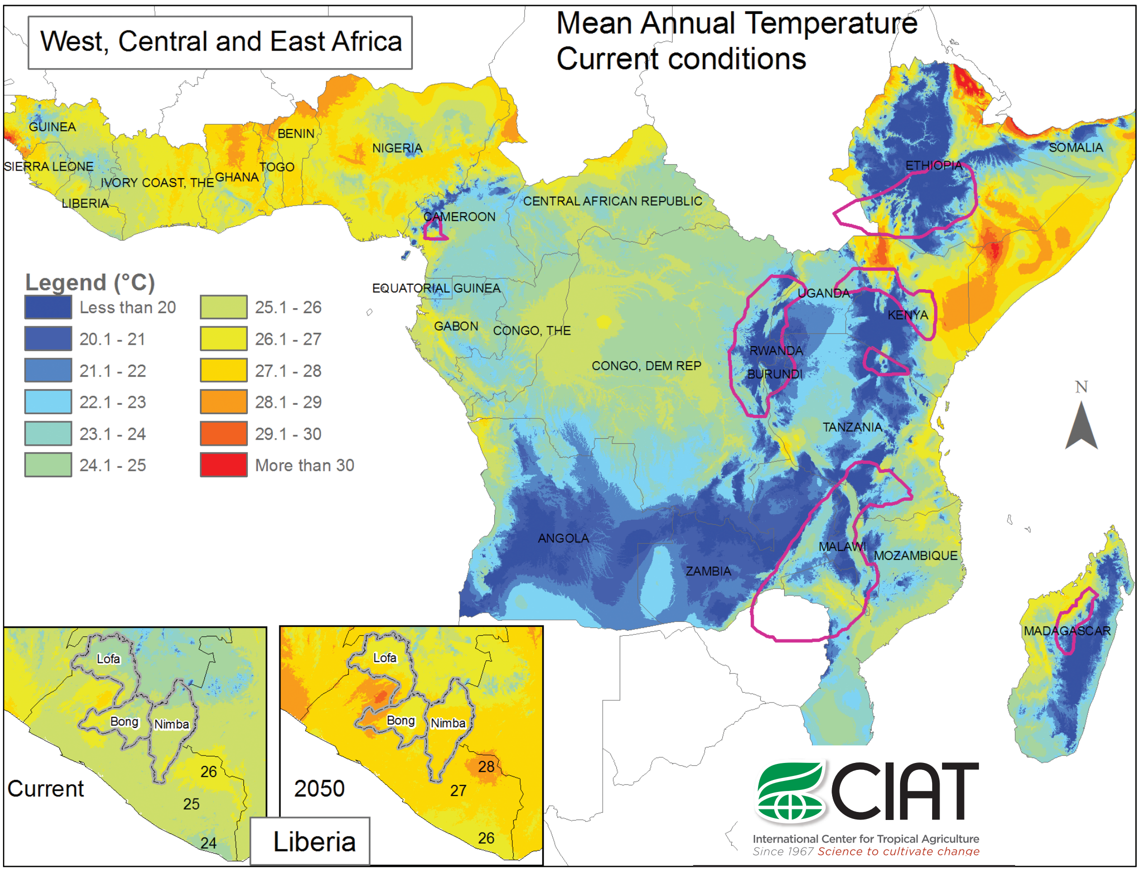

Figure E.18. Comparing mean annual temperature (BIO 1, in mm) for Liberia and major Arabica coffee origins in Africa and Madagascar for current and projected 2050s climates.

The integrative climate model in Figure E.19 confirms these conclusions. Arabica coffee is grown for its superior quality, and therefore an origin of Arabica coffee can only compete on the global market if its climatic (and other) conditions permit to produce coffees of comparable quality and price as other major Arabica producers. Therefore, differently from the climate models we developed for cocoa and Robusta coffee, for which West Africa is a major global origin, this model was calibrated on the climatic conditions of a global set of Arabica coffee origins.[8]

The model shows favorable climatic conditions for the major Arabica origins in Ethiopia, the Rift Valley, around Lake Victoria, the highlands of Madagascar and Cameroon. Parts of the

[8] We calibrated the Maxent algorithm on a global reference dataset with 2861 occurrence locations of Arabica coffee. This dataset includes geo-referenced production locations from all important Arabica production countries. The majority of locations are geo-references of coffee farms. A subset was generated by geo-referencing known Arabica production administrative units such as municipalities. This dataset was then clustered by climate characteristics. From each cluster, a representative sample was included in the final training dataset to ensure sufficient representation of all global agro-ecological conditions in which Arabica is produced. To infer from this to conditions in Liberia, the Maxent algorithm had to be calibrated to fit a well-generalizing model that allows the extrapolation in space. We combined several background sampling approaches that are suggested in the literature in an ensemble model (Bunn et al. 2014). We supplemented the bio-climatic variables from the WorldClim database (see Table E.1) with a variable for the number of consecutive months with less than 60 mm precipitation. The resulting ensemble model is the average of 45 individual model outputs for current conditions that were normalized. The same models were applied to the downscaled outputs of a representative set of five GCMs from the Fifth Assessment Report of the IPCC in the RCP 6.0 emissions scenario for the 2050s. The future impact data are the mean of 225 individual model outputs.

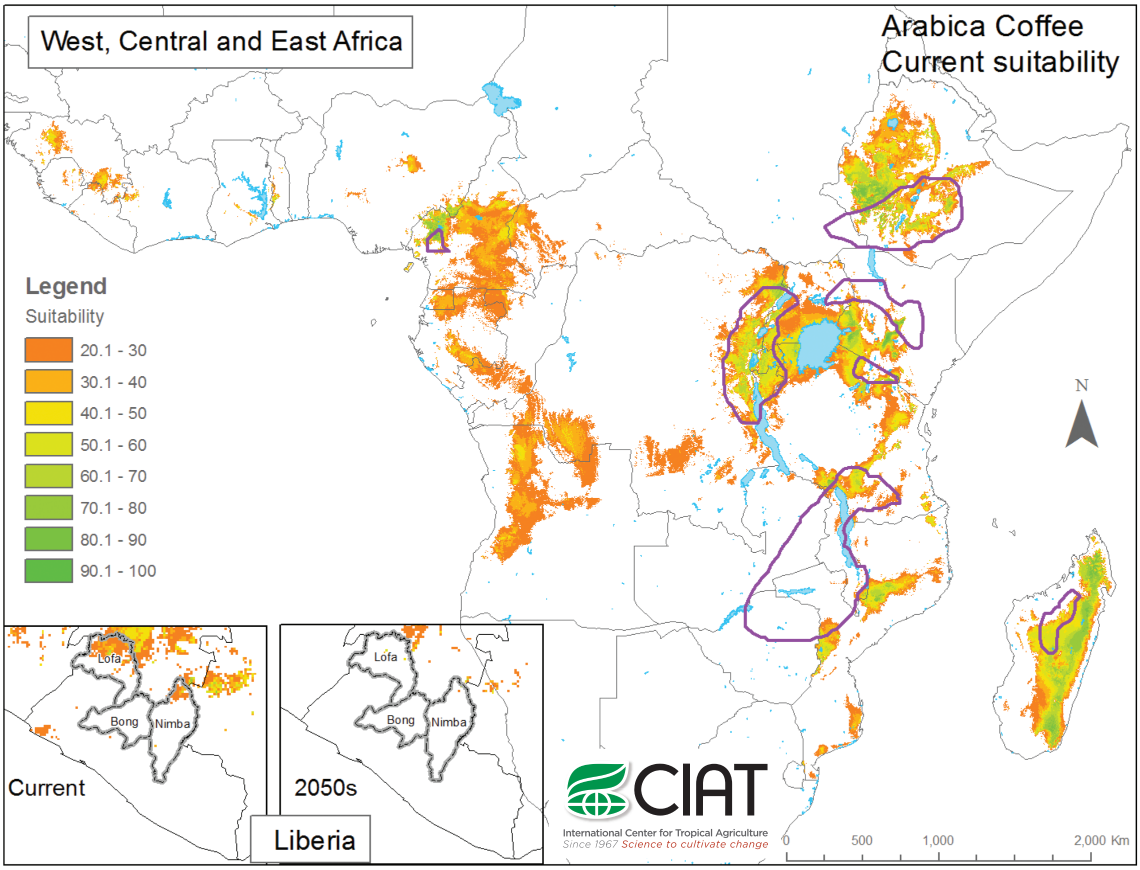

Figure E.19. Comparing the integrative climatic suitability (percent) as modeled with Maxent for Liberia in comparison to major Arabica coffee origins of Africa and Madagascar for current and projected 2050s climates.

Fouta Djalon in Guinea appear as moderately suitable, as do parts of the highlands on the border between Lofa County and Guinea and the area around Mount Nimba. However, suitability levels of the areas within the borders of Liberia are generally very low by these global standards. As a result of the projected temperature increase, even these low suitabilities are projected to have essentially disappeared by mid-century (Figure E.19), suggesting that by then climatic conditions comparable to those prevailing now in globally important origins of Arabica coffee would not be found anywhere in Liberia.

> *Since conditions for Arabica coffee in Liberia are already marginal now and are projected to become unsuitable within the next decades, it can be concluded that even for a shorter planning horizon (2030), and even more so for a medium-term horizon (2050s), the climatic conditions for Arabica coffee in Liberia are unfavorable.*

Part F – Adapting the cocoa and coffee supply chains in Liberia to climate change

1. Introduction

In this section, we propose and discuss a set of recommendations to reduce the vulnerability of the cocoa and Robusta coffee supply chains in Liberia to climate change. In doing this, we ask how the actors in the supply chains, especially the farmers, could be helped to reduce the vulnerability of the sector to climate change and to increase its resilience? We emphasize the importance of a participatory approach for many of the decisions involved. Among the most important of those is which crop or crops should be cultivated at a certain site. This decision should not be seen as pre-determined by what has been cultivated at the site before and can ultimately only be made by the – appropriately informed – farmer, ideally with the support of trained technicians.

We have divided our recommendations into eight components. Some of these components target commodity development strategy (e.g., low-carbon emissions strategy for the tree crop sector), while others are more technical in nature (e.g., design of a training and technical assistance curriculum). However, all of them are strongly interlinked and for a comprehensive strategy to make the smallholder tree crop sector of Liberia more sustainable and less vulnerable to climate change, all of them need to be addressed eventually.

While this implies that all components are in a way "priorities," it is possible to identify some "no-regret" actions as highest priorities for immediate implementation. These are marked in Table F.1. This classification does not imply that the other actions are less important, but rather that they may need more time for their implementation. For example, it is crucial that Liberia embarks on the selection and testing of tree crop germplasm that is adapted to its specific range of climates (that differs in some relevant aspects from the climates of neighboring countries from which tree crop germplasm could be obtained). However, doing this will take some time and, in the meantime, other elements of the strategy can and should already be implemented.

Beside classifying some recommended actions as "immediate, no-regret" options, we also use another way of classifying adaptation actions: "incremental," "systemic" and "transformational." These categories were developed under the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and refer to the degree of change that an adaptation strategy or component requires (Vermeulen et al. 2013). With incremental adaptation, this would be within the current logic of the system; for example, a change in management practice such as more or less shade or fertilizer use in a tree crop farm. Systemic adaptation would mean that a more substantial change is made but without changing the system as such; for example, if a coffee farm switches to a more drought- or heat-tolerant variety of coffee. While this would be a significant change for the farm, it would not greatly affect the supply chain. Transformational change would be required if, for example, the local climate changes so much that the current crop is no longer suitable, and the farm and supply chain need to transition to a new crop with different climatic requirements, or if farmers change their livelihood base completely and move to the city.

Transformational change could also be implied in the adoption of a new land-use policy. For example, if a country adopts a zero-deforestation policy where traditionally there was significant encroachment of agriculture into forests, this would be a transformational change, including for the way a country presents itself and its products on the international market. While we find this classification of adaptation actions helpful, it should be kept in mind that the assignment of specific actions to these three classes is somewhat arbitrary and that there are strong overlaps between classes for each component of this strategy.

The two classifications of adaptation actions are not always correlated. Many “immediate” adaptation measures will be incremental or systemic rather than transformational. However, some decisions that have the potential to be transformational are better taken immediately. For example, a zero-deforestation policy for the cocoa and coffee sectors is easier to adopt as long as these sectors are still relatively small than after they have started to expand vigorously, possibly attracting migrants looking for land from neighboring countries.

For each component, we outline initially why this component is important for the strategy. Following this, we provide specific recommendations. Both justification and recommendations are summarized at the beginning of each component section in a box.

2. Key components of cocoa and coffee adaptation strategy

Table F.1. Summary of adaptation actions for the cocoa and coffee supply chains of Liberia.

Component	Actions
Component 1: Forest conservation Promote a climate-friendly, low-carbon emissions tree crop strategy focusing on existing farm land, discouraging deforestation for tree crop expansion and emphasizing tree and forest conservation in the agricultural landscape	➤ Promote the adoption of a zero-deforestation policy for cocoa and coffee at national level ➤ Conduct community-level process to identify and map previously used farm land and focus project investments in those areas • Support land-use planning process led by government but involving other interested stakeholders to establish what land can be used for agriculture or remain under forest cover, focusing on cocoa and coffee belt ➤ Establish a process through which internal migrants and other people without land claims can obtain access to farm land (including slash-and-burn areas) to grow tree crops ➤ Include conservation of trees on farms and in the landscape, including riparian forests, in training curricula for extensionists and farmers
Component 2: Crop and site selection Promote cocoa and coffee farm development and rehabilitation only on pedo-climatically suitable sites, in locations with sufficient market access, and after consideration of alternative cash and food crop options	➤ Before initiating cocoa and coffee support programs at a specific locality, conduct workshops with farmers and other stakeholders discussing the pros and cons of different crop options, rather than assuming that past cocoa and coffee farms will remain under those crops in the future, and identify suitable sites for those crops ➤ Ensure that cocoa and coffee development policies are coordinated with those for other cash crops (e.g., rubber, oil palm, food crops) so that farmers have true alternatives to choose from • At sites with insufficient market access, delay tree crop development until infrastructure has been improved, or promote less perishable crops (e.g., rubber)
Component 3: Germplasm Support the introduction and selection of site adapted, productive, resistant and adaptable tree crop germplasm and its adoption by farmers	➤ Establish and promote protocol for cocoa and coffee farm rehabilitation and replanting that conserves existing, high-performing trees in farms as identified by farmers ➤ Develop public and/or private system providing cocoa and coffee planting materials to farmers at subsidized prices to avoid farmers planting their own unimproved seeds • Develop partnerships with public research institutes in the region to introduce promising cocoa and coffee varieties • Establish network of observation sites for cocoa and coffee genotypes, covering the rainfall gradient found within main cocoa- and coffee-producing counties and ideally also higher rainfall areas, for performance monitoring of genotypes • In view of already low and further decreasing climatic suitability, do not support new Arabica coffee planting • Conserve existing groves of Liberica coffee and explore market interest for this coffee
Component 4: Capacity building Develop or adapt a technological package for farmer training and technical support and implement it through agricultural extension program	➤ Develop a public-private partnership to reach farmers through an agricultural extension system composed of lead farmers guided by agronomists ➤ Establish a training facility, where public and private extension agents and farmer trainers are trained, with emphasis on hands-on training in the field ➤ Develop or adapt a standardized curriculum for cocoa and coffee farmer training ➤ Conduct survey of the occurrence of Cocoa Swollen Shoot Virus (CSSV) in the country ➤ Develop network of communal and/or private cocoa bud wood gardens, supplying farmers with planting or grafting material and technical support, under supervision of extension agents ➤ Develop a cocoa farm rehabilitation and replanting package emphasizing pruning and grafting, leading to smaller, more water-efficient trees for an overall hotter climate ➤ Emphasize diversification of cocoa and coffee farms with useful trees and crops that also provide microclimatic protection, reducing heat stress during the dry season; emphasize food species such as plantains, bananas, avocados, oil palm, etc. that increase food security, can be sold on local markets and are managed in part by women ➤ For cocoa farms, promote small plots surrounded by cordons of non-cocoa crop or fruit trees to reduce spread of CSSV if it appears in the country • Establish procedures facilitating farmers to grow and market native timber trees on their farms as a diversification option ➤ Emphasize fire control, especially in slash-and-burn areas, in farmer training to reduce fire risk to tree crop farms and forest in a hotter climate

(continues)

(continued)

Component	Actions
Component 5: Quality Make quality improvements through harvest and post-harvest practices and marketing resilient to climate change	➤ Create or maintain clear incentive for quality in cocoa and coffee pricing ➤ Provide co-funding and/or subsidized credit to farmer groups and cooperatives for solar driers and storage facilities in communities • Invest in road improvement, being careful not to improve access to previously inaccessible forest areas and inadvertently cause deforestation
Component 6: Finance Improve the availability of finance to tree crop farmers	• In order to afford better protection to providers of short-term credit to tree crop farmers, consider introducing a passbook system where loans are registered, built on the one used in Ghana ➤ Promote village savings groups ➤ Provide targeted, subsidized loan packages to farmers for farm rehabilitation, diversification, drying and storage infrastructure, supported by technical advice from extension service to reduce the risk of loan defaults ➤ Promote farm diversification as self-insurance strategy
Component 7: Food crops Increase yields and labor productivity in food crop production to free labor for work in tree crops	➤ Conduct survey among farmers and agricultural technicians about most limiting factors in increasing food crop production ➤ Ensure availability of healthy, productive seeds and planting materials as well as necessary tools • Consider removing import taxes for mineral fertilizer ➤ Support a network of local markets for the trading of food crops
Component 8: Climate monitoring Ensure a minimum of agro-meteorological and agro-ecological monitoring and make the data available	• Establish and maintain a minimum set of agro-meteorological stations, covering the main climatic gradients of the country, as well as the capacity and tools to collect, analyze, synthesize and publish the information ➤ Collaborate with regional and international meteorological services to provide timely weather and climate alerts to land users and the industry, including about expected variation in yields, pest and disease pressure, and wildfire risk in years with unusual climate (e.g., El Niño years)

Note: The arrows indicate "immediate, no-regret" actions, while the bullets indicate actions that may take more time to implement.

Component 1: Forest conservation

Promote a climate-friendly, low-carbon emissions tree crop strategy focusing on existing farm land, discouraging deforestation for tree crop expansion and emphasizing tree and forest conservation in the agricultural landscape.

Type of adaptation: TRANSFORMATIONAL

Why is this important?	Recommendations
• Deforestation for establishing new tree crop farms negates future value aggregation from accessing markets for zero-deforestation, certified, or low-carbon footprint commodities, thereby limiting capacity for adaptation • Maintains future income options for local communities and country from sustainable harvesting and marketing of timber and non-timber forest products, some of which could be used to finance adaptation in agriculture • Maintains opportunities in terms of forest conservation funding, such as REDD+ (United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries), that could benefit sustainable agricultural development and adaptation	➤ Promote the adoption of a zero-deforestation policy for cocoa and coffee at national level ➤ Conduct community-level process to identify and map previously used farm land and focus project investments in those areas • Support land-use planning process led by government but involving other interested stakeholders to establish what land can be used for agriculture or remain under forest cover, focusing on the cocoa and coffee belt ➤ Establish process through which internal migrants and other people without land claims can obtain access to farm land (including slash-and-burn areas) to grow tree crops

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Why is this important?	Recommendations
• Maintains competitive advantage compared to other cocoa- and coffee-producing countries, including in West Africa, that increasingly emphasize forest conservation policies in their commodity supply chains • Avoids creating a "forest frontier" culture where farm intensification and replanting are neglected while there is the option of shifting the farm to new forest land • Maintains microclimatic protection from forest environment that is particularly important for young tree crops (cocoa), thereby reducing vulnerability to climate extremes and change • Maintains other environmental services such as watershed protection and biodiversity conservation	➤ Include conservation of trees on farms and in the landscape, including riparian forests, in training curricula for extensionists and farmers

Why is this important?

Coffee and especially cocoa have been important deforestation drivers in West Africa and other parts of the tropical world (Ruf and Schroth 2004). For cocoa, this is relatively well documented for the second half of the 20th century when cocoa output from West Africa increased in an unprecedented way and drove massive deforestation especially in Côte d'Ivoire and Ghana (Ruf et al. 2015). Key ingredients of this West African commodity boom driving the replacement of lowland forest with cocoa and coffee farms were internal and external migrants who were not bound to their old farm land in the savannah or eastern forest regions but were willing to move to the forest frontiers to establish new farms on forest land. For the case of Côte d'Ivoire, it has been shown that pre-existing climate gradients (higher rainfall in the western compared to the eastern forest regions where cocoa was first introduced) and the deterioration of rainfall conditions between the 1960s and 1990s throughout West Africa, including some severe drought years especially in the 1980s, have contributed to these migrations, but only in a relatively minor way. Their main driver was the perception of the availability of new forest land for occupation and conversion into farm land (Ruf et al. 2015).

Liberia has still significant forest areas. Moreover, many of the old cocoa and coffee farms are still overgrown und unproductive (see Part B). Many farmers will be aware that cocoa grows and produces particularly well as the first crop after forest clearing, when the soil is rich from the ashes of the previous vegetation and the pressure of weeds and pests is relatively low. These ecological benefits constitute the so-called "forest rent." This traditional way of growing cocoa also follows almost logically from slash-and-burn practices that are wide-spread in the country and region. There is thus a significant risk that Liberia's farmers, especially the younger ones and those without a clear claim to existing farmland, may prefer to obtain a new piece of forest land and invest their labor and resources in the establishment of a new farm, rather than investing in the rehabilitation and replanting of an old, overgrown farm.

Moreover, with the establishment of peace in Liberia and the gradual improvement of the economy, Liberian forests will become increasingly attractive to current and prospective cocoa planters from other countries in the region, where new forest for planting is no longer available, and forest conservation laws are increasingly being enforced. Until a few years ago, cocoa prices were significantly lower in Liberia than in Côte d'Ivoire (see Part B), and this may have acted as a disincentive to prospective cocoa migrants. However, over the last years market conditions and cocoa prices have progressively improved in Liberia, and so this disincentive will disappear and Liberia may become an increasingly attractive migration destination for farmers from the region.

Opening Liberian forests to cocoa and coffee farming would have significant disadvantages for the country and the long-term prospects of its cocoa and coffee industries, including from a climate change adaptation point of view. International commodity markets are becoming increasingly demanding in terms of environmental sustainability criteria, as can be seen from commitments to 100% sustainable sourcing of cocoa by major brands and importing countries (Millard 2011). Zero-deforestation commitments for their supply chains are increasingly being made by major commodity traders and processors, driven mostly by the public pressure to reduce the massive deforestation in oil palm in southeast Asia and soy in Latin America, but applying equally to comparatively minor deforestation drivers (by global standards) such as cocoa and coffee. Encouraged by the prospect of international carbon funds, major cocoa-producing countries, such as Ghana and Côte d'Ivoire, are working to reduce or eliminate deforestation from their cocoa supply chains, while a country such as Brazil that is just re-emerging as a net cocoa exporter on the international market could make a zero-deforestation commitment for its cocoa supply chain with relatively little effort (Schroth et al. 2015a). Under these conditions, the expansion of cocoa and coffee farm land into forest in Liberia would risk to result in significant competitive disadvantages for the country on future commodity markets and perhaps even the future exclusion of the country's products from certain higher paying markets that emphasize a low-carbon footprint and require zero-deforestation.

In addition to these disadvantages on future commodity markets resulting from deforestation for cocoa and coffee expansion, there are also direct costs from replacing forest with farm land that may negatively impact on the country's and the communities' capacity for sustainable development and adaptation to climate change. These include future income options from the sustainable production of timber and non-timber products from the forest, but also opportunities on emerging REDD+ or other carbon markets (e.g., recent commitments to Liberia from the Government of Norway conditional upon forest conservation) that could generate financial resources for investment in sustainable agriculture and adaptation to climate change.

The opening of forests to cocoa and coffee farmers could also have significant disadvantages in terms of its impacts on production practices through its negative effects on farm innovation and intensification. It can be argued that in other West African countries (notably Côte d'Ivoire and Ghana), the availability of forest land for farming has slowed or even prevented necessary adaptation processes in smallholder tree crop production in the sense that intensification and replanting decisions were delayed or avoided as long as there was the prospect of moving to new forest land once the current farm became too unproductive and degraded. On the other hand, as forests became unavailable, farmers increasingly invested time and resources in replanting and, gradually, in farm intensification (Ruf et al. 2015). It is important that Liberia does not encourage the development of a similar forest frontier attitude among tree crop farmers that its West African neighbors are still struggling to overcome.

It should be mentioned that shaded tree crop farms can make a substantial contribution to reducing carbon emissions and conserving carbon stocks not only by following zero-deforestation principles, but also by storing substantial amounts of carbon in the farm vegetation itself. For example, in the cocoa region of southern Bahia, Brazil, trees in cocoa farms contribute more than 50% to the total carbon stocks in the landscape (Schroth et al. 2015b), and in the same region it has been shown that relatively high carbon stocks in the cocoa farms are still compatible with doubling average cocoa yields (Schroth et al. 2014). A distinguishing element of many African tree crop landscapes are the large remnant trees from the previous forest vegetation (often with a diameter at breast height of 1 m or more) whose conservation is particularly important because they contain a disproportional part of the carbon stocks in the farm and landscape and once they are lost their carbon stocks are difficult or impossible to restore through tree planting. In the future, agricultural landscapes with higher than average tree cover and carbon stocks may also qualify for carbon payments, complementing REDD+ carbon credits from forest conservation.

Very important from both a carbon and a biodiversity point of view are also forest remnants in the landscape which were spared from clearing, perhaps because of their cultural value (sacred groves) or because they are located on soil that is unsuitable for agriculture. Such forests are easily lost to wildfires if they are not specifically protected, or are cleared for short-term slash-and-burn agriculture and then soon abandoned. Forest strips along watercourses (riparian forests or buffer strips) have the additional value of protecting these watercourses from sedimentation and pollution with agricultural runoff, and thereby improve their water quality. They are also very important for biodiversity conservation because many animals use these riparian corridors as habitat, food source and for their displacements through the landscape (Schroth et al. 2004; Schroth et al. 2011a).

Last but not least, the presence of forests and trees in the landscape is also important for creating favorable conditions for the tree crops themselves. Trees reduce wind speeds which is important for wind-sensitive tree crops such as cocoa. They also reduce air temperatures and create a humid, protective microclimate through their ETP of water that they acquire even during the dry season from deeper subsoil horizons. This is important especially for young trees, and thus for the success of farm rehabilitation and replanting efforts. With the disappearance of forest from the countryside, this protective effect is lost, and this can have serious consequences for the replanting success and long-term sustainability of cocoa and (to a lesser extent) coffee farming. In some old cocoa production areas in eastern Côte d'Ivoire, the replanting of cocoa has become extremely difficult, in part because this protective effect of the forest in the landscape has been lost. Trees and forest remnants in the landscape can also reduce the spreading of wildfires that have escaped from slash-and-burn areas, and they can host predators of crop pests including birds and bats (Maas et al. 2015). As will be discussed in more detail below, landscapes that form a mosaic of land-uses could also be more resilient to the spread of certain crop diseases such as the Cocoa Swollen Shoot Virus (CSSV).

Recommendations

For the reasons outlined above, we recommend that Liberia adopts a zero-deforestation policy for its cocoa and coffee industries and implements it country-wide. This would fit very well with the forest conservation and REDD+ policies developed by the Government of Liberia (FCPF/UN-REDD 2012; Fouladbash and Currie 2015). Implementing such a policy requires a land-use planning exercise to define and delineate forest and non-forest land, as a basis for delineating those areas where agriculture in general, and specifically the planting of tree crops, should take place. This exercise would eventually have to comprise the whole country, but could start at a smaller scale, focusing on the cocoa and coffee belt and specifically those areas where project investments are intended. Countries such as Brazil have carried out similar planning exercises for crops like oil palm (Filho et al. 2010). In Liberia, the definition of forest requires extra care after the long phase of conflict, during which many rural areas were abandoned by their population and farms were invaded by secondary forest.

To prevent this process from delaying investments in the cocoa and coffee supply chains without preempting the results of the land-use planning process, among the first steps in each community or other administrative or spatial unit receiving project support should be to identify in a participatory way those areas that are or have previously been farm land. This exercise could distinguish (1) the immediately available farm land (land currently under crops or young fallow land); (2) the agricultural land reserve (old fallow or secondary forest land); and (3) mature forest land. Project support for farm rehabilitation or establishment could then be tied to the farm being located on "class 1" land or in certain cases (e.g., migrants without local land claims, with consent of the local community) in "class 2" land, but never in "class 3" land. This would minimize the risk of supporting tree crop establishment on land that is later included in the forest category by the more comprehensive REDD+ land-use planning process. Criteria for distinguishing between the classes would have to be clear and transparent, and all farm locations receiving project support would have to be geo-referenced and their location checked against the local land-use map. This would initially only require a point measurement, but in cases of doubt (farms directly bordering on forest areas), the whole farm would need to be mapped. With GPS, such farm mappings can be carried out fairly quickly by local staff and the resulting maps of farm locations can serve many purposes, including the monitoring of project progress and future planning.

It is important that agreements about the location of project investments on previous farm land and the conservation of forest land is made with the entire communities and fully supported by their leaders and local government. For communities, it is relatively easy to know where their members are farming, clearing forest, etc. Therefore, if communities feel that it is in their common interest to follow rules established and agreed with the project and local government (e.g., about farm locations), then it is relatively easy for them to enforce these rules with their members. Community agreements to prevent coffee farming from encroaching into protection forest have, for example, been used with success in Sumatra, Indonesia (Schroth et al. 2011b).

Component 2: Crop and site selection

Promote cocoa and coffee farm development and rehabilitation only on pedo-climatically suitable sites, in locations with sufficient market access, and after consideration of alternative cash and food crop options.

Type of adaptation: SYSTEMIC

Why is this important?	Recommendations
• During periods with favorable cocoa (and coffee) prices and government support programs, these crops have often been established on unsuitable sites where farms turned out later to be unproductive and unprofitable, especially under increased environmental pressure • On marginal sites (e.g., shallow or wet soils), sensitive tree crops, such as cocoa and coffee, may suffer during years with unusually high or low rainfall conditions • Farmers returning to rural areas may rehabilitate cocoa and coffee farms initially for lack of alternative options, but switch to other crops later in which case initial investments in labor and resources would be wasted	➤ Before initiating cocoa and coffee support programs at a specific locality, conduct workshops with farmers and other stakeholders discussing the pros and cons of different crop options, rather than assuming that past cocoa and coffee farms will remain under those crops in the future, and identify suitable sites for those crops • In areas with predominantly unfavorable or heterogeneous soil and topographic conditions, conduct GIS analyses to classify and identify suitable sites ➤ Ensure that cocoa and coffee development policies are coordinated with those for other cash crops (e.g., rubber, oil palm, food crops) so that farmers have true alternatives to choose from

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Why is this important?	Recommendations
• Marginal sites for cocoa and coffee could be used more profitably for other crops with less or different requirements (e.g., rubber, oil palm or lowland rice) or forest • Where market access is not ensured during the harvest season or transport costs are too high, perishable tree crop products, such as cocoa and coffee, may spoil or reach markets in poor quality, jeopardizing efforts at improving quality at national level	• At sites with insufficient market access, delay tree crop development until infrastructure has been improved, or promote less perishable crops (e.g., rubber)

➤ Immediate, no-regret actions.

Why is this important?

Under increasing climate pressure and changing conditions on the international markets putting increasing demands on producers in terms of productivity and quality, it is important that perennial crops, such as cocoa and coffee, are only planted at sites that are suitable now and will remain suitable for at least the next generation of tree crops. In the past, this simple rule has not always been respected and especially during boom times with high commodity prices and favorable government policies, tree crops, such as cocoa, have often been planted on unsuitable (e.g., acidic, sandy, shallow...) soils where the productivity of the trees remained low or declined rapidly with increasing tree age, and where high levels of inputs would have been needed to maintain productivity. For example, on acidic soils in western Côte d'Ivoire, farmers have been forced to adopt mineral fertilizer application to reduce premature yield declines and mortality of their cocoa trees (Ruf and Schroth 2004).

Under climate change conditions, there is the added requirement that sites need to remain suitable for at least another generation of trees, that is at least 20 to 40 years. This is an important consideration especially for northern Nimba and Lofa Counties, where dry season temperatures and the water demand during the dry season are projected to increase over the next decades, and where it is therefore particularly important to avoid shallow or sandy soils with a low water holding capacity that are likely to lose their suitability for a drought-sensitive crop such as cocoa.

Site selection is not only a matter of biophysical suitability of course, but also involves questions of production costs and market access. Under the current poor road conditions in many rural areas of Liberia, making transport costly and unreliable especially during the rainy season, necessary inputs such as seeds and agrochemicals may not reach the farms in time for the current cropping cycle, and the harvested products may lose quality or degrade before they can reach the market. At such sites, investments in tree crops may only be worthwhile in combination with investments in a basic transport, drying and storage infrastructure (see Component 5).

Investing in a tree crop that is or will soon become unsuitable for a given site is not only a waste of resources, but has also opportunity costs. For example, soils that are too infertile for cocoa may still be adequate for coffee or rubber, and a site with a high water table may be better used for oil palm or irrigated rice, while shallow soils may best remain under forest. Where market access is too unreliable and transport too costly, farmers may, for the time being, be better advised to grow food crops for local consumption and sale than to invest in tree crops for the international market.

It should be noted that in the current situation where people arriving in the rural areas have limited alternatives and generally no access to credit, some farmers may rehabilitate their old cocoa or coffee farms as a short-term strategy but later switch to other crops (e.g., rubber or oil palm) as these options become available to them, in which case initial investments may be lost. It is, therefore, important to invest in farm rehabilitation for a certain crop only after considering alternative options and coming to the conclusion that cocoa or coffee farming is the medium-term, preferred option for the farmers concerned, as well as to coordinate programs for different crops.

Recommendations

In Part E, we showed that in northern Nimba and Lofa Counties, especially the heat- and drought-sensitive cocoa will increasingly be vulnerable to high dry season temperatures in an overall warmer climate and, despite the shorter future dry season, will remain sensitive to drought especially during years with unusually dry weather (e.g., El Niño years). Overall, northern Nimba and Lofa are the areas where heat and drought conditions will be most limiting to cocoa, and where the selection of deep soils and the use of shade are most important, but these rules also apply further to the South.

However, the resolution of the climatic suitability maps is limited by the resolution and quality of the data used to create them, and the resulting uncertainty is further compounded by the general uncertainty of global climate model predictions. It is, therefore, necessary to use this information as guidance and to complement it through a more site-specific process of identifying suitable and unsuitable sites for cocoa and coffee that should also take into account local knowledge and experiences. This could be done through participatory field visits and stakeholder workshops with farmers, traders, local government, non-governmental organizations (NGOs) and other interested parties, and should have as objective the identification of sites of currently highest suitability for cocoa and coffee within each community or landscape, where support programs for cocoa and coffee rehabilitation or replanting should initially focus on, as well as the identification of sites that are unsuitable for cocoa and coffee. These workshops should be organized at the community level to ensure that participants have an intimate knowledge of the area.

Bong County is climatically the most suitable for cocoa among the three cocoa belt counties. However, it has areas mapped as Leptosols (shallow soils) or plinthic Ferralsols (soils with a waterlogged subsoil horizon), which are not suitable neither for cocoa nor for coffee (see Part C). However, soil maps prepared at this scale always show only the dominant soil type in a mapping unit, while other potentially suitable soils in the same landscape may not be shown. This possibility needs to be evaluated through exploratory field visits, and suitable sites could then be identified and mapped out through a participatory process as explained above.

The question of crop selection should be discussed through workshops at community level. It should not be assumed that farms where cocoa or coffee has been grown in the past also need to remain under these crops in the future. In Côte d'Ivoire, many cocoa farmers have recently switched to rubber or oil palm as their diversification or primary crop, while many current Ivorian cocoa farms have been under coffee some years or decades ago (Ruf and Schroth 2015b). Tree crop farmers in West Africa (and elsewhere) are much more dynamic in their crop choices than is commonly perceived. Where farmers have a preference for a different crop than cocoa or coffee, this should not be discouraged, although it should be made clear that such decisions are made on the basis of adequate and impartial information. Ideally, support programs for cocoa and coffee should be closely coordinated with similar programs for rubber, oil palm and food crops so that farmers have a free choice of the crop or combination of crops they would like to invest in. A degree of diversification, especially with food crops, should always be encouraged (see Component 4).

Component 3: Germplasm

Support the introduction and selection of site-adapted, productive, resistant and adaptable tree crop germplasm and its adoption by farmers.

Type of adaptation: SYSTEMIC

Why is this important?	Recommendations
• Farmers are currently using mostly local planting material that may not be optimally suited to current and future environmental conditions • Climatic conditions in Liberia vary both in space and time, and the selection of tree crop germplasm needs to adapt to this variability • Liberia's current (and future) climate is somewhat different from that of neighboring countries (e.g., Côte d'Ivoire, Ghana) from where planting material has been or could be introduced • Climate change models can show future trends, but germplasm selection needs to take into account uncertainty and local variation	➤ Establish and promote protocol for cocoa and coffee farm rehabilitation and replanting that conserves existing, high-performing trees in farms as identified by farmers ➤ Develop public and/or private systems providing cocoa and coffee planting materials to farmers at subsidized prices to avoid farmers planting their own unimproved seeds • Develop partnerships with public research institutes in the region to introduce promising cocoa and coffee varieties • Establish network of observation sites for cocoa and coffee genotypes, covering the rainfall gradient found within main cocoa- and coffee-producing counties and ideally also higher rainfall areas, for performance monitoring of genotypes • In view of already low and further decreasing climatic suitability, do not support new Arabica coffee planting • Conserve existing groves of Liberica coffee and explore market interest for this coffee

➤ Immediate, no-regret actions.

Why is this important?

Cocoa and coffee farmers in Liberia currently depend mostly on local, unimproved germplasm from their own and neighboring farms for replanting and rehabilitating their farms. The exception are those farmers who benefit from a donor-funded project that makes improved planting material available or have access to a privately run cocoa nursery where improved seedlings, presumably from hybrid seed brought in from other countries in the region (particularly Ghana and Sierra Leone), are being sold, and who have the necessary cash to buy them. Whether improved coffee seeds are available for sale in the country and how much demand there is for them is unclear. On the short term, importing and distributing hybrid seed from other cocoa-producing countries in the region is an appropriate strategy to quickly address the issue of the lack of improved planting material for rehabilitating the many over-aged cocoa farms. On the medium term, it needs to be kept in mind that, for example, Ghana's climate and soil conditions are somewhat different from those of Liberia (see Part E) and that climate conditions are going to change further over the coming decades. Also, both cocoa and coffee are grown over a considerable range of climatic conditions in Liberia, and different genotypes may perform differently at the hotter and drier (northern Nimba) from the cooler and wetter (southern Bong and adjacent counties) end of the range. For example, coffee genotypes adapted to a long dry season tend to have a lower resistance to fungal diseases, while rust-resistant varieties tend to be less drought tolerant (Montagnon and Leroy 1993). There is thus a clear need to match varieties to sites. Cocoa is less drought tolerant than Robusta coffee, and less research has been carried out on its drought resistance, but genotypes may differ in their resistance to fungal diseases, such as black pod, which is particularly important under high rainfall (and under high shade) conditions. Since in tree crops such as cocoa and coffee, the selection of the planting material will influence the farm performance for the next 20 to 40 years, it is important that farmers make use of the best available germplasm when replanting or rehabilitating their farms. To ensure that extension services can provide farmers with competent advice in this decision now and in the future, it is necessary to monitor the performance of a range of genotypes over a gradient of climatic conditions and over time, thereby tracking eventual changes in their relative performance. This is best done in connection with climate monitoring (see Component 8).

Recommendations

Since existing cocoa germplasm collections in Liberia have been largely abandoned or even destroyed during the war, hybrid seeds have been introduced from Ghana and small clonal gardens have been established, including one in Nimba County. Selected cocoa varieties have been introduced from Reading, UK, and have been planted at the CARI research station in Bong County. It is not advisable to wait for the distribution of improved germplasm until further in-country monitoring of these varieties has occurred, because this would mean several years of delay. As a first approximation, it can be assumed that cocoa and coffee varieties that do well in western Côte d'Ivoire and Ghana also do well in the Liberian cocoa and coffee belt. The same is true for Sierra Leone, which has a climate comparable to that of the cocoa-producing counties of Liberia.

While the introduction of new cocoa and coffee germplasm is important to catch up with the progress in plant breeding in other countries, it should not be assumed that these new varieties are necessarily superior to all germplasm already present in the country, including in the farmers' fields. Therefore, it is important that protocols for cocoa and coffee farm rehabilitation (to be discussed further under Component 4) conserve valuable germplasm that may already be present on those farms. While unproductive trees should be eliminated and replaced, productive trees as identified by the farmers should be conserved because they can serve as a source of vegetative material for grafting on the same and other farms.

In parallel to these efforts to identify and introduce suitable cocoa and coffee germplasm, a monitoring program for newly introduced and high-performing local varieties of cocoa and coffee at a network of sites should be established. These monitoring sites should include two to three sites covering the range of rainfall conditions found within the main cocoa and coffee belt, as well as one site with higher rainfall in case cocoa expands further to the South. At least one location should be located in northern Nimba County, which is the hottest and driest part of the cocoa and coffee belt. These monitoring sites would serve two purposes: (i) to detect differences among cocoa and coffee genotypes in their specific suitability for cooler-wetter and hotter-drier sites and thus be able to recommend the best varieties to farmers in different parts of the country; and (ii) to infer from the relative performance of the genotypes on a climatic gradient their future performance under a changing climate. For example, it might be observed that some cocoa genotypes do not tolerate well the high dry season temperatures in the North now and this would indicate future problems since average and maximum temperatures are projected to increase. Or a certain Robusta coffee genotype may perform well with a 3-month dry season but suffer excessively from fungal diseases in an area where the dry season is only 1–2 months, and this could indicate future disease problems since the dry season is projected to become shorter on average. Care should be taken that the sites for these performance trials are chosen on the typical soils of each climatic zone, keeping in mind that in the past, research stations have often been chosen on untypical sites. Climate data should be regularly collected at or close to each of the sites (see Component 8).

In parallel to this, a public or private system to produce and deliver improved cocoa and coffee planting materials to the farmers needs to be developed. For both cocoa and coffee, it is important to offer improved germplasm to farmers at the lowest price possible in order to avoid that they use their own unimproved seeds, as is common throughout Africa and would immediately compromise the next generation of tree crops. This does not necessarily mean that seeds or seedlings have to be distributed for free, which often leads to waste and may not be sustainable. It could mean to subsidize private or communal nurseries based on the number of trees delivered or successfully established in the field, or to provide subsidized credit to farmers or farmer groups for purchasing seedlings and other inputs for farm rehabilitation.

In view of the negative evaluation of the future climatic prospects of Arabica coffee in Liberia (see Part E), it is not recommended to develop a specific strategy or activities for that crop. On the other hand, groves of Liberica coffee existing in the country should be conserved because over the medium term there might be interest on the market for this species, especially if produced in the country from which it originates (see considerable interest currently in specialty Arabica coffee from its country of origin, Ethiopia). However, research is needed considering that Liberica coffee has suffered from a disease epidemic in the 1950s (T. Leroy, CIRAD, pers. comm.), and therefore any actions should be preceded by a detailed market and agronomic evaluation.

Component 4: Capacity building

Develop or adapt a technological package for farmer training and technical support and implement it through an agricultural extension program.

Type of adaptation: INCREMENTAL / SYSTEMIC

Why is this important?	Recommendations
• Owing to the conflict, many farmers have not been involved in agriculture for many years, and younger ones possibly never; even those who have practiced farming in the recent past may never have received specialized agricultural training • Agricultural development strategies that have been common and often quite successful in the 1970s and 1980s prior to the conflict, emphasizing specialization on a single crop at farm and even country level, have often failed subsequently and are unsuitable under variable and changing climate and international market conditions • Future climate change requires adaptation strategies that do not follow in a straightforward manner from past experiences; for example, the climate record of Liberia since the 1960s shows progressive drying while current climate models indicate a future climate that will be hotter but with a shorter dry season • Climate and environmental change may have indirect effects, especially through changes in pest and disease pressures, that farmers may not be able to adjust to without specialized technical support	➤ Develop a public-private partnership to reach farmers through an agricultural extension system comprised of lead farmers guided by agronomists ➤ Establish a training facility, where public and private extension agents and farmer trainers are trained, with emphasis on hands-on training in the field ➤ Develop or adapt a standardized curriculum for cocoa and coffee farmer training ➤ Conduct survey of the occurrence of Cocoa Swollen Shoot Virus (CSSV) in the country ➤ Develop network of communal and/or private cocoa bud wood gardens supplying farmers with planting or grafting material and technical support, under supervision of extension agents ➤ Develop a cocoa farm rehabilitation and replanting package emphasizing pruning and grafting, leading to smaller, more water-efficient trees for an overall hotter climate ➤ Emphasize diversification of cocoa and coffee farms with useful trees and crops that also provide microclimatic protection, reducing heat stress during the dry season; emphasize food species, such as plantains, bananas, avocados, oil palm, etc. that increase food security, can be sold on local markets and are managed in part by women ➤ For cocoa farms, promote small plots surrounded by cordons of non-cocoa crop or fruit trees to reduce spread of CSSV if it appears in the country • Establish procedures facilitating farmers to grow and market native timber trees on their farms as diversification option ➤ Emphasize fire control, especially in slash-and-burn areas, in farmer training to reduce fire risk to tree crop farms and forest in a hotter climate

➤ Immediate, no-regret actions.

Why is this important?

Specialized agricultural training and technical assistance are in short supply throughout the tropical world, and cocoa and coffee are no exception to this. In many cases, cocoa farmers in Côte d'Ivoire and Ghana receive their first professional training when they are being prepared for third-party certification, for which training is a precondition. In Liberia, training and technical assistance for farmers are arguably even more important than in its neighbor countries. Many farmers returning to rural areas have not been involved in farming for many years, and younger people possibly never. Even those who have farmed already in the 1980s or during the conflict may not have benefited then from any technical training or support. Moreover, agricultural practices have changed since the 1980s in many ways. Environmental issues such as deforestation and climate-smart practices were low on, or absent from, the development agenda then, while today they could be crucial for ensuring access to interesting markets (see Component 1).

Agricultural development strategies have also changed, from a focus on specialization at farm and even (sub)national level following green revolution-type intensification strategies prior to the 1980s, to a much greater emphasis now on spreading risks through crop diversification (Schroth and Ruf 2014; Ruf and Schroth 2015b). This change in strategy is not only a consequence of climate change influencing development agendas, but also of the failure in the 1990s of some development pathways previously considered successful that were based on excessive specialization on certain crops, such as coffee in Vietnam. Even without extension support, many farmers now diversify themselves, often mostly to adapt to changing market conditions, although this is also an excellent strategy to adapt to climate change (Schroth and Ruf 2014; Ruf and Schroth 2015b).

Another reason why farmers in Liberia are in particular need for specialized technical advice is that, climatically speaking, West Africa is at a crossroads. During the 1960s to 1990s, rainfall throughout the sub-region deteriorated with the notable drought years of the early 1980s, which led to severe cocoa and coffee yield decreases and widespread bushfires in the forest zones of Côte d'Ivoire and Ghana (Ruf et al. 2015). The decrease in annual rainfall, which reached 30% in the savannah zone of West Africa, was also measurable in Liberia where it led to a more intensive dry season (see Part D). However, climate data from other parts of West Africa suggest that there has been a slight recovery of average rainfall over the first decade of the century, and climate models also predict for Liberia that future climates will be characterized by warmer temperatures and a shorter dry season (Parts D and E). Future climatic conditions will thus not follow in a straightforward manner from past experience. Farmers will need specialized technical support to adjust to those conditions in order to avoid possible mal-adaptations, i.e., adaptations that end up increasing rather than reducing their vulnerability to climate change. Particularly important in this situation of transition and uncertainty are "no-regret" practices that can reduce farmers' vulnerability within a wide range of climate scenarios. These are emphasized here.

It should also be remembered that the most serious impacts of climate change are often indirect. For example, a decrease in the length of the dry season may benefit the cocoa plants directly, but hurt them indirectly in the wetter parts of the country through higher fungal disease pressure. Similarly, warmer temperatures may still be within the physiological range tolerated by a crop but could trigger pest outbreaks or wildfires for which the farmers are not prepared. Especially the pest and disease situation of cocoa needs careful monitoring and competent technical advice to farmers under climate change conditions, while Robusta coffee is, generally speaking, a fairly robust species and does not suffer too much from pests and diseases.

Recommendations

To be able to train farmers and support them with technical advice requires an extension structure in place. Many developing countries, especially in Africa, do not have a public agricultural extension service anymore, although Ghana (through Cocobod – the Ghana Cocoa Board) and Côte d'Ivoire (through Anader – National Agency for Support to Rural Development) have structures that reach part of their cocoa and coffee producers, with shared public and private funding. Much farmer training in those countries is also carried out by traders and NGOs. This is also to some extent the case in Liberia. Extension services where large numbers of smallholder farmers are directly reached on a regular basis by trained agronomists are in most cases too expensive; therefore, training is often provided to smallholder farmers through lead farmers as intermediaries. Lead farmers are themselves farmers and therefore familiar with the crops and the situation of their fellow farmers, but have received a basic training in good agricultural practices that they can pass on to their peers in a farmer field school setting. For this to work well, they need to be supervised and backed up by trained agronomists. Various ratios of farmers to lead farmers and lead farmers to technicians are possible, and cost sharing options between public and private sectors could be considered. Key is that technical assistance should not be conceived as a "project" with limited geographical coverage (often excluding more marginal areas) and a fixed start and end date, but rather as a key ingredient of sustainable rural development that should be available to every farmer. It can be argued that many problems in cocoa and coffee farming in Africa would be less intractable if there were comprehensive extension systems in place through which governments and other stakeholders could regularly communicate with the farmers.

An extension system would need a simple training facility, possibly linked to a university, as well as a training curriculum. Currently, training curricula for cocoa farmers are being developed with international assistance, for example in Côte d'Ivoire and Ghana, and it might be possible to adapt these. Even for the technicians, and much more so for the lead farmers, the focus of the training should be on hands-on training in the field. A key capacity of a technician should be to diagnose the situation of a farm and to provide farm-specific recommendations for crop and farm improvement, since no two farms are exactly the same. Correspondingly, a lead farmer needs to be able to follow up on these recommendations and support and monitor their implementation. This direct interaction with the individual farmer is particularly important in the current situation in Liberia where many farms require rehabilitation. We now discuss a number of topics that should be covered in such training curriculum.

Farm rehabilitation

A protocol for the rehabilitation of old and overgrown cocoa and coffee farms needs to be developed or adapted. On old farms, many of the cocoa or coffee trees will often have grown to very large size. Other trees will have died forming gaps in the canopy which are the target of mirid attacks. As is common in plantations established from (possibly unselected) seed, there will be a large variability in yields per tree, with many trees having low (or no) productivity. The initial objective will be to fill gaps, cut out unproductive trees and replace them with productive trees, either hybrid seedlings or (preferably for cocoa) grafted seedlings. This under-planting of an over-aged, degraded stand with new seedlings is also a phase when a (partial) crop change is possible. In fact, many cocoa farms in eastern Côte d'Ivoire have been established by under-planting old and degraded former coffee farms. In the subsequent management of the farms, frequent and intensive pruning of the trees should be encouraged to keep them small and easy to harvest and to monitor for pests and diseases. In a hotter future climate, and especially at the drier end of the range of climates under which cocoa is grown in Liberia, large tree crops have the disadvantage that they consume a lot of water owing to their large leaf area; therefore, the management of plant size through frequent pruning will become increasingly important.

Shade use

In Liberia, both cocoa and coffee should be grown under shade. On fertile soils and/or with high inputs of agrochemicals, these tree crops can be grown with little or no shade, but Liberia has basically no fertile soils (see Part C) and the availability of fertilizers is limited and costly. The projected increase in temperature over the next decades makes shading even more necessary because maximum temperatures during the dry season could otherwise reach critical levels for tree crops that are fully exposed to the sun. This is especially so in northern Nimba and Lofa Counties but also applies to the rest of the cocoa belt (see Part E). A certain shade level has been found to be highly effective in reducing extreme temperatures. As a rule, 30 to 40% shade may be appropriate. If shade levels are too high, fungal diseases may increase, especially in cocoa. This is especially the case if the shade trees are only a little higher than the tree crops. Therefore, the shade canopy should preferably be well above the canopy of the tree crops to ensure adequate ventilation. This can be best achieved by using timber trees for shade because these develop a long bole. Introduced legume trees, such as *Gliricidia sepium,* grow fast but have no economic value and are therefore often not adopted by smallholder farmers in Africa. Their role as a provider of medium-term shade is better served by bananas and plantains.

Diversification

The term "shade trees" is somewhat misleading because in Africa shade trees in cocoa and coffee are often useful trees in their own right, and the shade canopy is thus a component of the diversification strategy of the farm. Farm diversification should be encouraged even if it leads to reduced numbers of tree crops per hectare, and thus reduced per-hectare yields of the tree crop. The principle of surrounding and subdividing cocoa plots with tree crops that are non-hosts of the vectors of the CSSV will be discussed below. But diversification of farms with other crop and tree species is also a strategy of self-insurance to reduce income risks, increase and diversify income sources, increase food security and also increase the role that women play in the farming household[9] since they are often in charge of food crops (Schroth and Ruf 2014; Ruf and Schroth 2015b). The employment of fruit trees such as plantains, bananas, avocados, African plum, small numbers of improved oil palm, etc. as shade trees should thus be encouraged even if they do not have ideal shade characteristics. In general, the income diversification and increased food security weigh higher for smallholder farmers than agronomic criteria for ideal shade trees. In other words, some competition of the shade trees will be accepted by the farmers if the shade trees themselves have value. Trees that are direct sources of cocoa or coffee pests or diseases should be avoided.[10] For the intensification of food crop production to free time for tree crops, see Component 7.

Timber trees

Over the medium to long term, timber trees can also be an important source of income diversification and insurance for major expenses, including expenses for farm replanting every 20 to 30 years or for unexpected expenses such as health care. Both cocoa and coffee can be grown very well together with certain timber species (the African mahoganies being an example among many others). In tree crop farms, these timber species generally grow much faster than in forest. Unlike some countries in Latin America, West African countries have for many years missed the opportunity of building a timber industry based on timber grown sustainably on their cocoa and coffee farms because they did not give farmers the ownership over native farm trees, or only subject to complicated administrative procedures. As a consequence, farmers have often actively destroyed the timber trees on their cocoa and coffee farms as a safeguard against loggers coming into their farms and destroying their cocoa and coffee trees when cutting and pulling out the logs, and this has played a role in the progressive transition to low-shade practices (Ruf 2011). Currently, Ghana is putting in place a tree registration process to enable cocoa farmers to produce native timber trees on their farms. Liberia should make sure that procedures for the use and commercialization of farm trees by the farmers are clear and that

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9 In line with Liberia's Poverty Reduction Strategy (Republic of Liberia 2008).

10 For examples of such trees, see Schroth et al. (2000).

simple administrative procedures are in place to allow farmers to commercialize timber produced on their farms. It is also very important that farmers own their trees in the context of benefit sharing in carbon projects that include agricultural landscapes (see Component 1).

Pest and disease control

Once farms have been rehabilitated, and basic farm management has been introduced, pest and disease control will soon become a critical factor influencing yields of cocoa (less so of Robusta coffee which has few biotic enemies). In West Africa, cocoa is under strong pressure from black pod fungi (*Phytophthora* spp.) and mirids as the most damaging insect pests. Fungicide and insecticide applications are much more efficient if they are being carried out with a motorized sprayer than with a manual (knapsack) sprayer because the motorized sprayer covers a larger area. However, motorized sprayers are too expensive for individual farmers. Moreover, for safety and health reasons, people applying pesticides need to wear protective clothing and equipment and should have undergone a special training. Good experiences have been made in Ghana and Côte d'Ivoire with spraying gangs of young, specifically trained and equipped people who are hired by farmers for applying pesticides on their farms. Such spraying gangs can be set up as small independent companies, owning their own equipment, or as specially trained members of a farmers cooperative or association that owns the equipment.

CSSV prevention

One of the key threats to cocoa in West Africa is the Cocoa Swollen Shoot Virus (CSSV). This virus has haunted the cocoa industry of Ghana from the 1930s to the present and been the cause of extensive eradication campaigns involving the destruction of many tens of millions of cocoa trees. In Côte d'Ivoire, the virus has also recently been found to be widespread and is now the object of a government program. The virus cannot be treated once it has affected a cocoa plant; therefore, the objective must be to prevent its introduction and spread, which involves either infected vegetative material (not seeds) or an insect vector. It is recommended to contract a team of specialists, possibly from Ghana, to conduct a survey in the main cocoa-producing areas of Liberia, including along the border to Côte d'Ivoire, to see if and to what extent CSSV is already present in the cocoa tree population. If it is present, a special strategy may need to be developed to contain it. The following recommendations are designed to make cocoa farms more resistant to the introduction and spread of the virus, but not to eradicate an existing virus population.

CSSV is spread by mealy bugs and, although certain stages of these can fly, they usually spread by walking from one infected cocoa tree to a neighboring one when the crowns are in physical contact. The virus has found favorable conditions for spreading and has been difficult to eradicate in parts of Ghana where cocoa farms are small, and the cocoa basically forms a continuous canopy in the landscape. Authorities in Ghana now recommend a sort of box plots where small areas of cocoa are surrounded on all sides by a few lines of tree crops that are no hosts to the mealy bug vectors. Citrus trees are one such option. This design principle should be used in all farm rehabilitation in Liberia whether or not the virus is already present because it makes the farm landscape more resilient to a later introduction and spread of the virus. Basically, in no cocoa farm, should cocoa be planted right to the farm boundary, which should always be formed by other tree crops (e.g., citrus, plantains, oil palms). Larger farm plots could also be subdivided internally with non-host tree crops. Since a minimum of diversification is desirable even for small farms (see above), this measure is essentially cost free to the farmer if it is implemented right at the set-up or replanting of a farm, and no established cocoa trees need to be destroyed. If trees need to be destroyed, then a compensation may have to be paid, as is practice in Ghana, but this might only be justified once the virus is known to be present and a threat in an area, and could (partly) be provided in the form of non-cocoa tree seedlings.

Plant propagation

CSSV can also be spread through infected vegetative plant material (e.g., bud wood for grafting) and in Côte d'Ivoire grafting has recently been forbidden by the government to prevent the further spread of the virus. On the other hand, grafting has a considerable advantage in cocoa because it allows the formation of more homogeneously productive stands of smaller, more intensively managed trees. In Liberia, an added advantage is that, differently from Côte d'Ivoire, Ghana or Brazil where most farmers still need to learn grafting, many farmers may already be familiar with grafting from previous work with rubber. It is thus recommended that Liberia pursues a mixed strategy of hybrid seeds (imported or produced locally) and grafting, leaving the choice which technology to use to the farmers, but shifting the balance progressively to grafting.

The fastest approach to introduce grafting in cocoa would probably be to support skilled individuals in the communities to set up private bud wood gardens and nurseries, and to give subsidized loans to the local farmers to purchase these seedlings. The setting up of private cocoa nurseries has been promoted with considerable success in Sulawesi. An alternative approach would be to set up communal bud wood gardens and nurseries where appropriately trained lead farmers and technicians help interested farmers to produce their own grafted seedlings. This approach may be a little slower but would have a larger learning effect. Farmers learning how to graft in the communal nursery could then also do it themselves in their farms, possibly using bud wood from their own most productive cocoa trees. Whether private or communal, the nurseries would require frequent supervision by technicians to control for the absence of CSSV from the bud wood gardens and to ensure that only high-quality germplasm is being propagated. This germplasm could be collected from individual highly productive trees on the farms or in the future from successful introductions of cocoa germplasm from other countries. It is, therefore, very important that such productive trees are being identified and conserved when overgrown cocoa farms are being rehabilitated (see Component 3).

Fertilizer use

There is currently significant debate and research on ways to make mineral fertilizers available to cocoa farmers in Ghana and Côte d'Ivoire. These discussions, which also include the ideal composition of mineral fertilizers for cocoa depending on the specific soil conditions as well as the profitability of fertilizer application depending on the characteristics of the farm, should be closely monitored and lessons applied in Liberia. As a rule, fertilizer application in cocoa farms is more likely to be profitable if the trees are not too old and if the farm already has a certain level of productivity; otherwise, the yield response may not compensate for the additional cost of the fertilizer. Obviously this depends also on the price of fertilizer relative to that of cocoa or coffee and it has been found that in Ghana, where fertilizers are subsidized, cocoa farmers use more fertilizer and consequently have higher average yields than in Côte d'Ivoire where fertilizers are not subsidized (for the question of subsidizing fertilizer, see also Component 7).

Despite Liberia's infertile soils, it is likely that during the initial phase of the rehabilitation of the tree crop sector, mineral fertilizer may not be the most limiting factor for increasing yields, especially in farms that have been abandoned for several years so that soil conditions had some time to recover (as they do under a bush fallow). Fertilizer application is most likely to be worthwhile once farms have been fully rehabilitated or replanted with new trees, good agricultural practices (e.g., pruning) are regularly implemented, and weeds, pests and diseases are being controlled. At this stage, the farms will already have a yield level of several hundred kg per hectare. Once a significant number of cocoa farms in an area have reached this state, the latest research results and recommendations from the afore-mentioned projects in Côte d'Ivoire and Ghana (especially the southwest of both countries where climate and soil conditions are most similar to those in Liberia) should be followed.

Insufficient attention has been paid to the effects of liquid fertilizers containing micronutrients that are available on the market in Ghana and could be imported from there. Some cocoa farmers in Ghana and also in Brazil report significant yield increases from the application of micronutrients as liquid fertilizers (G. Schroth, pers. observation). Liquid fertilizers can be applied with the same motorized sprayers that are used for pesticide applications, and this certainly contributes to their popularity with some cocoa farmers. However, some tests should be made before making any wide-spread recommendations to farmers.

Controlled burning

Most tree crop farmers in Liberia also practice slash-and-burn agriculture (Fouladbash and Currie 2015). Slash-and-burn agriculture is always a threat to fire-sensitive tree crop farms and, in a hotter future climate, this will be even more the case (Schroth et al. 2009). Wildfire, probably originating from slash-and-burn agriculture, has destroyed many cocoa and coffee farms in Côte d'Ivoire and Ghana during strong El Niño years in the 1980s (Ruf et al. 2015). In order to manage this threat, controlled fire use in slash-and-burn plots should be a constant topic in farmer training, complemented by awareness campaigns to reach also those farmers who do not participate in the formal trainings (see also Component 1).

Component 5: Quality

Make quality improvements through harvest and post-harvest practices and marketing resilient to climate change.

Type of adaptation: INCREMENTAL / SYSTEMIC

Why is this important?	Recommendations
• Predicted shortening of dry season can further emphasize negative effects of poor road conditions and lack of adequate storage facilities in villages on quality of perishable products such as cocoa and coffee • Faster and possibly less regular ripening of cocoa in a warmer climate in combination with a tendency for the dry season to become shorter may result in a larger percentage of cocoa being harvested during the rainy season, increasing the need for artificial drying	➤ Create or maintain clear incentive for quality in cocoa and coffee pricing ➤ Provide co-funding and/or subsidized credit to farmer groups and cooperatives for solar driers and storage facilities in communities • Invest in road improvement, being careful not to improve access to previously inaccessible forest areas and inadvertently cause deforestation

➤ Immediate, no-regret actions.

Why is this important?

Because cocoa consumption is currently growing faster than its production, price prospects on the international cocoa markets are quite favorable over the next 5–10 years, unlike those for coffee. However, Liberia will have to compete in a market where relatively high quality standards are being set by Ghana with its stringent internal quality control procedures and increasingly also by Côte d'Ivoire. Producing consistently high-quality bulk cocoa[11] is essential for Liberia to re-establish itself and grow in the international cocoa market.

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[11] As distinct from specialty cocoas produced by some countries in Latin America, Asia-Pacific and Madagascar.

Significant progress has already been made in improving the quality of Liberian cocoa, suggesting that the country's cocoa farmers know in principle how to produce good-quality cocoa. Important obstacles to cocoa quality improvement in Liberia are, however, the poor processing, storage and transport infrastructure. Moreover, climate change has the potential to influence cocoa quality negatively. Currently, most cocoa in Liberia is harvested at the end of the rainy season and beginning of the dry season, which facilitates the sun drying of the fermented cocoa. With the projected shortening of the dry season, a larger percentage of the harvest may have to be dried during the rainy season, so that the risk of insufficiently dry and moldy beans could increase. Increasing ambient temperatures could also accelerate the ripening of the cocoa pods, with the same effect. If pod ripening becomes less uniform, the harvesting of unripe or overripe pods by farmers struggling to obtain sufficient quantities of beans for fermenting during one harvesting round could become an added problem, although this problem should decrease with overall increasing yields. If farmers use fire for artificial drying, the problem of smoke flavor in the cocoa could also increase.

Recommendations

The most basic rule for making cocoa quality resilient to climate change is that farmers must have a strong motivation for producing good-quality cocoa. In several cocoa-producing countries, this is not the case (e.g., Indonesia) and, consequently, the quality of the product is often low. In Liberia, farmers receive a price differential depending on cocoa quality, and it seems that this has already helped to increase quality. Another approach, used in several countries, is that the government sets quality standards, and cocoa that does not meet these standards is rejected. For the time being, the price differential approach seems preferable because it helps new farmers enter the business, but the differential should be sufficiently large to provide a strong incentive for continuous quality improvement.

Key steps in the production of quality cocoa are harvest, fermentation, drying, storage and transport. Correct harvesting (only ripe pods) and fermentation (for which the low-tech West African methods are adequate, as shown by Ghana being the "gold standard" for bulk cocoa quality) need to be taught in farmer field schools and be rewarded through the price differential. However, for drying and storage, the farmers need a certain physical infrastructure. Elevated mats as common in Ghana are good during the dry season, but artificial drying is necessary for cocoa harvested during the wet season. Solar driers have been successfully introduced in some producer groups and are used by traders and have apparently already made a difference in cocoa quality. Given the poor road conditions in many parts of the country, farmers and cooperatives should then have a place to store their dry cocoa away from rain, rodents and insects until it can be taken to the buying center. Currently, this is usually the home, but with increasing production, this will not be adequate. It is recommended that, in communities with a significant number of cocoa producers, solar driers and suitable storage space are built, possibly via subsidized loans to cooperatives or farmer groups or through joint funding where farmers would provide the man power and would then manage these facilities collectively.

Component 6: Finance

Improve the availability of finance to tree crop farmers.

Type of adaptation: SYSTEMIC

Why is this important?	Recommendations
• Better managed and more profitable farms are less vulnerable to income shocks from unusual weather events or pest and disease outbreaks; therefore, there is an increased need for short-term finance for inputs and labor to enable more intensive farm management • Farm rehabilitation, replanting with improved crop germplasm, farm diversification and improved drying and storage infrastructure to adapt to changing weather conditions require medium-term finance	• In order to afford better protection to providers of short-term credit to tree crop farmers, consider introducing a passbook system where loans are registered, built on the one used in Ghana ➤ Promote village savings groups ➤ Provide targeted, subsidized loan packages to farmers for farm rehabilitation, diversification, drying and storage infrastructure, supported by technical advice from extension service to reduce the risk of loan defaults ➤ Promote farm diversification as self-insurance strategy

➤ Immediate, no-regret actions.

Why is this important?

Cocoa and coffee farmers depend on finance to pay for their ongoing expenses during the cropping cycle, such as pesticide and fertilizer applications and labor to help in the harvesting and pod breaking. This type of short-term credit is usually provided by the trade. It is also common that traders pre-finance farmers cooperatives so that these are able to buy the harvest from their members and then sell it on to the same trader, at which point the loan is discounted from the sales price. At the present time, when many farmers need to rehabilitate their farms and cooperatives need to build their drying and storage infrastructure, there is additional need for finance that cannot be paid back over one season, but needs a several-year time frame. Climate change reinforces the need for finance because it obliges farmers to adapt, if only by intensifying their management practices through more intensive pruning, more regular pest and disease control and the use of improved planting material, thereby making their farms more productive and thus better able to absorb shocks from unusual weather events and market volatility.

Currently, both short-and medium-term finance are difficult to obtain for tree crop farmers in Liberia. In the absence of finance to purchase improved planting material, farmers may opt for cost-free local seeds, thereby compromising the future productivity of their farms. They may not be able to apply pest and disease control in a timely manner, thereby compromising both the quantity and quality of their production. They may be obliged to grow their traditional crop (say, coffee) because the trees are already present on the farm, even if they consider another crop such as cocoa or rubber more profitable and suitable for the site. Lack of finance thus restricts the farmers' ability to make decisions, including decisions that would make them less vulnerable to future climate change.

To some extent, the scarcity even of short-term finance seems to be related to a poor pay-back discipline of the farmers, which reduces the willingness of the trade to advance money for the cropping season. This problem is not unique to Liberia but could be more serious here because farmers may have a higher need and fewer options for obtaining credit. It may also be that Liberian farmers have still less confidence in the slowly reemerging agricultural sector and therefore prefer to apply the funds they have obtained in other sectors such as mining.

Recommendations

Considering the large role that the trade plays in providing short-term finance to cocoa producers and their organizations, it would be important to provide better protection against farmers defaulting on their loans. Ghana has addressed this same problem through a passbook system where loans are registered, so that farmers who have obtained a loan from one trader can (in theory) not sell their harvest to another one and avoid the loan repayment. It should be evaluated if a similar system (which could also be on line) could be introduced for tree crop farmers in Liberia. Village savings associations, on the other hand, would make farmers less dependent on short-term finance from the trade and could be promoted. The strengthening of farmer groups and cooperatives through training and supervision in financial matters should be a key component of the technical assistance system that has been discussed before (Component 3). Cooperatives meeting certain criteria in terms of internal structure and financial management could qualify for medium-term loan packages for investments in processing and storage infrastructure. It is very important that loans are accompanied by the appropriate technical advice and support to reduce the risk that farmer groups and cooperatives default on their loans.

There do not seem to be any current examples on yield or weather insurance for tree crops in West Africa and, unless it is well designed, a weather insurance system might even delay necessary adaptation decisions. For the time being, the best way to reduce the risk of sudden environment-related yield and income shocks for tree crop farmers is the diversification of farms with several crops that somewhat differ in their environmental requirements (including cocoa and coffee, or cocoa and rubber which are both common combinations in Côte d'Ivoire, with the former two crops often being planted on the same field and the latter two on separate plots on the same farm). The same strategy is also an effective protection against price fluctuations on the international commodity markets (Schroth and Ruf 2014).

Component 7: Food crops

Increase yields and labor productivity in food crop production to free labor for work in tree crops.

Type of adaptation: SYSTEMIC

Why is this important?	Recommendations
• Tree crops (especially coffee) are labor intensive, and large time investment by farmers in slash-and-burn production of food crops limits their availability for tree crops • Overcoming immediate food security needs may increase farmers' interest in producing tree crops for income • Women are particularly active in food crop production; therefore, investing in this sector would strengthen their role in the farming household • Intensifying food crop production and investing spare time in tree crops should have the environmentally desirable effect of reducing the total land area under slash-and-burn agriculture	➤ Conduct survey among farmers and agricultural technicians about most limiting factors in increasing food crop production ➤ Ensure availability of healthy, productive seeds and planting materials as well as necessary tools • Consider removing import taxes for mineral fertilizer ➤ Support a network of local markets for the trading of food crops

➤ Immediate, no-regret actions.

Why is this important?

Liberia has a relatively low population density, and a large part of its rural population is engaged in slash-and-burn agriculture for the production of food crops for their own consumption and local trade, including those growing tree crops (Fouladbash and Currie 2015). Given the poor road and market infrastructure and widespread poverty, the local production of food crops is essential for local food security. However, the fact that a large percentage of the farmers' time is spent on slash-and-burn agriculture also implies that labor will be a limiting factor in the further development of the cocoa and coffee sectors. Coffee production is highly labor intensive, with about 250–300 working days required to produce 1 tonne of coffee, of which around 80% are devoted to harvesting (ECOWAS 2007). Cocoa is somewhat less labor intensive than coffee, and this is a reason why it has tended to replace coffee in some West African countries. However, it is to be expected that most farmers will only be able to dedicate the necessary amount of time to farm rehabilitation and management of cocoa and coffee farms that is needed for satisfactory levels of productivity if they are able to reduce correspondingly the time they dedicate to food crop production.

If food crop production can be intensified so that farmers' food crop needs are satisfied with a smaller amount of time, it is to be expected that this will increase their interest in tree crop production, which allows to earn cash and is generally a lighter and, in many cases, a preferred task compared to food crop production in the slash-and-burn system. More efficient food crop production may particularly make the task of feeding the family easier for female farmers who typically carry a very large share of the burden of food crop production in West Africa (Fouladbash and Currie 2015).

If higher productivity and yields in food crop production allow farmers to shift a larger percentage of their time and land from slash-and-burn agriculture to tree crop agriculture, this would be environmentally desirable because it may imply less area under short-cycle crops with regular burns and overall lower carbon stocks in the landscape, compared to a landscape where a larger percentage of the land is under shaded tree crops (Lawrence et al. 2009; Schroth et al. 2015b).

Recommendations

Intensifying food crop production is often difficult because farmers can only invest very limited resources, other than their own labor, in food crop production. In fact, the use of slash-and-burn practices is a response to this limitation because external inputs (such as fertilizers) are replaced by the cost-free ashes of the burnt fallow vegetation. In order to understand the farmers' principal limitations and find the most effective and efficient ways to support them to produce food crops more intensively, on a smaller area and with less labor, it is recommended to carry out a survey with farmers and technicians working in the region about forms of support most desired by the farmers. This should obviously include a representative percentage of women who, as mentioned, are very involved in food crop production, processing and trade (Republic of Liberia 2008). The most limiting factor will most likely be time. There are various ways to increase the efficiency with which the farmers' time is used in food crop production. These include the availability of healthy and productive planting materials (vegetative or seeds, depending on the specific crop). Farmers may be encouraged to use mixed cropping (e.g., tuber+cereal+legume). A (temporary) subsidy on mineral fertilizers for use in food crop production could also be considered, but this should come with the necessary technical assistance since farmers do not necessarily know which crops do or do not respond to mineral fertilizer (e.g., maize or rice may respond more than root crops, and on light soils more than on clayey soils). Subsidizing mineral fertilizer, as a means of intensifying food crop production and reducing the area used for slash-and-burn agriculture, has been proposed as part of a green development strategy because of its potentially significant overall carbon benefits if it leads to less area being used for slash-and-burn agriculture (Lawrence et al. 2009). A first step for this could be to allow the tax-free importation of agricultural inputs and supplies, including fertilizer used both in food and tree crop production. Finally, supporting a network of local markets where surplus food production can be sold should also provide additional encouragement for intensifying agricultural practices and allow farmers to specialize on tree crop production and buy some of their food if they so wish.

Component 8: Climate monitoring

Ensure a minimum of agro-meteorological and agro-ecological monitoring and make the data available.

Type of adaptation: SYSTEMIC

Why is this important?	Recommendations
• Agro-meteorological and agro-ecological data are currently very scarce in Liberia, limiting the resolution and precision of analyses of crop climatic suitability, climate-crop interactions, and climate change vulnerabilities and impacts	• Establish and maintain a minimum set of agro-meteorological stations, covering the main climatic gradients of the country, as well as the capacity and tools to collect, analyze, synthesize and publish the information ➤ Collaborate with regional and international meteorological services to provide timely weather and climate alerts to land users and the industry, including about expected variation in yields, pest and disease pressure, and wildfire risk in years with unusual climate (e.g., El Niño years)

➤ Immediate, no-regret actions.

Why is this important?

It is currently very difficult to obtain detailed, reliable, up-to-date agro-meteorological information for Liberia. Yet, climate information is particularly important for a country like Liberia that (i) comprises a relatively wide range of climatic conditions from savannah to per-humid rainforest climates, and (ii) is located in a region where average climate conditions have undergone significant shifts over the last 50 years (becoming drier) and where there are indications that future climatic trends will be qualitatively different from those of the recent past (see Parts D and E). Detailed climate information is important for analyzing patterns in climatic suitability for certain crops within the country as well as their changes over time. Without such information, it can easily be (and often is) assumed that parts of a country that have been used for a certain crop in the past will also be suitable for that crop in the future. Yet, the example of neighboring Côte d'Ivoire shows that areas in the eastern rainforest belt that in the 1960s and 1970s were considered the core of the cocoa belt had basically become unsuitable for reproducing the crop by the 1990s, although the reasons for this were then still obscure and are only now slowly being understood (Ruf et al. 2015). The recognition that parts of some countries may actually have to switch crops as climate change progresses is still relatively recent and the idea of a planned, organized transition for the affected farmers and local traders from one supply chain to another even more so. Obviously, such complex transitions would have to be planned on the basis of reliable current and (near-)future climate information. Even where such fundamental changes are not (yet) needed, as is the case for Liberia, agro-meteorological information is needed for advising farmers about recommended crop varieties and farming practices. For example, there is a range of Robusta coffee varieties available that are suitable for either drier or wetter conditions (see Component 3), and shade recommendations for tree crops should reflect a balance between protecting crops from heat stress during the dry season and avoiding a damp microclimate favoring fungal diseases during the wet season (Component 4). Rainfall and sunshine conditions during the post-harvest season will inform investments in drying and storage infrastructure and their spatial prioritization (Component 5), while the degree of year-to-year variability (i.e., uncertainty) of the climate will influence the importance of crop diversification as a strategy of self-insurance and environmental risk mitigation (Component 6). All these decisions will rely on local weather and (longer term) climate information.

In order to make best use of agro-meteorological information and convert it into practical advice to farmers, this information should best be collected in context with agro-ecological information, such as the yields of the principal crops and varieties grown in the area, pest and disease outbreaks, etc. Currently, it is difficult to even obtain spatially detailed information about the main crops cocoa and coffee, and much less is information available about their yield patterns in space and time that could be related to weather patterns and trends. Particularly useful would also be observations about the severity of pest and disease attacks during the respective cropping cycle collected together with local weather information so that in the future, extensionists and farmers could be alerted about expected trends and outbreaks, and genotype selections for specific parts of the country could be progressively adapted to changes in weather patterns and their implications for pest and disease pressures.

Recommendations

According to Topor (2010), the Ministry of Agriculture has been planning to set up a network of small weather stations throughout the country. This is a valuable initiative. These stations should be simple and robust so that they require only a minimum of maintenance. Care should be taken that the stations cover the main climatic gradients in the country, including the main rainfall gradient within the cocoa and coffee belt. Collected weather information should immediately be made available on an open internet site so that it is readily accessible to users. Agro-ecological information could be collected within the area for which each climate station is representative. This would include the yields of main crop species and varieties and information about pests and diseases. This information could perhaps be collected by agricultural extensionists working in the area, or through a special program of a university that could also be in charge of further analyzing the data and making the results available.

Collaboration with international organizations on analysis of and alerts to global and regional climate patterns, such as El Niño years, is also strongly encouraged. As mentioned earlier, the implications of the massive shifts in rainfall patterns in West Africa over the past 50 years for crop suitability are only slowly being fully understood in the region, and the wildfires in the drought years 1982 to 1984 with their catastrophic impacts on the cocoa and coffee outputs of West Africa could have been much reduced through timely alerts to the farmers (Ruf et al. 2015).

Part G – Concluding remarks

In this final section of the report, we offer some broader observations and recommendations for a cocoa and coffee strategy for Liberia. The following discussion is based in part on our analysis in the previous parts of this report, and in part on our understanding of the broader dynamics of the cocoa and coffee industries in Africa and the world.

Climate vulnerability of cocoa and coffee production at regional level

In Part E, we have put the climate change vulnerability of cocoa and coffee in Liberia into the context of the West Africa region, which for cocoa is by far the most important production region globally, responsible for around two thirds of global cocoa output. The region also used to be an important Robusta coffee producer, but its importance for this crop has declined over the last decades. We have pointed out that, overall, the climatic suitability of this region for producing cocoa and coffee will decrease over the next decades, chiefly as a result of increasing maximum temperatures and evaporative demand during the dry season, which in West Africa is already relatively intensive. An increase in average temperature would not be a limiting factor for the two crops which support higher average temperatures elsewhere, but increased maximum temperatures during the dry season could become an important stress factor in some areas, especially where cocoa and coffee are grown with little or no shade. The systematic use of useful shade (or companion) trees in cocoa and coffee farms, especially but not only in the northern parts of Liberia (Nimba and Lofa Counties), is among the most important recommendations of this report. Whether the warmer temperatures and shorter dry season will lead to higher pest and disease pressures is impossible to say at this point. However, it is likely that the increased heat stress and evaporative demand during the maximum of the dry season, especially in the northern parts of the cocoa belt, will increase the susceptibility of cocoa and coffee trees to biotic stressors. Overall, then, the conditions for producing cocoa and coffee in West Africa will become more difficult (Läderach et al. 2013).

The deterioration of the climatic conditions will, however, not affect the whole region uniformly. In a study on cocoa, it has been shown that at national level in Côte d'Ivoire and Ghana, the region's largest cocoa producers, the transition areas between forest and savannah will be most negatively affected, while impacts in the most humid areas in the southwest of both countries as well as the very limited areas at higher elevation will maintain or even increase their suitability for growing cocoa (Läderach et al. 2013). Within this scenario of a spatially differentiated regional decline of the cocoa and coffee climate of West Africa, Liberia is a country that is projected to maintain suitable climatic conditions for growing these crops far into the 21st century. This is especially because Liberia offers the possibility for these crops to expand southward, into cooler and wetter climates. This gives the country an advantage over other countries in West Africa. At the same time, global demand for cocoa is projected to further increase as new consuming countries enter the market.

This puts Liberia into a potentially advantageous position as a country that could increase and then maintain cocoa (and coffee) output as that of other countries in the region might stagnate or decrease. At least for cocoa, this does not even require Liberia to enter into direct competition for markets with its regional neighbors since global cocoa demand is expected to exceed global supply in the coming years, with the prospect of a looming cocoa supply gap of up to 1 million tons within the next decade. The question, then, is how Liberia could position itself to best take advantage of this economic opportunity for its farmers and national development.

Strategic expansion of cocoa and coffee production within Liberia

Climatic conditions will thus remain suitable for growing cocoa and coffee in the current cocoa counties of Liberia (Nimba, Lofa and Bong) until and beyond the 2050s, provided that some safeguards are taken. These include especially the use of shade to reduce maximum temperatures during the dry season, the location of cocoa and coffee farms on deep soils with high water holding capacity (avoiding sandy and shallow soils), and the maintenance or restoration of forest cover in the landscape to reduce the impact of dry winds, especially during the dry season.

However, our analysis of climate change vulnerabilities was based on data for average years. There will of course be exceptionally dry (and wet) years in the future, just as there were exceptional years in the past. It is even expected that extreme years might be more frequent in the hotter, future atmosphere than they are now. Of particular importance in West Africa have been El Niño years that have caused severe droughts particularly in the 1980s (Ruf et al. 2015), and similar climate events are to be expected in the future. Cocoa and coffee production is sensitive to such weather extremes, and it is to be expected that years of high and low rainfall in the future will be accompanied by corresponding fluctuations in national and regional cocoa and coffee outputs.

How can Liberia buffer itself against and perhaps even take advantage of such regional fluctuations in production? Liberia is in a unique position within the West African cocoa belt in that it has a wider range of suitable climates for cocoa and coffee than other countries in the region, reaching from the margin of the savannah in the north to very humid climates in the south of the country. Currently, cocoa and coffee production is concentrated in the North (Nimba, Lofa and Bong Counties) whose climate is broadly comparable to that of other parts of the West African cocoa and coffee belt (Part E). However, most or all other counties of Liberia are producing or have recently produced at least small quantities of cocoa and coffee (Part B) and are therefore broadly suitable for these crops, as also confirmed by our analysis. By expanding cocoa and coffee production further South, Liberia could increase the range of climates under which relevant quantities of these commodities are produced, and by doing so stabilize its aggregate national production against year-to-year weather fluctuations. Particularly dry years would presumably affect production in northern Nimba and Lofa Counties, but much less so in the south of Nimba or neighboring counties (Grand Gedeh, River Cess, Grand Bassa, etc.). On the other hand, an exceptionally wet year might result in unusually high black pod (cocoa) and rust (coffee) pressure in those wetter counties in the South, but less so in the North.

By expanding cocoa and coffee production along the dry-wet gradient within the country, Liberia could reduce year-to-year fluctuations of its cocoa and coffee output and potentially position itself as a particularly reliable producer of these commodities in terms of quantity and quality. The advantages of this strategy on the global market could greatly outweigh the increased technical and logistical complexity of growing a commodity under a range of climatic conditions, possibly requiring different varieties to cover the different site conditions.

Obviously, this reduced vulnerability of cocoa and coffee production to year-to-year weather fluctuations at national level resulting from a greater climatic amplitude would not mean that individual farmers growing these crops at a given location would be less vulnerable to climate fluctuations. This strategy can reduce climate vulnerability at national but not at farm level. It therefore always needs to be complemented by the afore-mentioned practices to reduce the climate vulnerability of cocoa and coffee production at farm level, as well as some diversification of income options to reduce the vulnerability of livelihoods, as discussed in Part F.

Will cocoa and coffee become threats to Liberia’s forests?

The favorable position of Liberia as an island with a wide range of climates in an increasingly hot subcontinent where agricultural production will increasingly come under pressure from high temperatures and drought stress during the dry season may result in the country also being seen as a desirable destination for cocoa and coffee farmers in search for better farm sites. The population of West Africa is traditionally highly mobile and for over half a century farmers from the drier savannah countries and regions have been migrating to the less populated but more productive forest areas where crops such as cocoa, coffee, oil palm and rubber can be grown (ECOWAS 2007; Ruf et al. 2015). Could Liberia in the future attract “climate refugees,” including cocoa and coffee farmers from the wider region whose crops and farms begin to fail under the pressures of climate change?

During the past half-century, opportunities in the cocoa and coffee sectors of Côte d’Ivoire and Ghana have not only attracted farmers from drier countries in the region (the Sahel), but also caused a massive flow of internal migrants from the central and eastern parts of both countries to their respective southwestern regions where now most of the cocoa production of Côte d’Ivoire and Ghana are located. It has been a matter of debate to what extent these migrant flows were motivated by the search for a more humid climate that offered better conditions for producing cocoa than the increasingly drought-prone eastern forest zones of these countries where cocoa was first introduced. If climate was a major motivation for the migration of cocoa farmers from the cocoa hubs of the 1960s and 1970s in eastern Côte d’Ivoire to the southwestern areas where most cocoa is produced now, then it could be expected that further heating and drying of the climate might trigger similar migrations in the future, with possibly Liberia as their main destination. This, in turn, could put additional pressure on Liberia’s forest resources and the institutions in charge of their conservation and sustainable management.

Ruf et al. (2015) studied the relationships between climate and cocoa migrations in Côte d’Ivoire on the basis of historic climate data and interviews with migrants and came to the conclusion that while drought was a motivation for migration decisions, far more important was the perception that forest was available for planting in the southwestern parts of the country. Even during the very dry 1980s when wild fires repeatedly ravaged cocoa and coffee farms in the eastern and central parts of the country’s forest zone, most migrants were not driven by a deteriorating climate but attracted by the perceived opportunities of an open forest frontier. In other words, they were not “climate refugees” but entrepreneurs taking advantage of an opportunity to improve their livelihoods (available forest land). Where farmers affected by drought and wildfire had no opportunities for acquiring new forest land for planting, they often stayed, replanted their farms and intensified and adapted their production practices to the changing environmental conditions, rather than migrating elsewhere (Ruf et al. 2015).

These findings have important implications for Liberia. They suggest that even some decades from now when cocoa and coffee farms in many parts of West Africa will presumably come under increasing climatic pressure and Liberia will stand out as the least drought-prone country in the region, the attraction of climate migrants would not be an automatism determined by climatic gradients in the subcontinent, but would depend very much on specific policies implemented in the country. In the hypothetical case that Liberia decided to open its forests to prospective cocoa and coffee planters, as Côte d'Ivoire did half a century ago, it could become an important destination for migrants from the region in search for land for planting and for taking advantage of the "forest rent" (see Part F). If, on the other hand, the country established, implemented and communicated a zero-deforestation policy for tree crop development, in line with its general forest conservation policies and REDD+ strategy (FCPF/UN-REDD 2012; Fouladbash and Currie 2015), migrant fluxes might be more modest as farmers in neighboring countries affected by climate change may instead adapt their farming systems, and potentially their crops, to the changing environment. In this sense, Liberia's decisions with regard to its tree crop development policies could have important implications for the tree crop sectors of neighboring countries as well.

Can Liberia itself become unsuitable for growing cocoa and coffee?

We have shown in Part E that Liberia, including its most continental parts in Lofa and northern Nimba Counties, will remain suitable for growing cocoa and coffee through the 2050s if protective measures such as appropriate shade use are taken. However, climatic pressures will be mounting especially through increasing maximum temperatures during the dry season and increasing evaporative demand (ETP). Fortunately, this increased water demand will be satisfied by the relatively high annual rainfall in all of Liberia and by a predicted tendency towards a shorter dry season.

We have highlighted the need to grow cocoa and coffee under shade to reduce maximum dry season temperatures, to select deep soils with high water holding capacity to supply the trees with water during phases without rainfall in the dry season, and to manage the landscape in such a way that farms are protected to the extent possible from dry winds from the savannah that affect the area (and much of the West African forest zone) during the dry season (the *harmattan*). We have also emphasized the need to prune cocoa trees to small size so that they are more water efficient. Current climate models have low predictive power for time horizons beyond the 2050s, and it is also not possible to know how carbon emissions (dependent on economic development and technological choices around the globe) will evolve. Therefore, it is not possible to say at what point in time maximum temperatures and dry season water demand will have increased so much that cocoa and coffee cannot be grown anymore in northern Liberia in spite of these measures, and whether this point will be reached in the second half of the 21st century.

However, we can speculate about the forces and triggers that would move cocoa and coffee from viable to unviable crops in those areas. As shown in Part E, the most limiting factors for both crops in Liberia will be maximum temperatures and water demand during the dry season. High maximum temperatures require shade that can easily be provided by trees. In many parts of the tropics, cocoa, coffee and also tea are grown under the shade of trees that often also have other economic functions. However, in climates with a long and intensive dry season, tree crops are often grown with little or no shade, because shade trees would compete with the tree crops for water during the dry season if rainfall does not provide enough moisture for both. This is the case for some coffee areas in parts of Africa (Foster and Wood 1963) and Brazil. The fact that cocoa in Nigeria around Ibadan is grown with little shade has also been interpreted as a response to insufficient water reserves during the dry season to support both cocoa and shade trees (Wood and Lass 2001). From these relationships, we can deduce that the hottest and driest parts of Liberia would become unsuitable for growing current varieties of cocoa and coffee when the maximum dry season temperatures required the use of shade trees while the insufficiency of rainfall during the dry season prevented their use. Whether and by when this will happen is not possible to predict but, thanks to the projected weakening of the dry season, it will most likely be after 2050 even in the driest parts of Nimba and Lofa Counties.

Strategic investments in the cocoa and coffee sectors

This gives some time to adapt cocoa and coffee varieties to the changing climatic conditions. Breeding and selection criteria include tolerance to high temperatures and water-use efficiency for the drier end of the climate spectrum, and tolerance to diseases (e.g., black pod for cocoa, rust for coffee) for the wetter end. As pointed out in Part F, a monitoring and selection program to adapt cocoa and coffee varieties to climate change should best take place at locations that are strategically placed on a climate gradient, for example, reaching from the northern tip of Nimba into Bong County and potentially continuing from there into the wetter parts of southern Liberia. A breeding program carried out at a single location in the country, in contrast, would be much less meaningful in terms of adapting cocoa and coffee germplasm for the future climate conditions. A breeding and selection program should also build as much as possible on achievements of neighboring countries in the region and be implemented in collaboration with their institutions. For Robusta coffee, the work done by the National Center for Agricultural Research (CNRA) in Côte d'Ivoire is particularly relevant here, while for cocoa, a close collaboration with Côte d'Ivoire and Ghana as well as Sierra Leone would be indicated.

Besides the rebuilding of the country's infrastructure for post-harvest processing, storage, transport and marketing of agricultural products, as outlined in Part F, perhaps the most important and most urgent investment for preparing the cocoa and coffee supply chains of Liberia for climate change is in technical capacity. The insufficiency of technical assistance continues to be a major impediment to the modernization of the cocoa sectors of neighboring countries, despite significant international investments and favorable prices on the international market. Liberia is a small country with a still relatively modest number of farmers and this in a way makes the task of establishing a system of technical assistance that reaches all of the country's farmers more feasible. This could start with the tree crop farmers, as outlined in Part F, and then expand to farmers not growing market crops with the objective of also integrating them into the national markets for agricultural products, without abandoning food production for their own consumption and the local market. Any agricultural development strategy, be it intensification, diversification, climate change adaptation, or integration with a national forest conservation strategy, requires effective communication channels between the decision makers at government level and the local farmers. In many countries, these communication channels, if they exist, do not reach all farmers. For Liberia to position itself as an important future agricultural commodity producer and to effectively integrate small farmers into commodity production for international markets, it will need such functioning communication channels through a country-wide technical assistance system.

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