

# Climate change and its effects on banana production in Colombia, Costa Rica, the Dominican Republic, and Ecuador

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## Executive summary

### Chapter 1: Objectives and structure of the report

It is the major objective of this research to provide a science-based assessment of the past and future climate change effects in some of the major banana producing regions of selected Latin American countries – including impacts on banana yields and prices, as well as on farmers' income and profitability, and effects on biodiversity. The specific focus of this report will be on Colombia, Costa Rica, the Dominican Republic, and Ecuador. By looking at the situation and particularities of climate change and banana production in the regions of Antioquia, Magdalena and La Guajira in Colombia, Heredia in Costa Rica, Valverde and Azua in the Dominican Republic, as well as El Oro in Ecuador, similarities and differences between these regions shall be identified in order to derive sound policy and business implications with respect to sustainable banana production now and in the future.

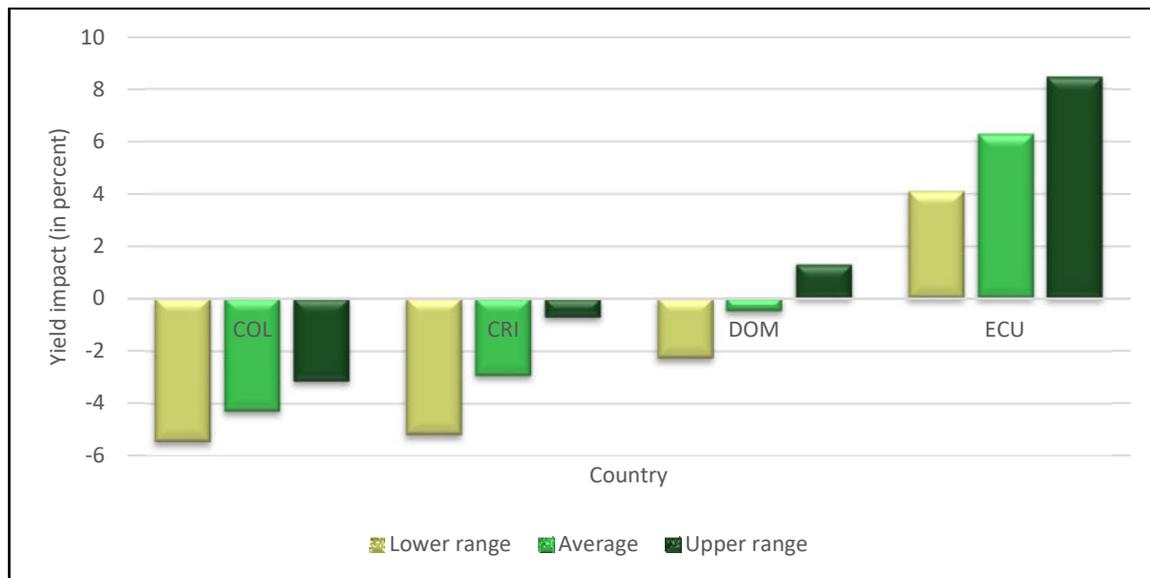
The report is structured accordingly and first gives a concise overview of the basic facts about climate change and its impacts on agriculture at the national level of Colombia, Costa Rica, the Dominican Republic, and Ecuador. This is followed by a closer look at the four Latin American countries to provide a projection of future climate changes to be expected in the main banana producing regions of these countries. This again is followed by a comprehensive ex-post assessment of the climate change impacts on banana yields over the last 30 years in Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde, as well as in specific banana production areas located within these regions. This ex-post assessment is complemented by an ex-ante quantitative estimation of potential climate change impacts on banana yields. Yield is, however, only one variable that may be affected by climate change, but banana production might also be affected by changes in the suitability of the production area as well as by changes in the incidence of pests and diseases. In addition, the changing production conditions will also have an effect on market prices and will, thus, have an influence on farm profitability and income. Moreover, environmental aspects can be affected as well. These aspects will be additionally analyzed before recommendations for sound private and public decision-making are presented along with suggestions for the targeted formulation and implementation of policy and research efforts.

### Chapter 2: Status quo of the scientific discussion

According to the current state of knowledge, temperature is already increasing in the selected countries, and a future increase in temperature is projected. Regarding the quantity and distribution of precipitation, the results are less uniform. Most models and experts still agree that climate change often has negative effects on agricultural production, and banana production in the four countries of Latin America and Caribbean (LAC) is predicted to be affected as well. However, the direction and magnitude of potential changes in banana yields seem to vary in each country. Out of the countries

we focus on, Colombia and Costa Rica will potentially be affected most, while the Dominican Republic may experience smaller losses and Ecuador could even benefit from climate change in terms of banana yields. This is also visualized in figure A.

**Figure A:** Predicted banana yield impacts of the RCP 8.5 climate scenario in 2050 for Colombia, Costa Rica, the Dominican Republic, and Ecuador compared to 1970–2000



Source: Own figure based on Varma and Bebbler (2019a).

It is important to point out, however, that the available information on potential climate change-related banana yield losses or gains at the national scale should not be overestimated. Climate projections always entail a considerable degree of uncertainty and, in addition, may even differ within a country. In fact, the yield effects presented in figure A are based only on average temperature and precipitation and explicitly do not account for other factors such as the climate-driven increase in the frequency of extreme events, or the risk posed by established or emerging diseases. To improve our understanding of climate change impacts on banana production, it is therefore necessary to zoom into the most important banana producing regions of the countries analyzed in this study.

### Chapter 3: Observed and projected climate developments

For the seven selected banana producing regions in LAC, we consequently analyze the observed climate as well as the projected climate change by 2050 and 2070. We do this by looking at the development of average annual temperature and precipitation as well as the number of dry months (months with less than 60 mm precipitation) and potential evapotranspiration (PET). With respect

to these variables, the following can be stated for their historical/observed averages in the period from 1990 until 2018 in the selected seven regions:

- Due to its location between the Andes and the coast of Ecuador, El Oro shows a steep east-west gradient in temperature ranging from around 15°C in the east to around 25°C in the west. Meanwhile, the Costa Rican region of Heredia displays a north-south gradient ranging from temperatures of less than 20°C in the south to more than 25°C in the north. In the Dominican Republic, temperatures in Valverde are on average between 25 and 27.5°C, while temperatures in the more southern region of Azua range from 17.5 to 25°C. In comparison with the other regions considered in this study, the Colombian regions show the largest temperature range. Antioquia covers the tail of the Andes with temperatures between 15 and 17.5°C as well as lowlands and coastal regions, where temperatures range from 25 to 27.5°C. And the most northern Colombian regions of Magdalena and La Guajira display average temperatures ranging from 10°C in the Sierra Nevada de Santa Marta to 30°C at lower altitudes.
- La Guajira in Colombia also shows the largest precipitation range of all the regions considered. In fact, the driest sub-region can be found here in northern Colombia: The northeast of La Guajira is a desert with a large area receiving less than 500 mm of precipitation per year. In contrast, in the western parts of La Guajira precipitation levels of up to 3,000 mm are observed. El Oro in Ecuador as well as Valverde and Azua in the Dominican Republic receive moderate precipitation of around 500 to 1,500 mm per year. Magdalena in Colombia receives similar precipitation amounts of around 1,000 to 1,500 mm in most of the region, except for the Sierra Nevada de Santa Marta, where annual precipitation rates of up to 4,000 mm are found. Antioquia shows a large precipitation range with a drier center, where annual rainfall is around 1,000 to 1,500 mm, while most precipitation is experienced on the western slopes of the Andes with up to 6,000 mm. The climatic conditions in Costa Rica are overall rather wet. The region of Heredia, thus, experiences annual precipitation levels of 3,000 to 4,500 mm on average.
- The observed number of annual dry months reciprocally reflects the distribution of precipitation. Consequently, El Oro at the Ecuadorian Pacific coast experiences between six and ten dry months per year. In the north of La Guajira even ten to eleven dry months per year are observed on average, while fewer dry spells are experienced in the east with an average of one month locally. The number of dry months in the neighboring region of Magdalena is similarly low with most of the region staying below six months per year. The third Colombian banana producing region of Antioquia has a maximum of two dry months per year locally. In Costa Rica, the numbers of dry months are also low, and in Heredia the average is below one month per year. In the Dominican Republic, however, local conditions vary strongly. The number of dry months in Azua and Valverde ranges from two to eight months in most areas.
- As PET is a non-linear function of temperature, the spatial distribution strongly resembles the temperature distribution, however, the spatial variability is stronger. Accordingly, the

Colombian regions of La Guajira, Magdalena and Antioquia show the largest range in annual PET from 500 to 2,250 mm. The annual PET sum of El Oro in Ecuador is comparatively low with values between 500 and 1,500 mm. An almost similar range can be observed for Heredia in Costa Rica, where the annual PET sum is between 750 and 1,500 mm locally. The same PET range can also be observed in the Azua region, while Valverde, also in the Dominican Republic, has a PET sum of 1,250 to 1,500 mm per year.

All future climate analyses – for the periods until 2050 and 2070 – are run for two different climate change scenarios. First, we use the Representative Concentration Pathway (RCP) 2.6, the so-called “peak” scenario which is in line with the Paris Agreement. In addition, we also use the RCP 8.5 scenario which represents a trajectory of high emissions or a Business as Usual (BAU) scenario. With respect to temperature, the projected changes for the seven banana producing regions are presented in Figure B.

**Figure B:** Calculated difference of the near-surface temperature, compared to 1990–2018, for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Region	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	0.99°C	1.98°C	1.13°C	3.20°C
Azua	0.87°C	1.74°C	0.90°C	2.82°C
El Oro	0.94°C	1.75°C	1.04°C	2.81°C
Heredia	0.78°C	1.43°C	0.81°C	2.26°C
La Guajira	0.88°C	1.60°C	0.93°C	2.55°C
Magdalena	0.97°C	2.00°C	1.16°C	3.30°C
Valverde	0.97°C	1.84°C	0.97°C	2.95°C

Source: Own figure.

The projections clearly show that by 2050 temperatures will increase everywhere in the seven selected banana producing regions. Under the strong mitigation scenario RCP 2.6 the warming rates only differ slightly amongst regions and are between 0.76°C in Heredia and 0.99°C in Antioquia. Under the BAU scenario RCP 8.5, the warming distribution in 2050 looks strikingly similar, while warming rates are roughly doubled everywhere in the seven regions. Conditions will not substantially change by 2070 under the RCP 2.6 scenario, although temperatures will be slightly higher than those predicted for 2050. However, a stronger increase in temperatures is expected for RCP 8.5 by 2070. Average temperatures in the seven banana producing regions are then expected to increase between 2.16°C in Heredia and 3.30°C in Magdalena.

The projected changes in precipitation for the seven banana producing regions are presented in Figure C. The projected changes under RCP 2.6 by 2050 are generally small but already show a wide range across the different regions. While changes are negligible in El Oro in Ecuador with a decrease of less than 1 percent, precipitation is expected to increase on average by around 5 percent in the Colombian region of La Guajira. As for the RCP 8.5 scenario, annual precipitation changes projected for 2050 are – on average – slightly stronger, and not everywhere consistent with the direction of the changes projected for RCP 2.6. For instance, a decrease in precipitation can now be observed in Azua in the Dominican Republic, as well as in the Colombian regions of La Guajira and Magdalena. With a decrease of less than 1 percent on average the precipitation changes in El Oro are again negligible as already projected under the RCP 2.6 scenario. In turn, the strongest drying trend of the seven regions is expected in Valverde in the Dominican Republic, where precipitation is projected to decrease by around 12 percent on average.

**Figure C:** Calculated difference of the annual precipitation, compared to 1990–2018, for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Region	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	-2.02 %	-6.61 %	-3.02 %	-12.06 %
Azua	2.07 %	-8.09 %	-0.48 %	-18.69 %
El Oro	-0.75 %	-0.86 %	-0.64 %	2.86 %
Heredia	4.11 %	1.78 %	1.58 %	4.93 %
La Guajira	5.37 %	-5.90 %	-3.98 %	-18.75 %
Magdalena	0.91 %	-8.89 %	-4.61 %	-17.92 %
Valverde	-4.72 %	-11.78 %	-5.10 %	-22.61 %

Source: Own figure.

By 2070, projected changes of annual precipitation remain small under the strong mitigation scenario RCP 2.6. The most obvious difference to 2050 is that the direction of precipitation changes in La Guajira is reversed going from positive to negative, now decreasing by approximately 4 percent, while e.g. the precipitation changes in Heredia, Azua and El Oro are negligible with 1 to 2 percent on average. In contrast, precipitation changes in 2070 will be much more pronounced for the RCP 8.5 scenario: The Colombian banana producing regions will become substantially dryer with precipitation decreasing on average by 12 percent in Antioquia, 19 percent in La Guajira, and 18 percent in Magdalena. The two regions located in the Dominican Republic will also experience precipitation decreases of on average 23 percent in Valverde and 19 percent in Azua. In contrast, El Oro in Ecuador as well as Heredia in Costa Rica are expected to experience precipitation increases of around 3 and 5 percent, respectively.

The projected annual precipitation changes are also reflected in the projected changes of the number of dry months per year. Generally, the seven selected regions show a tendency towards a higher number of dry months with the strongest increases in banana producing regions located in Colombia and especially in the Dominican Republic. The only exception to this trend is projected for Heredia in Costa Rica, where dry months are expected to decrease in the future.

With respect to PET, the projected changes by 2050 range from increases by 10 percent in Heredia to 19 percent in Magdalena for the RCP 2.6 scenario and from 20 percent in Heredia to around 50 percent in Magdalena for the RCP 8.5 scenario. By 2070 and under the RCP 2.6 scenario only very small changes in PET are expected compared to the changes in 2050. Most notable is the change in Magdalena, where PET will increase from 19 percent in 2050 to 23 percent in 2070. By 2070 the climate models project a strong increase in annual PET under the RCP 8.5 scenario, with larger differences across the seven regions. While in Heredia, Costa Rica, the projected PET change will still only be 33 percent on average, the change will be highest in the Colombian region of Magdalena with an increase of annual PET by more than 90 percent.

## Chapter 4: Ex-post assessment of climate change impacts on yields

We use a sophisticated methodological concept known as a dynamic process-based model to determine the yield impacts of observed climate change. For this purpose, climate change is initially defined as the change in annual temperature and yearly precipitation in a selected region. Our method is based on calculating a climate-yield coefficient. This coefficient quantifies the difference between the obtainable yield for observed climatic conditions in the banana producing regions and the achievable yield under an optimal climate for banana production. To calculate it, the observed annual average temperature and precipitation for each region/area are needed. In addition, the minimum, optimum and maximum temperature and precipitation describing the suitable climatic ranges for banana production are also needed for our calculations.

Our results show that the regional climate is very variable and never optimal for banana production across the regions. This means that suboptimal climate conditions cause losses in banana production. Throughout the years, the annual average climatic conditions seem to have been relatively favorable in Magdalena, Antioquia and Heredia, whereas they were for instance slightly less favorable in El Oro and Azua. In any case, a uniform trend across all regions is not apparent. There are regions (Antioquia in Colombia, Heredia in Costa Rica, and El Oro in Ecuador), where a (small) decrease of annual yield losses can be identified over the past three decades. In opposite to that, there are regions (Azua and Valverde in the Dominican Republic, as well as La Guajira and Magdalena in Colombia), where a (small) increase of yield losses over time becomes evident. By and large, the results do not change when zooming into the banana production areas within the selected regions. However, since banana production is concentrated in areas where temperature and precipitation are closer to the optimum, suboptimal climatic conditions cause fewer losses.

In addition, it can be stated that all but one region (namely El Oro in Ecuador) experienced an increase in annual climate fluctuation. This can be considered an initial indicator of higher uncertainty due to already occurring climate change. In other words: The number and/or intensity of "good" but also of "bad" years for banana production is increasing and the annual yield is, thus, more often or more strongly influenced by annual changes in temperature and precipitation than by the long-term trends in these variables, which are much more subtle. One conclusion of our analysis therefore is that it is not so much the underlying trend of climatic changes, but rather the uncertainty associated with climate change that should be an immediate cause for concern regarding banana production.

In fact, rising temperatures are considered to increase the frequency and/or severity of several types of extreme weather events already today, particularly leading to more droughts, more intense but less frequent rains, cold snaps, heat waves, and more violent storms. All these events have the potential to impact banana productivity in a temporary but serious way. Extreme weather events have had devastating impacts on local and regional banana production in the selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador in the past 30 years. Temporarily, temperatures that were too hot and/or too cold, or conditions that were too wet and/or too dry, have often led to yield depressions at short notice that go (far) beyond the annual yield impacts resulting from the variability of average annual temperatures and yearly precipitation levels. Yield changes of plus or minus 20 percent compared to the achievable yield can be related to "normal" annual weather fluctuations, while yield depressions of 80 percent and even more (up to a total loss) have been reported as the outcome of extreme events.

## Chapter 5: Ex-ante estimation of climate change impacts on yields

The dynamic process-based yield model can also be used to determine the yield impacts of projected climate change. For this ex-ante analysis, the projected annual changes in temperature and precipitation due to climate change (see figures B and C) will be used to run scenario analyses for two spatial levels. First, we consider the regions of Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde as targets of our analysis. By doing so, we zoom from the national level to the regional level. In a second step, we duplicate this approach by looking even closer into specific banana production areas located within the regions of Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde. Hence, we also zoom from the regional to the local level.

Our results for the regional level still neglecting particularities in banana producing areas within the regions (see below) show that the potential yield developments due to climate change are not uniform across the seven regions. Regardless of the chosen scenario, climate change may create a yield benefit for banana producers in Antioquia and El Oro. In both regions the current average annual temperatures are still below 25°C, what means that the inherent temperature increases due to climate change would be favorable for banana production. At the same time, the precipitation changes projected for these regions are very small or even "positive", so that the temperature-

related trend is supported or at least not counteracted. In opposite to that, climate change will most probably be unfavorable for banana production in La Guajira and Magdalena as well as in Valverde. These three regions are currently experiencing average annual temperatures close to the optimum. Further temperature increases will therefore tend to lower yields as temperatures move away from the most suitable conditions for banana growth. This trend will also be supported by precipitation changes in the three regions. Finally, results for Azua and Heredia are somewhere in between. In both regions average annual temperatures are currently below the temperature optimum for banana production and are expected to increase, again potentially leading to an increase in banana yields. However, both regions will most likely also see a worsening of the precipitation situation. Consequently, taken together both trends will rather act to further limit regional banana yields.

By zooming from the regional level to the local level we can substantiate these findings. Figure D shows the yield impacts for the specific banana production areas.

**Figure D:** Climate change impacts on yields for specific banana production areas in the selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador under various scenarios compared to 1990–2018

2050 RCP 2.6	2070 RCP 2.6	2050 RCP 8.5	2070 – RCP 8.5
Area in Antioquia			
-3.5 %	-3.6 %	-6.8 %	-12.9 %
Area in Azua			
-0.9 %	-2.5 %	-9.0 %	-21.6 %
Area in El Oro			
0.6 %	2.6 %	2.7 %	4.0 %
Area in Heredia			
-4.1 %	-2.9 %	-4.2 %	-9.8 %
Area in La Guajira			
-1.0 %	-3.9 %	-5.8 %	-9.4 %
Area in Magdalena			
1.1 %	1.2 %	1.7 %	-0.9 %
Area in Valverde			
-2.8 %	-3.1 %	-8.0 %	-17.4 %

Source: Own figure.

In the case of Antioquia, zooming into the specific banana production area located in Urabá reveals that this area is already facing a temperature above 25°C in the reference period and that it will

therefore most probably face future yield decreases as temperatures are projected to increase in any of the chosen scenarios. In the specific banana production area of Azua the rise of temperatures above the optimal level combined with precipitation levels that are still too low will act to decrease banana yields in any scenario. In the region of El Oro the local temperature near/east of Machala is already close to 25°C in the reference scenario, and future temperature increases will therefore partially lead to temperatures higher than optimal. In combination with precipitation levels that are still very low, this will result in an almost negligible yield effect to be expected from climate change. Future temperatures that will be higher than optimal are also expected in the local banana production area in Heredia. In combination with increasing precipitation levels that are too high for optimal banana growth already today, climate change will lead to slightly decreasing yields. Similarly, in the local production area of La Guajira future changes in temperature and precipitation are predicted to result in yield decreases. In the banana production area of Magdalena the projected changes in local precipitation and temperature will probably not alter the yield situation in a significant way. Finally, in the banana production area of Valverde the situation basically does not change when compared to the broader region, where climatic conditions are expected to lower banana yields in the future.

We now apply the same approach as Varma and Bebbler (2019a), who aimed at assessing the "affectedness" of a country's banana production in the face of climate change by using the three criteria "at risk", "adaptable" and "advantage". Using this approach, we show that by zooming in from the national to the regional and furthermore to the local level we can achieve a substantiation of this assessment. The results are shown in figure E.

**Figure E:** Risk assessment for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador using the RCP 8.5 scenario in 2050

Assessment of Varma and Bebbler (2019a)		Own assessment for the regional level		Own assessment for the local level in ...	
Colombia	At risk	Antioquia	Advantage	... Antioquia	At risk
		La Guajira	At risk	... La Guajira	At risk
		Magdalena	At risk	... Magdalena	Adaptable
Costa Rica	Adaptable	Heredia	Adaptable	... Heredia	Adaptable
The Dominican Republic	Adaptable	Azua	Adaptable	... Azua	At risk
		Valverde	At risk	... Valverde	At risk
Ecuador	Advantage	El Oro	Advantage	... El Oro	Adaptable

Source: Own figure.

From the above it can be concluded that our analysis is robust and leads to differentiated outcomes if local and uncertainty aspects are added. In fact, the more the focus of the analysis is on the local

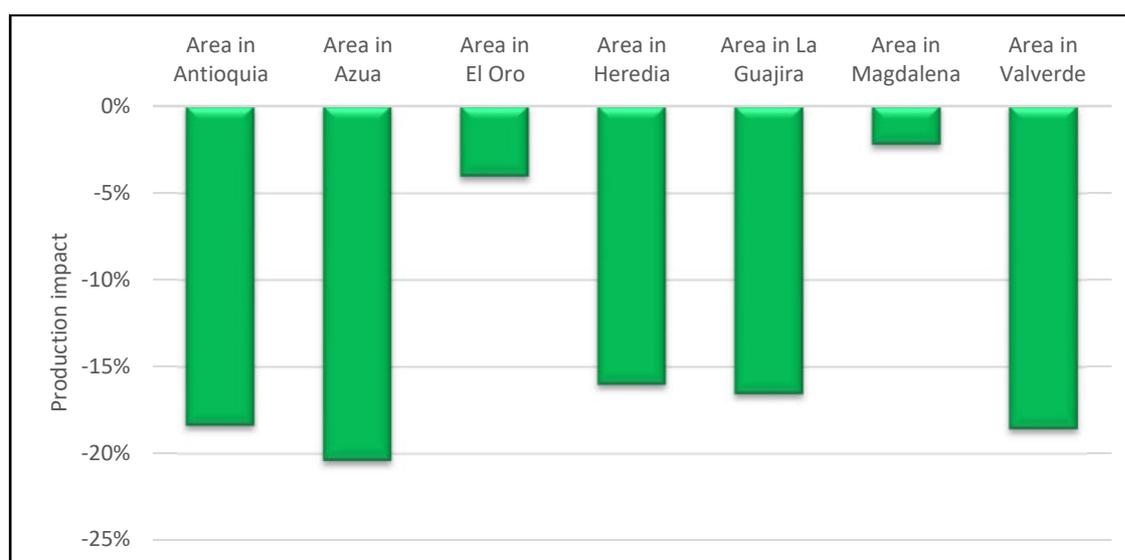
level, the more the aspect of uncertainty must be considered. To better cope with this uncertainty, alternative climate model runs can be used and predictions with respect to the regional and local susceptibility to more frequent and/or severe weather events must be made. For the latter, we arrive at the conclusion that such events will become more likely in future. Hence, short-term considerations (extreme events and subsequent potentially devastating yield impacts) must be distinguished from mid-term to long-term considerations (i.e. fluctuating yield impacts around the trend) when it comes to assessing the projected impact of climate change on banana yields in the study regions.

## Chapter 6: Analyses of other than yield impacts of climate change

Apart from direct impacts on yields, shifts in the suitability of production areas are also essential to be taken into consideration. In this respect, we find that remarkable shifts may be the outcome in the broader LAC region and that in selected regions and production areas the impacts due to lower/higher yields might be "enhanced" by changes in the suitability of area. In these cases the climate change impacts will therefore be greater than suggested by the direct yield impacts alone. It can also be concluded that the pressure of various pests and diseases will increase with climate change. In particular, diseases may spread further and cause increasing damages. The potential production impacts can be exemplified for the Black Sigatoka disease.

The direct yield impacts resulting from climate change, as well as the impacts of changing suitability of area and Black Sigatoka disease pressure can be merged to provide a condensed overview of the aggregated climate change impacts on banana production. Figure F displays the results for the RCP 8.5 scenario in 2050. Accordingly, all banana production areas are expected to suffer losses.

**Figure F:** Accumulated production impact of various drivers of climate change for specific banana production areas and the RCP 8.5 scenario in 2050



Source: Own figure and calculations.

Production losses from climate change are equivalent to a supply shortage. Hence, various other economic variables will be affected by these losses as well. Market and trade volumes will shrink accordingly, and this will tend to increase domestic as well as international banana prices. However, we find that the relative price increases will usually be smaller than the relative production decreases. This means that market revenues that can be generated from banana production will shrink. In combination with production costs that will most probably increase due to necessary adaptation measures on-farm, this will act to decrease farm income.

Our results have given evidence that banana production is affected by climate change and will continue to be so in the future. However, banana production is also a contributor to climate change. Therefore it is crucial to also look at the mitigation potential on-farm. Inorganic fertilizers and plant waste landfills have the highest carbon footprint in banana production. Consequently, options for reducing greenhouse gas (GHG) emissions from banana production should target these two sources first. Two other major sources for GHG emissions are postharvest losses and land use changes. Each banana that is wasted has been produced in vain and, hence, each unit of waste represents an opportunity to further reducing on-farm GHG emissions. This holds especially true if the demand is partially supplied by bananas produced on areas formerly dedicated to other ecosystems than agriculture. The use of newly cultivated land for banana production potentially releases much more GHG emissions than production on areas that are already under agricultural use. Considering the above, all options must be used to sustainably intensify banana production where possible.

The same applies to threats related to biodiversity that can be linked to banana production and climate change. These risks are numerous. The impact, however, is always site-specific. Negative biodiversity impacts can be reduced by many measures, e.g. by implementing polycultures, integrated pest management and organic management practices. Moreover, banana production requires large areas of land, while at the same time natural land that is not used for banana production (or agricultural production in general) can be dedicated to preserving biodiversity. The question now is: What can be done on-farm and along the banana value chain when pressure on land increases? Again, to avoid substantial biodiversity losses all options must be considered to sustainably intensify banana production where possible. This will essentially help to avoid or reduce land use changes and to preserve as much natural and nature-like habitats as possible. Nevertheless, many interactions within this complex system must still be understood and scientifically analyzed to fully assess the biodiversity changes and changes in other environmental aspects that might result from the increasing impacts of climate change on banana production.

## Chapter 7: Recommendations

Climate change impacts on banana production are robustly covered in this study. However, some important aspects regarding the study's scope and limitations must be considered and lead to concrete research needs to improve the assessment of climate change impacts on banana production:

- Climate models can be selected based on different approaches. Therefore, future studies should ideally use different model ensembles for their analyses to enable a comparison and discussion of the different resulting climate futures and their results for banana production.
- Our approach to calculate a climate–yield coefficient is but one amongst various methods to analyze the climate impacts on banana yields. Once more data and better information become available other methods should additionally be used.
- We calculated the climate–yield coefficient using average annual temperature and precipitation as endogenous variables, and specific optimum, minimum and maximum values of these variables to define an ecological niche. As the optimal growing conditions for bananas may differ between regions and management regimes, further regional analyses looking into specific ecological niches for banana production might provide additional insights.
- Yield is multi-factorial and depends on many factors other than climate variables. An integration of such factors and their interlinkages would add value to the analysis.
- Probability considerations with respect to tipping points were also not included in our analysis. Enlarging uncertainty analyses to take account of potential tipping points is an important requirement for further research on the topic.
- Water availability considerations must also be elaborated in more detail. Given the great impact of water availability on banana yields and the delay factor of noticeable impacts, it is crucial for further investigations to look at potential impacts on irrigation and water availability in a broader interregional context including hydrological conditions.
- Finally, adaptation efforts within the banana sector are not included in our study. Including these is likely to at least alleviate the adverse effects climate change might have.

In fact, on-farm adaptation measures must cope with changes in temperatures, water availability, winds, and a higher frequency and severity of extreme weather events. In this respect, a first important issue is integrated water resource management including aspects such as climate-smart irrigation, recovery after water stress events, soil moisture management, climate-smart professional practices, and improved water and nutrient efficiency. Other adaptation measures include building dikes to block floods, improving the soil organic matter and the drainage of the soils. Noteworthy is also, that the plants' recovery after extreme events can and should be helped by cleaning up fallen plants, selecting replacement suckers and replanting. Also moving from monocropping to a more diverse cropping system or agroforestry system can reduce the impacts of extreme events. Canals built around the banana plants might also help to combat flooding and avoid standing water. In addition, banana growers should generally resort to supplementary irrigation if possible.

As high temperature events seem to pose more problems to banana production than low temperature events, an important preventive measure can be the use of banana varieties adapted to higher

temperatures. Therefore, varieties adaptable to the different regional conditions must be identified or developed. Another option that might be quicker to implement and more effective given the heterogeneous conditions in which bananas are grown, is to adapt key production processes and technologies to the changing climate. This includes the points mentioned above as well as different pre-harvest and post-harvest processes. To cope with high gusts of wind, banana trees can furthermore be tied through string reinforcements and windbreaks. Having robust systems for recovery in place – like rapid infrastructure repair, disease-free rhizomes, and equipment re-supply – is also considered crucial to limit the overall impacts of climate change and in particular of extreme events. More precisely, climatic variability caused by the El Niño Southern Oscillation must also be considered. This argues for paying increased attention to providing flood, drainage, and emergency systems for a wider range of adverse rainfall outcomes. Supporting the meaningful application of plant protection products for the control of pests and diseases and promoting appropriate fertilization methods is also deemed to be of substantial importance.

Sound policy making can enable and foster a transition towards climate-smart banana production. Educational programs and extension services should be supported and made available at low costs. Targeted education and training programs should also promote the diversification of incomes and reduce the existing regional dependencies on banana production. Political decision-making should therefore more frequently consider and promote agricultural diversification in areas where banana production is especially threatened by climate change. Also infrastructure should be enhanced and developed in such a manner that it improves access to markets, inputs and technologies while reducing post-harvest losses. In the context of our study the sharing of information and knowledge across the LAC region is especially important and should be significantly facilitated. The dissemination of climate information to banana growers could be an additional important policy issue.

Research is a policy topic of its own when it comes to managing climate change. With respect to banana production, research is vital to develop and test the necessary management practices for farmers to cope with climate change impacts. Such research should be of high priority in banana-related scientific and development activities. More generally, the data availability for banana research needs to be considerably improved, what requires among others to intensify the collaboration between plant, agricultural and climate sciences. Further research efforts must also be made to explore the effect of abiotic stresses and of possible adaptation options for banana production. A specific focus of research policy should also be directed towards plant breeding. Moreover, research can also help to improve and adapt land use policies in to better facilitate climate change adaptation. Policy makers of banana importing countries can also do their part by establishing policies to promote consumer acceptance of other banana varieties apart from the Cavendish banana and to reduce food loss. Finally, a regional or global framework in research should be fostered with the aim of facilitating mutual exchange as well as common data collection and analysis. The present study can be seen as a first attempt towards establishing such a regional and global research framework on climate change and banana production. However, the challenges ahead are still numerous and require cooperation and collaboration between all stakeholders involved and at all levels to ensure banana production can continue to thrive also in the future.

## Resumen ejecutivo

### Capítulo 1: Objetivos y estructura del informe

El principal objetivo de este informe es proporcionar una evaluación científica de los efectos pasados y futuros del cambio climático en la producción bananera de algunas de las principales regiones productoras de América Latina y el Caribe (ALC). Por ende, la investigación incluye los impactos del cambio climático en el rendimiento y en los precios del banano, impactos en los ingresos y la rentabilidad de la producción, así como posibles repercusiones en la diversidad biológica. El presente informe se centrará específicamente en Colombia, Costa Rica, la República Dominicana y el Ecuador: Al examinar la situación y las particularidades del cambio climático y la producción bananera en las regiones de Antioquia, Magdalena y La Guajira en Colombia, Heredia en Costa Rica, Valverde y Azua en la República Dominicana, así como El Oro en Ecuador, se identificarán las similitudes y diferencias entre estas regiones a fin de derivar recomendaciones adecuadas para el ámbito político y empresarial con respecto a una producción bananera sostenible, hoy y en el futuro.

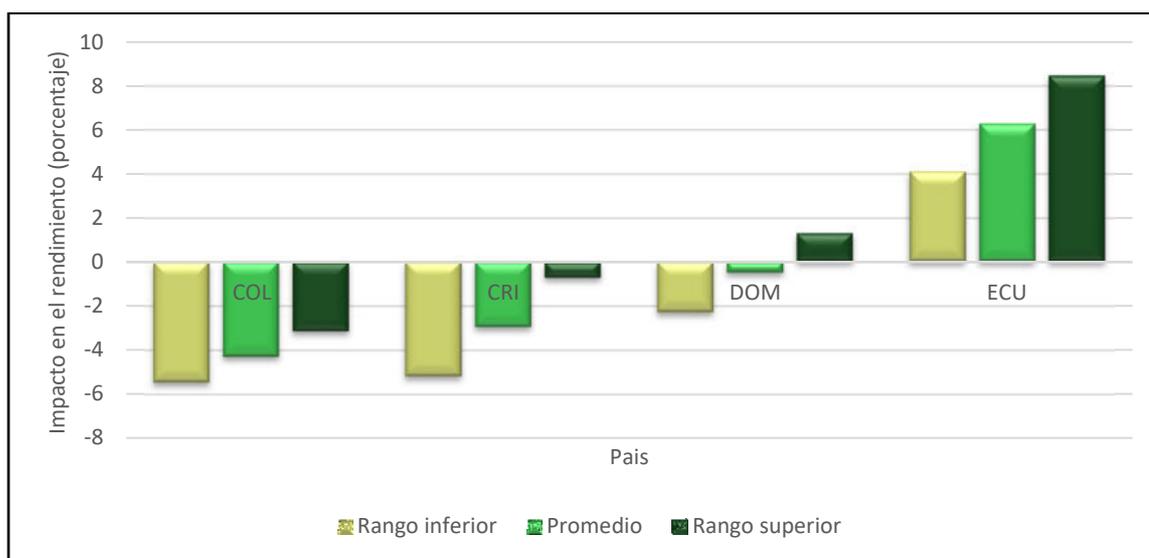
El informe está estructurado de manera que en primer lugar se ofrecerá un resumen general y conciso de los hechos, y se presentarán informaciones básicas acerca del cambio climático y sus impactos en la agricultura de Colombia, Costa Rica, República Dominicana y Ecuador a nivel nacional. A continuación, se examinará más de cerca a estos cuatro países y a sus principales regiones productoras, al proporcionar una proyección de los cambios climáticos que han de esperarse en estas regiones en el futuro. A ello le seguirá una evaluación ex post de los impactos que el cambio climático ha tenido durante los últimos 30 años en los rendimientos de las siete regiones seleccionadas, así como en las zonas específicas donde se concentra la producción de banano dentro de estas regiones.

Esta evaluación se complementará con una estimación cuantitativa ex-ante de los efectos que el cambio climático tendría en el rendimiento del banano en el futuro. Sin embargo, el rendimiento resulta ser sólo una de las variables que pueden verse afectadas por el cambio climático. La producción de bananos también podría verse afectada por cambios en la idoneidad de la zona de cultivo, así como por cambios en la incidencia de ciertas plagas y enfermedades, ambos causados por el cambio climático. Además, los cambios en las condiciones de producción tendrían también un efecto en los precios de mercado y, por lo tanto, afectarían la rentabilidad y los ingresos de las explotaciones agrícolas. Por otra parte, aspectos medioambientales también podrían verse afectados. Estos aspectos serán analizados adicionalmente antes de presentar recomendaciones que faciliten la toma de decisiones adecuadas en el ámbito privado y público, así como sugerencias para la formulación e implementación de políticas y proyectos de investigación.

## Capítulo 2: Estado actual de la discusión científica

Según el estado actual del conocimiento, las temperaturas medias en los países seleccionados van en aumento, y según las proyecciones estos aumentos continuarán en el futuro. En cuanto a la cantidad y distribución de las precipitaciones, los resultados son menos uniformes. Aun así, la mayoría de los expertos y modelos climáticos coinciden en que el cambio climático suele tener efectos negativos en la producción agrícola, y se prevé que la producción de banano en los cuatro países de ALC incluidos en este informe también se verá afectada. Sin embargo, la dirección y la magnitud de los posibles efectos en el rendimiento del banano varían en cada país. De los cuatro países, es de esperarse que Colombia y Costa Rica se verán potencialmente más afectados, mientras que la República Dominicana podría experimentar pérdidas menores y Ecuador podría incluso beneficiarse del cambio climático a través de un aumento de los rendimientos. Estos resultados son visualizados en la Figura A.

**Figura A:** Impactos climáticos previstos en el rendimiento del banano en Colombia, Costa Rica, República Dominicana y Ecuador en el año 2050 según el escenario climático RCP 8.5 (período de referencia: 1970–2000)



Fuente: Figura propia basada en Varma y Bebbber (2019a).

Sin embargo, es importante señalar que la información disponible sobre posibles aumentos o reducciones del rendimiento del banano relacionados con el cambio climático no debe ser sobreestimada. Las proyecciones climáticas siempre conllevan un grado considerable de incertidumbre y, además, estas proyecciones pueden incluso diferir dentro de un mismo país o región. De hecho, los efectos en el rendimiento que se pueden observar en la Figura A están basados únicamente en la temperatura y las precipitaciones medias y no tienen en cuenta otros factores, como el aumento de la frecuencia de los fenómenos extremos que también es causado por el cambio

climático, ni el riesgo que supone el aumento de la incidencia de ciertas enfermedades. Por lo tanto, para mejorar nuestro entendimiento de los efectos del cambio climático en la producción bananera de los países analizados, es necesario hacer un acercamiento y enfocar nuestro análisis en las regiones productoras de bananos más importantes dentro de estos países.

### Capítulo 3: Evolución del clima histórico y proyecciones climáticas

Para las siete regiones productoras de banano seleccionadas en ALC, analizamos a continuación la evolución del clima respecto a las observaciones históricas, así como el cambio climático proyectado para los años 2050 y 2070. Para ello analizamos los cambios en los promedios anuales de la temperatura y la precipitación, así como en el número de meses secos (meses con menos de 60 mm de precipitación), y en la evapotranspiración potencial (ETP). Con respecto a los promedios históricos/observados de estas variables durante el período de 1990 a 2018, se puede afirmar lo siguiente:

- Debido a su ubicación que va desde las faldas de los Andes hasta la costa del Ecuador, la región de El Oro muestra un pronunciado gradiente de temperatura que se extiende desde los 15°C al extremo Este a los 25°C al extremo oeste de la región. Mientras tanto, Heredia en Costa Rica muestra un gradiente de temperatura del Norte al Sur con temperaturas de menos de 20°C en el extremo sur hasta más de 25°C en el extremo norte de la región. En la República Dominicana, las temperaturas en Valverde se ubican en promedio entre los 25 y 27,5°C, mientras que las temperaturas en la región más meridional de Azua oscilan entre los 17,5 y 25°C. El mayor gradiente de temperatura se observa en las regiones colombianas: En Antioquia, las temperaturas en ciertas zonas situadas cerca de los Andes oscilan entre los 15 y 17,5°C, mientras que en las zonas de tierra baja y en las regiones costeras las temperaturas oscilan entre los 25 y 27,5°C. Así mismo, Magdalena y La Guajira registran temperaturas medias que van desde los 10°C en la Sierra Nevada de Santa Marta hasta los 30°C en zonas más bajas.
- La Guajira en Colombia también muestra la más amplia gama en los niveles de precipitación de las regiones consideradas. En efecto, el área más seca de las regiones evaluadas se encuentra en el extremo noreste de la Guajira: se trata de un desierto con un área considerable que recibe menos de 500 mm de precipitación al año. En cambio, en las partes occidentales de La Guajira se observan niveles de precipitación de hasta 3.000 mm. El Oro en Ecuador, así como Valverde y Azua en la República Dominicana, reciben precipitaciones moderadas de unos 500 a 1.500 mm por año. La región de Magdalena en Colombia recibe cantidades similares de precipitación de alrededor de 1.000 a 1.500 mm en la mayor parte de la región, excepto en la Sierra Nevada de Santa Marta, donde los niveles de precipitación anual pueden llegar hasta 4.000 mm. Antioquia muestra grandes diferencias en los niveles de precipitación con una zona central más seca, donde la precipitación anual es de alrededor de 1.000 a 1.500 mm, mientras que la mayor parte de la precipitación se da en las laderas

occidentales de los Andes con niveles de hasta 6.000 mm. Las condiciones climáticas en Costa Rica son en general bastante húmedas. En la región de Heredia, por lo tanto, se miden niveles de precipitación anual de 3.000 a 4.500 mm en promedio.

- El número anual de meses secos constituye un reflejo de la distribución de las precipitaciones. Por consiguiente, El Oro en la costa Pacífica ecuatoriana experimenta entre seis y diez meses secos al año. En el norte de la Guajira se observan incluso de diez a once meses secos al año en promedio, mientras que en el este de la región se observan menos períodos secos con un promedio de un mes a nivel local. El número de meses secos en la región vecina de Magdalena es igualmente bajo, y la mayor parte de la región permanece por debajo de los seis meses por año. La tercera región bananera colombiana de Antioquia tiene un máximo de dos meses secos por año a nivel local. En Costa Rica, el número de meses secos también es bajo, y en Heredia el promedio es inferior a un mes por año. En la República Dominicana las condiciones locales varían mucho, y el número de meses secos en Azua y Valverde oscila entre los dos y ocho meses en la mayoría de las zonas.
- Como la ETP es una función no lineal de la temperatura, la distribución espacial de esta variable se asemeja mucho a aquella de la temperatura, sin embargo la variabilidad es más pronunciada. Por lo tanto, las regiones colombianas de La Guajira, Magdalena y Antioquia muestran las mayores diferencias en la ETP anual con niveles de 500 a 2.250 mm. La suma anual de la ETP en El Oro en Ecuador es relativamente baja con valores entre 500 y 1.500 mm. Niveles casi similares se pueden observar en Heredia, Costa Rica, donde la suma anual de la ETP se sitúa entre 750 y 1.500 mm. Los mismos niveles de ETP pueden observarse también en la región de Azua, mientras que en Valverde, también en la República Dominicana, se observa una ETP de 1.250 a 1.500 mm por año.

A continuación, todos los análisis dirigidos hacia el futuro – es decir para los períodos hasta 2050 y 2070 – serán realizados utilizando dos escenarios de emisiones alternativos. En primer lugar, utilizaremos la Trayectoria de Concentración Representativa (RCP, por sus siglas en inglés) 2.6, es decir, el escenario climático que está en línea con el Acuerdo de París. En segundo lugar, utilizaremos el escenario RCP 8.5 que representa una trayectoria de emisiones altas o un escenario de "Business as Usual" (BAU). Con respecto a la temperatura, los cambios proyectados para las siete regiones productoras de bananos son presentados en la Figura B.

Las proyecciones muestran claramente que para el 2050 las temperaturas aumentarán en todas las siete regiones productoras de banano seleccionadas. En el escenario RCP 2.6 los niveles de calentamiento difieren sólo ligeramente entre las regiones y están entre 0,76°C en Heredia y 0,99°C en Antioquia. En el escenario RCP 8.5, la distribución del calentamiento en el 2050 resulta ser bastante similar, mientras que los niveles parecen duplicarse aproximadamente en todas las regiones. Según el escenario RCP 2.6., las temperaturas ya no aumentarán sustancialmente entre el 2050 y el 2070. Sin embargo, las temperaturas sí aumentarían a un nivel mayor en el escenario RCP 8.5, con niveles proyectados entre 2,16°C en Heredia y 3,30°C en Magdalena en el 2070.

**Figura B:** Cambios proyectados de la temperatura anual según los escenarios climáticos RCP 2.6 y RCP 8.5 para las regiones productoras de banano seleccionadas de Colombia, Costa Rica, la República Dominicana y el Ecuador (período de referencia: 1990–2018)

Región	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	0.99°C	1.98°C	1.13°C	3.20°C
Azua	0.87°C	1.74°C	0.90°C	2.82°C
El Oro	0.94°C	1.75°C	1.04°C	2.81°C
Heredia	0.78°C	1.43°C	0.81°C	2.26°C
La Guajira	0.88°C	1.60°C	0.93°C	2.55°C
Magdalena	0.97°C	2.00°C	1.16°C	3.30°C
Valverde	0.97°C	1.84°C	0.97°C	2.95°C

Fuente: Figura y cálculos propios.

Los cambios proyectados en las precipitaciones para las siete regiones productoras de banano son presentados en la Figura C.

**Figura C:** Cambios proyectados de la precipitación anual según los escenarios climáticos RCP 2.6 y RCP 8.5 para las regiones productoras de banano seleccionadas de Colombia, Costa Rica, la República Dominicana y el Ecuador (período de referencia: 1990–2018)

Región	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	-2.02 %	-6.61 %	-3.02 %	-12.06 %
Azua	2.07 %	-8.09 %	-0.48 %	-18.69 %
El Oro	-0.75 %	-0.86 %	-0.64 %	2.86 %
Heredia	4.11 %	1.78 %	1.58 %	4.93 %
La Guajira	5.37 %	-5.90 %	-3.98 %	-18.75 %
Magdalena	0.91 %	-8.89 %	-4.61 %	-17.92 %
Valverde	-4.72 %	-11.78 %	-5.10 %	-22.61 %

Fuente: Figura y cálculos propios.

Para el 2050, los cambios según el RCP 2.6 son generalmente pequeños, pero muestran grandes diferencias entre las regiones. Mientras que los cambios en las precipitaciones pueden considerarse

como insignificantes en El Oro, con una disminución de menos del 1 por ciento, se espera que las precipitaciones aumenten en promedio alrededor del 5 por ciento en la región colombiana de La Guajira. En cuanto al RCP 8.5, los cambios en las precipitaciones anuales proyectados para el 2050 son - en promedio - ligeramente más pronunciados, y no siempre consistentes con la dirección de los cambios proyectados para el RCP 2.6. En la región de Azua, por ejemplo, ahora se puede observar una disminución de las precipitaciones, así como también en las regiones colombianas de La Guajira y Magdalena. Con una disminución de menos del 1 por ciento en promedio, los cambios en la precipitación anual proyectados para El Oro son nuevamente insignificantes, como se observó en el escenario RCP 2.6. A su vez, en Valverde, en la República Dominicana, se proyecta la disminución de las precipitaciones más alta, de alrededor del 12 por ciento.

En el año 2070, los cambios proyectados de la precipitación anual siguen siendo pequeños en el escenario RCP 2.6. En comparación al 2050, la diferencia más evidente es que la dirección de los cambios se invierte en La Guajira, donde los niveles de precipitación ahora disminuyen aproximadamente un 4 por ciento. Los cambios en las precipitaciones en Heredia, Azua y El Oro serán muy pequeños, con promedios del 1 al 2 por ciento. Por otro lado, los cambios en las precipitaciones en el 2070 serán mucho más pronunciados para el escenario RCP 8.5: las regiones productoras de banano de Colombia se volverán más secas, con una disminución de las precipitaciones del 12 por ciento en Antioquia, 19 por ciento en La Guajira y 18 por ciento en Magdalena. Las dos regiones de la República Dominicana también experimentarán disminuciones de las precipitaciones de un promedio del 23 por ciento en Valverde y 19 por ciento en Azua. Por el contrario, se espera que El Oro en Ecuador así como Heredia en Costa Rica experimentarán aumentos de las precipitaciones de alrededor del 3 y 5 por ciento, respectivamente.

Los cambios de las precipitaciones anuales también se ven reflejados en los cambios proyectados del número de meses secos por año. En general, las siete regiones seleccionadas muestran una tendencia hacia un mayor número de meses secos, y los aumentos más fuertes se prevén para las regiones en Colombia, y especialmente, en la República Dominicana. La única excepción a esta tendencia se prevé para Heredia, en Costa Rica, donde se espera que los meses secos disminuyan en el futuro.

Con respecto a la ETP, los cambios proyectados para el 2050 van desde aumentos del 10 por ciento en Heredia hasta el 19 por ciento en Magdalena para el RCP 2.6, y aumentos de aproximadamente el doble, variando desde 20 por ciento en Heredia hasta alrededor de 50 por ciento en Magdalena para el RCP 8.5. Las proyecciones bajo el RCP 2.6 muestran sólo diferencias muy pequeñas para el 2070 en comparación con el 2050. Lo más notable es el cambio en Magdalena, donde la ETP aumentará de 19 por ciento en el 2050 a 23 por ciento en el 2070. Para 2070 los modelos climáticos sí proyectan un fuerte aumento de la ETP bajo el escenario RCP 8.5, con mayores diferencias en las siete regiones. Mientras que en Heredia el aumento proyectado de la ETP todavía será de sólo un 33 por ciento en promedio, el cambio será más pronunciado en la región colombiana de Magdalena con un aumento de la ETP anual de más del 90 por ciento.

## Capítulo 4: Evaluación ex-post de los impactos del cambio climático en los rendimientos

En este estudio utilizamos un sofisticado concepto metodológico conocido como "modelo dinámico basado en procesos" para determinar los impactos observados/históricos del cambio climático en el rendimiento. Para este propósito, medimos el cambio climático a través de los cambios en la temperatura y la precipitación anual en una región seleccionada. Nuestro método se basa en el cálculo de un coeficiente de rendimiento climático. Ese coeficiente cuantifica la diferencia entre el rendimiento de bananos bajo las condiciones climáticas presentes y el rendimiento que podría obtenerse bajo las condiciones climáticas óptimas para este cultivo. Para calcular este coeficiente, es necesario contar con observaciones de temperatura media anual y de precipitación anual para cada región/área. También se necesita definir los valores de temperatura y precipitación mínimos, óptimos y máximos que describan las condiciones climáticas óptimas para la producción de banano.

Los resultados de nuestro análisis muestran que el clima a nivel regional es muy variable, y que en ninguna de las siete regiones el clima puede ser considerado como óptimo para la producción de bananos. Por consiguiente, se puede concluir que las condiciones climáticas subóptimas están causando pérdidas en el rendimiento. A lo largo de los años, las condiciones climáticas medias anuales parecen haber sido relativamente favorables para la producción de banano en las regiones de Magdalena, Antioquia y Heredia, mientras que fueron, por ejemplo, un poco menos favorables en El Oro y Azua. En todo caso, no se puede observar una tendencia uniforme: hay regiones (Antioquia en Colombia, Heredia en Costa Rica y El Oro en Ecuador), donde parece haber habido una (pequeña) disminución de las pérdidas en las últimas tres décadas. Por otro lado, hay regiones (Azua y Valverde en la República Dominicana, La Guajira y Magdalena en Colombia), donde se evidencia un (pequeño) aumento de las pérdidas en el rendimiento del banano a lo largo del tiempo. En general, los resultados no cambian cuando hacemos un acercamiento a las zonas de cultivo de bananos dentro de las regiones seleccionadas. Sin embargo, dado que la producción de bananos se concentra en zonas en las que la temperatura y las precipitaciones son generalmente más cercanas al nivel óptimo, las condiciones climáticas subóptimas causan menos pérdidas.

Además, nuestros resultados permiten ver que en todas las regiones, salvo en El Oro en el Ecuador, se ha producido un aumento de la fluctuación del clima anual. Esto parece indicar un aumento de la incertidumbre debido al cambio climático que ya se está evidenciando. En otras palabras: el número y/o la intensidad de los años que pueden considerarse como especialmente "buenos" y/o "malos" para la producción de bananos va en aumento, y vemos por eso que el rendimiento anual del banano parece estar más influenciado por los cambios a corto plazo en la temperatura y las precipitaciones, que por las tendencias de estas dos variables a más largo plazo. Una conclusión de nuestro análisis, entonces, es que no es tanto la tendencia a largo plazo de los cambios en las variables climáticas, si no que es más bien la creciente incertidumbre asociada al cambio climático, la que debería ser una causa inmediata de preocupación en relación con la producción de bananos.

De hecho, el aumento de las temperaturas también conlleva un aumento de la frecuencia y/o la gravedad de varios tipos de fenómenos meteorológicos extremos, que en particular se manifiestan a través de sequías, lluvias más intensas pero menos frecuentes, olas de frío, olas de calor y tormentas más violentas. Todos estos fenómenos pueden afectar gravemente la productividad del banano de manera temporal. En los últimos 30 años estos fenómenos ya han tenido efectos devastadores en la producción regional de bananos en las regiones seleccionadas de Colombia, Costa Rica, la República Dominicana y el Ecuador. A corto plazo las temperaturas demasiado altas o bajas, o las condiciones demasiado húmedas o secas, a menudo provocaron reducciones en el rendimiento del banano que fueron (mucho) más allá de los impactos resultantes meramente de la variabilidad de los medios anuales de las temperaturas y los niveles de precipitación. Mientras que cambios en el rendimiento de más o menos un 20 por ciento (en comparación con el rendimiento óptimo) suelen estar relacionados con las fluctuaciones "normales" del clima anual, se han observado reducciones del rendimiento del 80 por ciento, e incluso mayores (hasta llegar a pérdidas totales), como resultado de los fenómenos extremos.

## Capítulo 5: Estimación ex-ante de los impactos del cambio climático en los rendimientos

En lo siguiente se utiliza el mismo modelo dinámico basado en procesos empleado anteriormente para estimar los efectos que el cambio climático tendrá en los rendimientos del banano a futuro. Para esta evaluación ex-ante se ejecutarán dos análisis de escenarios, uno a nivel regional y uno a nivel local, utilizando los cambios proyectados para la temperatura y la precipitación anuales presentados en las Figuras B y C. En un primer lugar, el análisis se enfocará en las regiones completas de Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena y Valverde. En un segundo paso se aumentará el nivel de acercamiento al analizar los impactos en zonas específicas de producción de banano que se encuentran localizadas dentro de las siete regiones seleccionadas.

Los resultados a nivel regional, aún sin tomar en cuenta las particularidades de las zonas productoras de banano dentro de las regiones (véase más abajo), muestran que los efectos del cambio climático en los rendimientos del banano no serán uniformes en las siete regiones seleccionadas. Independientemente de si se utiliza el RCP 2.6 o el RCP 8.5, el cambio climático podría beneficiar el rendimiento del banano en las regiones de Antioquia y El Oro. Actualmente, en ambas regiones el promedio de la temperatura anual está por debajo de los 25°C considerados como óptimos para la producción de bananos, por lo que el aumento de la temperatura causada por el cambio climático sería beneficioso para la producción en partes de estas regiones. Al mismo tiempo, los cambios proyectados de las precipitaciones son tan pequeños o incluso "positivos" que no contrarrestarían los beneficios obtenidos a través del aumento de la temperatura. Por el contrario, los rendimientos del banano en La Guajira y Magdalena, así como en Valverde, muy probablemente se verán desfavorecidos por el cambio climático. Actualmente estas tres regiones cuentan con promedios de temperatura anuales alrededor del valor óptimo. En este caso, un mayor aumento de las temperaturas llevaría a una disminución de los rendimientos a medida que estas se alejarían del

óptimo para la producción bananera. Así mismo, los cambios en las precipitaciones proyectados para las tres regiones apoyarían esta tendencia. Finalmente, los impactos en las regiones de Azua y Heredia parecen ubicarse en un punto intermedio. En ambas regiones se observan temperaturas medias por debajo de la temperatura óptima en el escenario de referencia, y como las temperaturas irán en aumento, se espera que esto lleve también a un aumento de los rendimientos en el futuro. Sin embargo, es muy probable que en ambas regiones también se observe un empeoramiento de la situación de las precipitaciones. En conjunto, ambas tendencias contribuirán más bien a limitar los rendimientos del banano en estas regiones.

Pasaremos ahora del nivel regional al nivel local, lo que nos permitirá sustanciar considerablemente las conclusiones obtenidas hasta el momento. Los efectos del cambio climático en el rendimiento del banano a nivel local dentro de las siete regiones seleccionadas se ven resumidos en la Figura D.

**Figura D:** Impacto del cambio climático en los rendimientos del banano a nivel local dentro de las regiones seleccionadas de Colombia, Costa Rica, el Ecuador y la República Dominicana en diversos escenarios (período de referencia: 1990-2018)

2050 RCP 2.6	2070 RCP 2.6	2050 RCP 8.5	2070 – RCP 8.5
Zona en Antioquia			
-3.5 %	-3.6 %	-6.8 %	-12.9 %
Zona en Azua			
-0.9 %	-2.5 %	-9.0 %	-21.6 %
Zona en El Oro			
0.6 %	2.6 %	2.7 %	4.0 %
Zona en Heredia			
-4.1 %	-2.9 %	-4.2 %	-9.8 %
Zona en La Guajira			
-1.0 %	-3.9 %	-5.8 %	-9.4 %
Zona en Magdalena			
1.1 %	1.2 %	1.7 %	-0.9 %
Zona en Valverde			
-2.8 %	-3.1 %	-8.0 %	-17.4 %

Fuente: Figura y cálculos propios.

En el caso de Antioquia, si enfocamos nuestro análisis en la zona de producción bananera de Urabá, podemos observar que esta zona actualmente ya cuenta con temperaturas medias superiores a los 25°C. Por lo tanto es muy probable que esta zona se vea frente a futuras disminuciones del

rendimiento del banano en cualquiera de los dos escenarios climáticos analizados. En la zona de producción de bananos localizada en Azua, el aumento de las temperaturas por encima del nivel óptimo, combinado con niveles de precipitación bajos, igualmente llevará a una disminución del rendimiento en ambos escenarios. La temperatura cerca/al este de la ciudad de Machala en El Oro ya se encuentra cerca de los 25°C en el período de referencia, y por lo tanto un futuro aumento tendrá como resultado temperaturas medias anuales por encima del óptimo para la producción de bananos. En combinación con niveles de precipitación que seguirán siendo bajos, los efectos del cambio climático en el rendimiento de la zona se volverían casi insignificantes. En la zona productora localizada en Heredia también se prevén temperaturas más altas que las óptimas a futuro. Esto es acompañado por un aumento proyectado para el nivel de las precipitaciones que en el escenario de referencia ya superan el óptimo para el crecimiento del banano, por lo que aquí el cambio climático dará lugar a una ligera disminución de los rendimientos. También en la zona de producción local de La Guajira, los futuros cambios de temperatura y precipitaciones darán lugar a una disminución de los rendimientos. En la zona de producción bananera de Magdalena, los cambios en las precipitaciones y la temperatura local no afectarán considerablemente los rendimientos. Por último, en la zona de producción bananera de Valverde la situación es muy similar a aquella que encontramos para la región de Valverde en general.

En su estudio sobre los impactos del cambio climático en la producción bananera a nivel global, Varma y Bebbler (2019a) evalúan el grado en el que la producción bananera de un país es afectada por el cambio climático, categorizando a los países como "en riesgo", "adaptable" o "aventajado". Aplicando este mismo método, podemos mostrar que nuestro análisis, al enfocarse en el nivel regional y local, nos permite acentuar la evaluación hecha por estos autores (ver Figura E).

**Figura E:** Evaluación de los riesgos planteados por el cambio climático para las regiones y zonas productoras de banano seleccionadas de Colombia, Costa Rica, la República Dominicana y el Ecuador, en el 2050 utilizando el escenario RCP 8.5

Evaluación de Varma y Bebbler (2019a)		Evaluación propia a nivel regional		Evaluación propia a nivel local	
Colombia	En riesgo	Antioquia	Aventajado	... Antioquia	En riesgo
		La Guajira	En riesgo	... La Guajira	En riesgo
		Magdalena	En riesgo	... Magdalena	Adaptable
Costa Rica	Adaptable	Heredia	Adaptable	... Heredia	Adaptable
La República Dominicana	Adaptable	Azua	Adaptable	... Azua	En riesgo
		Valverde	En riesgo	... Valverde	En riesgo
Ecuador	Aventajado	El Oro	Aventajado	... El Oro	Adaptable

Fuentes: Figura y evaluaciones propios y basados en Varma y Bebbler (2019a)

Por lo tanto, podemos concluir que nuestro análisis es robusto ya que produce resultados diferenciados al incluir datos a nivel regional y local, así como al también tomar en cuenta la incertidumbre. De hecho, esta última no debe ser dejada de lado y debe ser incluida con mayor razón mientras más localizado sea el enfoque del análisis. Para tomar en cuenta la incertidumbre, se puede repetir el mismo análisis utilizando modelos climáticos alternativos, así como también se pueden incluir pronósticos con respecto a la susceptibilidad de las regiones y zonas de producción a un posible aumento de los eventos climáticos extremos. En cuanto a los eventos extremos, es conocido que el aumento del calentamiento global aumentará también la probabilidad de que tales eventos ocurran en el futuro. Por lo tanto, al tratar de evaluar el impacto proyectado del cambio climático en el rendimiento del banano, es importante hacer una distinción entre los impactos visibles a corto plazo (causados por eventos climáticos extremos, con impactos potencialmente devastadores en el rendimiento) y los impactos que suelen manifestarse durante períodos más prolongados (es decir, fluctuaciones en el rendimiento en torno a la tendencia de largo plazo).

## Capítulo 6: Impactos del cambio climático en factores adicionales al rendimiento

Además de los efectos directos del cambio climático en el rendimiento, es también esencial tener en cuenta los efectos que este tendrá en la idoneidad de las zonas de cultivo del banano. En efecto, se puede constatar que en la región estudiada se darán cambios notables en la idoneidad de las zonas de producción de bananos en el futuro, y que en determinadas regiones y zonas de producción los impactos directos del cambio climático en el rendimiento podrían incluso verse "potenciados" mediante cambios en la idoneidad de la zona. En estos casos los impactos causados por el cambio climático serían aun mayores que al solo tomarse en cuenta los impactos directos en el rendimiento. También se estima que el cambio climático causará un aumento considerable en la presencia de diversas plagas y enfermedades en los cultivos. En particular, las enfermedades se podrían propagar más rápidamente causando daños cada vez mayores. En el caso de la Sigatoka negra, los posibles impactos en la producción impulsados por el cambio climático se han podido ejemplificar en este estudio.

En lo siguiente, los impactos directos en la producción (véase el capítulo 5) deberán ser combinados con los impactos indirectos en la producción (cambios en la idoneidad de las zonas de producción y cambios en la incidencia de la Sigatoka negra), a manera de ofrecer un panorama más completo de los impactos agregados del cambio climático en la producción bananera de las zonas seleccionadas. La Figura F muestra los resultados obtenidos para el escenario RCP 8.5 en el 2050. Al analizar estos resultados, se vuelve evidente que todas las zonas incluidas en este estudio sufrirán pérdidas de producción causadas por el cambio climático.

**Figura F:** Impactos acumulados en la producción causados por diferentes factores relacionados al cambio climático en zonas específicas de producción de bananos en el 2050, utilizando el escenario RCP 8.5



Fuente: Figura y cálculos propios.

Las pérdidas sufridas en las zonas de producción se traducirán a la vez en una escasez de suministro de este producto a los mercados. Por lo tanto, es de preverse que ciertas variables económicas también se verán afectadas. Por ejemplo, a medida que el tamaño del mercado y el volumen del comercio se vean reducidos a causa de estas pérdidas, los precios nacionales e internacionales del banano tenderán a aumentar. Sin embargo, nuestros análisis también muestran que – a nivel relativo – los aumentos de los precios serían menores que la disminución de la producción, lo que en general significaría una reducción de los ingresos obtenibles a través de la producción del banano. En combinación con un probable aumento de los costos de producción debido a la creciente necesidad de implementar medidas de adaptación al cambio climático en las áreas de cultivo, esto actuará para reducir los ingresos de las explotaciones agrícolas.

Es evidente que el cambio climático ya está afectando la producción bananera en el presente, y que los impactos continuarán aumentando en el futuro. Sin embargo, se debe tomar en cuenta que la producción de banano también es un contribuyente al aumento del calentamiento global, por lo que es crucial también considerar el potencial de implementar medidas de mitigación eficaces en las explotaciones agrícolas. Se sabe por ejemplo que los fertilizantes inorgánicos y los vertederos de residuos vegetales causan una gran parte de la huella de carbono en la producción de bananos. Por consiguiente, las medidas para reducir las emisiones de gases de efecto invernadero (GEI) deberían primero centrarse en estas dos fuentes de emisiones.

Otras dos áreas que causan emisiones de GEI importantes son las pérdidas poscosecha y los cambios del uso de la tierra. En efecto, cada banano que se pierde o se desperdicia ha sido producido en

vano, y por lo tanto la reducción de las pérdidas poscosecha representa una oportunidad significativa para reducir las emisiones de GEI en las explotaciones agrícolas. Esto es especialmente cierto cuando la demanda del mercado es parcialmente abastecida por bananos producidos en áreas de cultivo nuevas que anteriormente fueron ocupadas por ecosistemas naturales. La utilización de nuevas tierras de cultivo para la producción de bananos tiene el potencial de liberar cantidades de GEI mucho más altas que la producción del cultivo en áreas ya dedicadas a la agricultura en el pasado. Para evitar estas emisiones, de lo posible se deberán evaluar y emplear las medidas y tecnologías necesarias para lograr una intensificación de la producción de bananos de manera sostenible.

Esta conclusión también se puede aplicar con relación a las amenazas para la biodiversidad vinculadas a la producción de bananos y al cambio climático. Los riesgos para la biodiversidad son numerosos, sin embargo los impactos siempre se darán de manera específica y localizada. Los efectos negativos sobre la biodiversidad pueden ser reducidos mediante ciertas medidas, entre las que se encuentran por ejemplo la policultura, la gestión integrada de plagas y las prácticas de la agricultura orgánica. Además es important mencionar que, de manera que la producción de bananos requiere de grandes cantidades de tierras de cultivo, aquellas tierras que no se utilicen para la producción de bananos contribuirán a preservar ecosistemas naturales y a la biodiversidad correspondiente. La pregunta importante, entonces, es: ¿Qué medidas se pueden tomar en las explotaciones agrícolas y a lo largo de la cadena de valor del banano cuando aumenta la presión sobre la tierra? Una vez más, para evitar pérdidas sustanciales de la biodiversidad deben considerarse todas las opciones disponibles para intensificar de manera sostenible la producción de bananos, siempre que esto sea posible. Esto ayudará de manera esencial a evitar cambios en el uso de la tierra y a preservar la mayor cantidad posible de hábitats naturales. No obstante, estamos hablando de un sistema complejo, dentro del cual muchas interacciones aún deben ser comprendidas más a fondo y analizadas científicamente antes de permitirnos evaluar plenamente los impactos potenciales que la producción de banano tendrá en la biodiversidad - y en otros aspectos ambientales - a causa del cambio climático.

## Capítulo 7: Recomendaciones

Los efectos del cambio climático en la producción de bananos han sido analizados con rigor en el presente estudio. Sin embargo, deben considerarse algunos aspectos importantes relativos al alcance y a las limitaciones del análisis ejecutado, que darán lugar a necesidades de investigación concretas para mejorar la evaluación de los efectos del cambio climático en la producción bananera a futuro:

- Los modelos climáticos pueden ser leccionados en base a diferentes enfoques. Por lo tanto, lo ideal sería que en estudios futuros se utilizaran diferentes conjuntos de modelos, a fin de permitir una comparación y discusión de los diferentes futuros climáticos resultantes y de sus resultados para la producción de banano.

- Nuestro concepto de calcular un coeficiente de rendimiento climático es solo uno de diversos métodos que pueden ser empleados para analizar los impactos climáticos en el rendimiento del banano. Una vez que mejore la disponibilidad de datos y que se disponga de mejor información, se deberán también utilizar otros métodos adicionales para hacer estos análisis.
- En nuestro análisis, calculamos el coeficiente de rendimiento climático utilizando la temperatura media anual y la precipitación anual como variables endógenas, y definimos ciertos valores específicos de estas variables como valores óptimos, mínimos y máximos para definir un nicho ecológico adecuado para el crecimiento del banano. Dado que las condiciones óptimas de cultivo del banano pueden diferir entre las regiones y de dependiendo del manejo del cultivo, análisis adicionales a nivel regional que examinen los nichos ecológicos específicos para la producción de banano podrían proporcionar información valiosa adicional.
- Se sabe que el rendimiento de los cultivos es un fenómeno multifactorial, y que este también depende de varios factores adicionales aparte de las variables climáticas. Por lo tanto, la integración de estos factores y de sus interrelaciones añadiría valor al análisis.
- Consideraciones con respecto a la probabilidad de alcanzar ciertos puntos críticos, o "tipping points" (que suponen puntos de inflexión en el sistema climático y de no retorno a las condiciones climáticas iniciales), tampoco ha sido incluida en nuestro análisis. Ampliar los análisis de incertidumbre para tomar en cuenta los posibles puntos críticos se considera importante.
- Además, las consideraciones sobre la disponibilidad del agua deberían elaborarse con más detalle de lo que se ha podido efectuar en este estudio. Teniendo en cuenta el gran impacto de la disponibilidad del agua en el rendimiento de los bananos, así como el retraso con el que se manifiestan los impactos del cambio climático en las cuencas hidrológicas, sería fundamental que futuras investigaciones examinen los impactos del riego y de la disponibilidad del agua en un contexto interregional más amplio, considerando los aspectos hidrológicos.
- Por último, en nuestro estudio no se han incluido los esfuerzos y medidas de adaptación por parte del sector bananero. Al incluir estos esfuerzos es probable que al menos se puedan aliviar ciertos efectos adversos del cambio climático en la producción de bananos.

Medidas de adaptación en las explotaciones agrícolas deben hacer frente a los cambios de temperatura, a la disponibilidad del agua, a los vientos y a una mayor frecuencia y gravedad de los fenómenos meteorológicos extremos. En este sentido, una primera cuestión importante es la gestión integrada de los recursos hídricos, incluyendo aspectos como el riego inteligente, la recuperación después de episodios de estrés hídrico, la gestión de la humedad del suelo, las prácticas profesionales inteligentes con respecto al clima ("climate-smart practices") y la mejora de la eficiencia en el uso del agua y los nutrientes. Otras medidas de adaptación incluyen la construcción de diques para bloquear las aguas de las inundaciones, la mejora de la materia orgánica del suelo y el mejoramiento

del drenaje de los suelos. Cabe señalar también que la recuperación de las plantas después de los fenómenos extremos puede y debe ayudarse mediante la limpieza de las plantas caídas, la selección adecuada de plantas de reemplazo, y la replantación. También el reemplazo del monocultivo por un sistema de cultivo más diverso o por un sistema agroforestal puede reducir los efectos de los fenómenos extremos. Los canales construidos alrededor de las plantas de banano también pueden ayudar a combatir las inundaciones y evitar el agua estancada. Además, los agricultores deberían recurrir al riego complementario, de ser posible.

Dado que los fenómenos de altas temperaturas parecen plantear más problemas a la producción de bananos que los de bajas temperaturas, una importante medida preventiva puede ser el uso de variedades de bananos adaptadas a temperaturas más altas. Por lo tanto, variedades adaptables a las diferentes condiciones regionales deben ser identificadas o desarrolladas. Otra opción que podría ser más rápida de aplicar y más eficaz dadas las condiciones heterogéneas en que se cultivan los bananos, es la de adaptar los procesos y tecnologías de producción a los cambios climáticos. Esto incluye los puntos mencionados anteriormente, así como diferentes procesos previos y posteriores a la cosecha. Además, para hacer frente a las ráfagas de viento fuertes, las plantas de bananos pueden atarse mediante refuerzos de cuerda y pueden protegerse mediante cortinas rompevientos. El hecho de contar con sistemas robustos para la recuperación – como la rápida reparación de la infraestructura, la distribución de rizomas libres de enfermedades y el reabastecimiento de equipos – también se considera necesario para limitar los impactos generales del cambio climático y, en particular, de los fenómenos extremos. Más precisamente, también debe considerarse la creciente variabilidad climática causada por el fenómeno del Niño (ENSO, por sus siglas en inglés). Esto aboga por que se preste mayor atención al suministro de sistemas de protección contra las inundaciones, de sistemas de drenaje y de sistemas de emergencia para poder hacer frente a una gama más amplia de impactos causados por las precipitaciones adversas. También se considera de gran importancia promover la aplicación de productos fitosanitarios para el control de plagas y enfermedades y la promoción de métodos de fertilización adecuados.

La formulación de políticas acertadas puede fomentar una transición hacia una producción de bananos "climáticamente inteligente". A nivel nacional y regional, los programas educativos y los servicios de extensión agropecuaria deben ser apoyados y puestos a disposición de los agricultores a bajo costo. Los programas de educación y capacitación también deberían promover la diversificación de los ingresos a manera de reducir las actuales dependencias regionales de la producción bananera. En este sentido, las políticas deberían considerar y promover con mayor frecuencia la diversificación agrícola en las zonas en que la producción de banano está especialmente amenazada por el cambio climático. Otro punto importante a considerarse es el mejoramiento y desarrollo la infraestructura de manera que se mejore el acceso a los mercados, los insumos y las tecnologías, reduciendo al mismo tiempo las pérdidas poscosecha. El intercambio de información y conocimientos en toda la región de ALC se considera especialmente importante y debería facilitarse considerablemente. La difusión de información sobre el clima a los productores de banano podría ser otra cuestión de política importante.

La investigación es un tema de política propio cuando se trata de gestionar el cambio climático. Con respecto a la producción de bananos, la investigación es vital para desarrollar y poner a prueba las prácticas de gestión necesarias para que los agricultores puedan hacer frente a los efectos del cambio climático. Por lo tanto, estas investigaciones deberían tener una alta prioridad en las actividades científicas y en los proyectos de desarrollo relacionados con la producción bananera. En términos más generales, es necesario mejorar considerablemente la disponibilidad de datos para la investigación sobre el banano, lo que, entre otras cosas, requeriría intensificar la colaboración entre las ciencias biológicas, agrícolas y climáticas. También se deben realizar más esfuerzos de investigación para explorar el efecto de los estresores abióticos y de las posibles opciones de adaptación. En este sentido, la política de investigación también debería centrarse específicamente en el mejoramiento del material genético de las plantas de banano. Además, la investigación también puede ayudar a mejorar y adaptar las políticas de uso de la tierra para facilitar una mejor adaptación al cambio climático. Los políticos de los países importadores de bananos también pueden poner de su parte estableciendo políticas para promover la aceptación por parte de los consumidores de otras variedades de bananos, aparte de la variedad Cavendish, y para reducir las pérdidas de alimentos. Y, por último, se debería fomentar un marco regional o mundial de investigación, con el fin de facilitar el intercambio mutuo, así como la recopilación y el análisis de datos. El presente estudio puede considerarse como un primer intento de establecer este marco regional y mundial de investigación sobre el cambio climático y la producción del banano. No obstante, los retos que se plantean son todavía numerosos y requerirán la cooperación y la colaboración de todas las partes interesadas, y a todos los niveles, para asegurar que la producción de banano pueda seguir prosperando en el futuro.

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## List of abbreviations

BAU	- Business as Usual
CATIE	- Centro Agronómico Tropical de Investigación y Enseñanza
CHIRPS	- Climate Hazards Group InfraRed Precipitation with Stations
CIAT	- International Center for Tropical Agriculture
CLAC	- Coordinadora Latinoamericana y del Caribe de Pequeños Productores y Trabajadores de Comercio Justo
CMIP5	- Coupled Model Intercomparison Project 5
COL	- Colombia
CORDEX	- Coordinated Regional Climate Downscaling Experiment
CORE	- Common Regional Experiment
CRI	- Costa Rica
DOM	- Dominican Republic
ECMWF	- European Centre for Medium-Range Weather Forecasts
ECU	- Ecuador
ENSO	- El Niño Southern Oscillation
EU	- European Union
FAO	- Food and Agriculture Organization
GCM	- General Circulation Model(s)
GDP	- Gross Domestic Product
GFDRR	- Global Facility for Disaster Reduction and Recovery
GHG	- Greenhouse Gas
GIZ	- Gesellschaft für Internationale Zusammenarbeit
IPCC	- Intergovernmental Panel on Climate Change
K	- Potassium
LAC	- Latin America and Caribbean
N	- Nitrogen
OECD	- Organisation for Economic Co-operation and Development
PET	- Potential Evapotranspiration
RCM	- Regional Climate Model
RCP	- Representative Concentration Pathway
TR	- Tropical Race
USAID	- United States Agency for International Development
USD	- U.S. Dollar

## 1 Objectives and structure of the report

All over the world, agriculture is highly dependent on the prevailing climate and weather conditions. Agricultural primary production and the supply chains based on it are therefore often at a high risk of being strongly affected by global climate change, potentially leading to lower and/or uncertain yields and sometimes even to total production losses. To ensure a sustainable food production and supply for a growing global population, mitigation as well as adaptation strategies for the agricultural sector are urgently needed, and – to be successful – these strategies must be based on thorough scientific research, including available knowledge of the interlinkages between climate change on the one hand and the physical, ecological and socio-economic dimensions of agriculture on the other hand.

In terms of world food security, bananas play an important role. The fruit is produced in more than 130 countries, it is the second major fruit crop produced in the world and represents a top source of starch (Siddiq et al., 2020). As such bananas are one of the most popular fruits imported by western countries, and consequently they are a source of income and especially of export revenue generation in some developing and emerging economies that should not be underestimated (Evans et al., 2020b). However, while local populations of the main exporting countries are dependent on banana plantations to secure and potentially improve their livelihoods, production conditions in these countries are still often deficient, and the future of banana production might increasingly be threatened or at least become uncertain in the face of ongoing climate change.

In this context, it is the major objective of this research to provide a science-based assessment of the past and future climate change effects in some of the major banana producing regions of selected Latin American countries – including impacts on yields and prices, as well as on farmers' income and profitability, effects in agroecological zones and impacts on biodiversity. In fact, the focus hereafter is on Colombia, Costa Rica, the Dominican Republic, and Ecuador<sup>1</sup>. By looking at the situation and particularities of climate change and banana production in Antioquia, Magdalena and La Guajira in Colombia, Heredia in Costa Rica, Valverde and Azua in the Dominican Republic, as well as El Oro in Ecuador, regional similarities and differences shall be identified leading to sound policy and business implications with respect to sustainable banana production now and in the future. Thus, a comparative assessment of the different production regions will allow us to provide important insights and to compare and learn more from our findings than by only looking at one single country or production region.

More particularly, and in full accordance with the terms of reference for this research, the study will focus on providing:

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<sup>1</sup> In accordance with the ISO 3166 international standard, the following abbreviations (country ISO codes) will occasionally be used: COL – Colombia, CRI – Costa Rica, ECU – Ecuador, and DOM – Dominican Republic.

- a concise overview of the basic facts on the topic of climate change and its impacts on agriculture at national scale in Colombia, Costa Rica, the Dominican Republic, and Ecuador, focusing specifically on the impacts of climate change on banana production,
- an analysis of the most recent climate change developments and a projection of future climate changes to be expected in some of the main banana producing regions of Colombia (i.e. Antioquia, Magdalena and La Guajira), Costa Rica (i.e. Heredia), the Dominican Republic (i.e. Valverde and Azua), and Ecuador (i.e. El Oro), based on state-of-the-art scientific research findings and particularly on the latest climate change modelling results,
- a comprehensive ex-post assessment of the climate change impacts that have already affected banana production in these regions over the last 30 years (i.e. since 1990), complemented by an ex-ante quantitative estimation of potential climate change impacts on banana production to be expected in the future (i.e. in the medium-term for 2050 and in the long-term for 2070) and under various Intergovernmental Panel on Climate Change (IPCC) scenarios in the selected regions, and
- a thorough knowledge base for necessary decision-making and policy advice by presenting a nuanced discussion of the obtained results in the context of viable agricultural and other policies, as well as public and private actions towards climate change adaptation and mitigation that are (or might be) applicable to banana production in the selected countries today, as well as in the medium- and long-term future.

To fully deliver the above results, various tasks must be performed. The tasks are as follows and straightforwardly define the structure of the report:

- First, a concise overview of the basic facts on the topic of climate change and its impacts on agriculture at the national level in Colombia, Costa Rica, the Dominican Republic, and Ecuador will be given in chapter 2 focusing specifically on the impacts of climate change on agriculture in general and on banana production in particular.
- Chapter 3 will then zoom into the four Latin American countries in the focus of this study to perform an in-depth analysis of the most recent climate change developments, and to provide a projection of future climate changes to be expected in these main banana producing regions of these countries.
- An ex-post assessment of the climate change impacts on banana yields over the last 30 years in the seven selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador, as well as in the specific banana production areas will follow in chapter 4.
- In chapter 5, this ex-post assessment will be complemented by an ex-ante quantitative estimation of potential climate change impacts on banana yields to be expected under selected IPCC scenarios until 2050 and 2070, respectively.

- Yield is only one variable that may vary due to climate change. However, banana production might also be affected due to changes in the suitability of the production area, as well as by an increase (or decrease) of the incidence of pests and diseases. These changing production conditions could also alter market prices and would consequently influence farm profitability and income. Moreover, biodiversity could be affected as well. These and selected other aspects that are also considered to be subject to change will additionally be analyzed in chapter 6.
- Based on the above results, recommendations for sound private and public decision-making will be presented in the final chapter 7, along with recommendations for targeted policy and research formulation and implementation.
- Various methods must be applied, and comprehensive data will be used to fulfill these tasks. More detailed information on the methods and data employed can be found in the annexes of this report.

Nevertheless, a few methodological particularities shall already be highlighted here, before the start of the various analyses:

- The ex-post analysis done in this study covers a time span of (almost) three decades, i.e. from 1990 until most recently. Consequently, the 30-year period normally referred to goes from 1990 to 2019. However, reliable statistical data often does not cover the most recent years, i.e. 2019 or even 2018, and in other cases, earlier years prior to the turn of the millennium are not appropriately covered. The specific data sets used within the study will therefore always very clearly be marked to define the relevant time horizon.
- The ex-ante analysis covers two scenarios. The scenarios aim at analyzing the potential situation in/around the years 2050 and 2070, respectively. Hereafter, the first-mentioned time horizon is considered the mid-term scenario and the second time span is considered the long-term scenario.
- All future analyses – for 2050 and 2070 – will be run for two climate change (i.e., IPCC) scenarios. First, the Representative Concentration Pathway (RCP) 2.6, the so-called “peak” scenario in line with the Paris Agreement, will be used. In addition, the RCP 8.5, the high emission or Business as Usual (BAU) scenario, will be in the focus of the study. Using these two scenarios, the whole range of potential future greenhouse gas (GHG) emissions will be displayed.
- The models and approaches used for the different analyses in this study are based on the latest scientific findings and represent the current state of the art in research on agricultural and environmental economics. This also means that the latest available climate models are used.

## 2 Status quo of the scientific discussion linking climate change and agriculture in countries of Latin America and the Caribbean

In accordance with the terms of reference for this research, a brief overview of the international discussion on agriculture and climate change will be given in the following, as an introduction to the more specific analysis of the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador. Based on an elaborate review of the available literature, the analysis will therefore start with some general findings for Latin America and the Caribbean (LAC) (sub-chapter 2.1) and will continue with specific findings for Colombia (sub-chapter 2.2.), Costa Rica (sub-chapter 2.3), the Dominican Republic (sub-chapter 2.4), and Ecuador (sub-chapter 2.5) before a brief summary is provided (sub-chapter 2.6).

### 2.1 Climate change and its consequences for agriculture in Latin America and the Caribbean

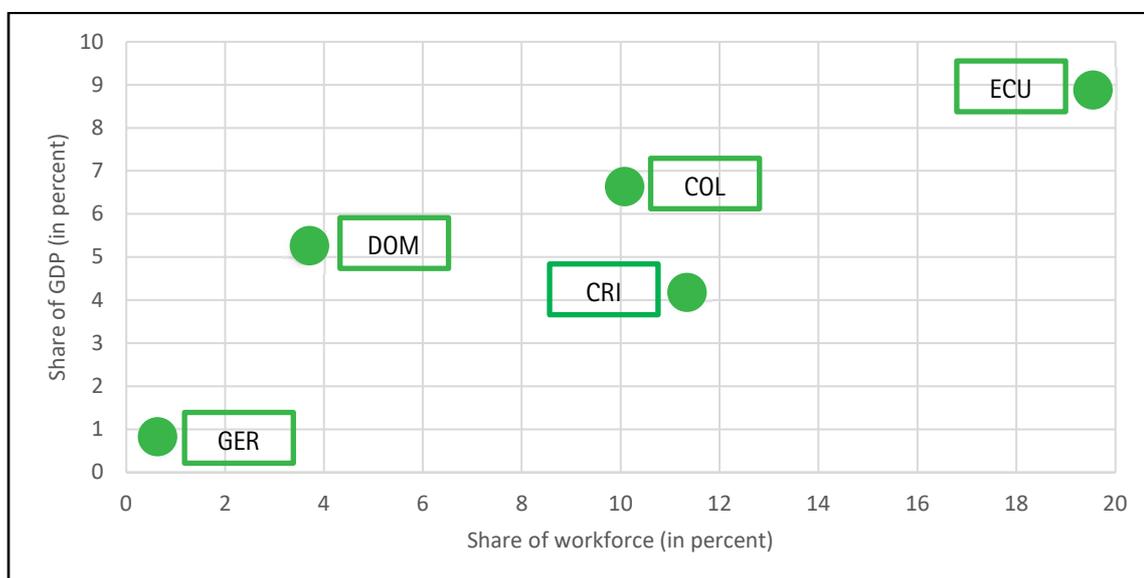
LAC can be considered a major agricultural producer and strong competitor in international markets for primary and food products. In fact, from its area of well above two billion hectares, almost 40 percent is used to produce crops and livestock (OECD and FAO, 2019). As a result, the structure of the region's agriculture is very diverse (Duff and Padilla, 2015): Large farms may account for much of the commercially produced food, feed, fuel, and fiber, whereas approximately half of the food produced in the region comes from smallholders. Due to the wide latitudinal range and a varying topography, this diversity is also mirrored in the region's biodiversity, and it is also a characteristic element of the region's agriculture-related macroeconomics as figure 2.1 displays.

More particularly, figure 2.1 visualizes the agricultural share of the workforce (based on data for 2018) and of the gross domestic product (GDP) (based on information for 2019) for the four countries of the LAC region in the focus of this study, as well as for Germany for comparison purposes. It becomes apparent that in all the selected countries agriculture contributes (much) more to employment and overall economic performance than, for instance, in Germany:

- While in Germany both shares are below 1.0 percent,
- the agricultural shares of workforce and GDP are considerably higher in the Dominican Republic, in Colombia and Costa Rica, and especially in Ecuador.

Since climate change is considered a major driver of agricultural development around the globe (see, e.g. FAO, 2018; Zabel, 2015), these economies in LAC might be more vulnerable and prone to suffer from the potentially negative impacts of climate change than, for instance, member states of the European Union (EU), when it comes to future temperature rises and the severity of weather events.

**Figure 2.1:** Agricultural share of workforce and GDP for selected countries of Latin America and the Caribbean in comparison with Germany



Source: Own figure based on FAO (2020b) and The World Bank (2020a).

In fact, the impacts of climate change on agriculture in the broader LAC region are projected to be significant in coming decades, and remarkable GDP decreases would be a consequence if climate change was not abated (Fernandes et al, 2012). A change in precipitation patterns, an increase in average temperatures, changes in carbon dioxide concentration levels, as well as a higher climate variability and more extreme weather events are considered to impact agriculture (among other sectors) in various ways: Changes in the agricultural potential of territories and changes in the type, distribution and intensity of pests and diseases come along with changes in crop yields; and this will have further consequences such as a change in the composition of crops, changes in the type of agricultural practices employed and in land use, changes in agricultural revenues and rural employment, changes in rural income, changes in agriculture's contribution to GDP and to the commercial balance, and, last but not least, an increase in food prices (FAO, 2017b). Consequently, attaining sustainable agricultural growth in the region is considered a challenge in times of climate change (OECD and FAO, 2019).

Taking this as a point of departure, country-specific findings provide more details and will be presented in the following. In alphabetic order, climate change and its impacts will separately be discussed for Colombia, Costa Rica, the Dominican Republic, and Ecuador. The following overview, thereby, distinguishes a discussion of the current climate from a discussion of already observed as well as projected climate change processes before impacts on agriculture in general and particularly on banana production are explained.

## 2.2 Climate change and its impacts on agriculture and banana production in Colombia

Various studies already had a look onto climate change in Colombia. Using information obtained from Boshell et al. (2018), GFDRR and The World Bank (2011a), Prager et al. (2020), The World Bank Group (2020b), Thomas et al. (2018), and USAID (2017a), the following can be summarized and subsequently stated with respect to past, current and future climate change in this specific country of the LAC region:

- Colombia's topography spans a wide spectrum ranging from arid deserts to wet tropical rain-forest. Consequently, the climate varies as well. The average annual temperature for Colombia as a whole is around 24 to 25°C, but ranges from approximately 27°C in the tropical zones, which are located lower than 1,000 m above sea level, to around 13°C in zones above 3,000 m above sea level<sup>2</sup>. Also, annual rainfall varies a lot within the country. On average, it is around 2,650 mm but may range from as much as 7,000 mm per year along the West Pacific coast and in the Andes<sup>3</sup> to less than 500 mm per annum in the arid desert zone. Although year-to-year variations of temperature and precipitation often appear to be relatively small for the country as a whole, inter-annual warmth and rainfall variability is affected by the El Niño Southern Oscillation (ENSO): On average, the climate between June and August is warmer and drier (colder and wetter) during El Niño (La Niña) years.
- Over the past decades, several climatic changes have already been observed in the country. Foremost, a trend towards slightly increasing average annual temperatures could be identified. The temperature may have increased in the order of approximately 1°C in the last 20 years. In addition, increasing trends of daily mean and minimum temperatures have been noted for the past 30 to 40 years. The number of hot days (and nights) has also increased by approximately 5 percent per decade. In opposite to that, a negative trend for the occurrence of cold nights is obvious. The trend as regards precipitation is less clear: While an increase in average rainfall from December to February/March is observed, decreasing rainfall between June and April seems to be less apparent. In fact, annual precipitation in past decades varied significantly, between -4 and 6 percent. Certainly, extreme rainfalls have increased in magnitude and frequency<sup>4</sup>, and there is also a positive tendency for consecutive dry days. Bridging temperature and precipitation, hydro-climatic records partly show significant positive trends in relative humidity and pan evaporation throughout the country.

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<sup>2</sup> This brief description of the broader range should not neglect the facts that (1) in some parts of the Caribbean region of the country temperatures higher than 36°C can occur and that (2) in some mountainous areas frost occurs or snow is permanently present.

<sup>3</sup> In some parts of the country, annual rainfall may locally reach a level of 11,000 mm or even 12,000 mm.

<sup>4</sup> For instance, it was found that the frequency of tropical cyclones passing through the Colombian maritime region has doubled since pre-industrial time.

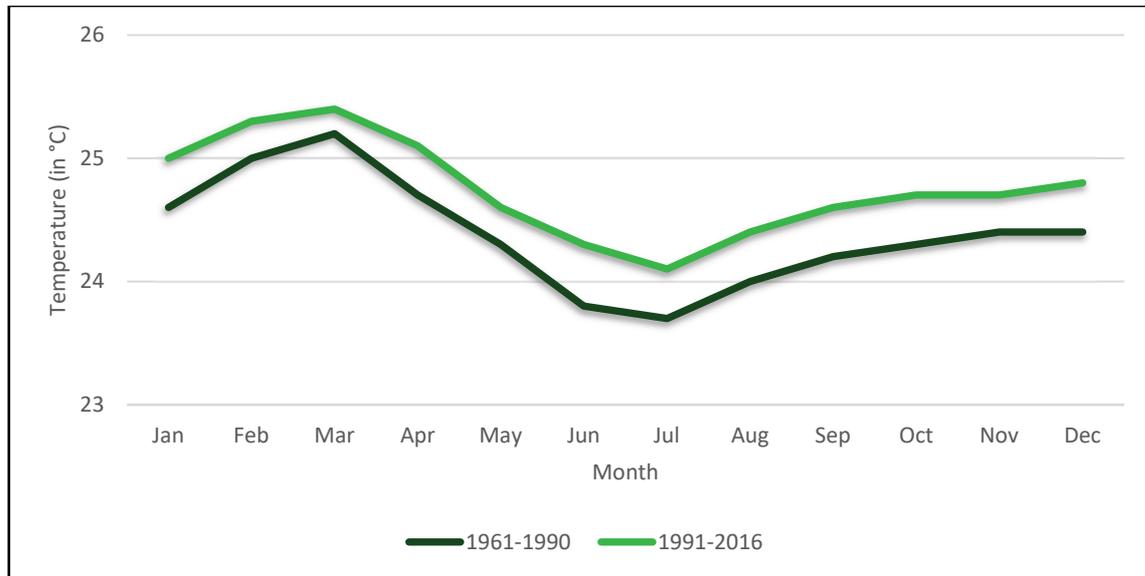
- Historic observations lead to projected changes for the future. Accordingly, until 2050 an increase in the average annual temperature accompanied by an increase in the number of hot days (and nights) and vice versa a decrease in the number of cold days and nights can be expected. In addition, a (slight) increase in average annual rainfall with a particularly large increase in December and January and a decrease during September and October can be anticipated. Also, a rather strong increase in extreme rainfall days (of up to a third) should be considered the new reality in the future.

More details substantiating and accentuating the above discussion of the past, current and future climate in Colombia can be found by looking at the following four figures using data from The World Bank Group (2020b) which are based on spatially and temporally referenced data as described in The World Bank Group (2018):

- Figure 2.2 displays the monthly temperatures for 1961–1990 and 1991–2016. The year 1990 marks the starting year of our ex-post analysis to be carried out below. Distinguishing the time before and after that starting year, hence, makes sense to indicatively point at major climate changes over time (before vs. after 1990). Comparing both time periods, a temperature increase becomes obvious. However, with less than 0.5°C this increase is smaller than it would be if only the past two decades were considered (see above). This might already point at the fact that temperature increases have gained a stronger momentum in the most recent two decades, compared to the previous four decades from the 1960s to the 1990s.
- Similarly, figure 2.3 visualizes the monthly precipitation for the two time periods 1961–1990 and 1991–2016. On average, overall rainfall increased by just 2 mm per month, i.e. by less than 1.0 percent over time. More pronounced (and interesting) in this case are the inter-annual changes: Rainfall particularly increased in December and March, whereas it particularly decreased in October and slightly also during August and September.
- In terms of trends, the temperature rise is projected to continue. Figure 2.4 presents the projected monthly temperatures for altogether four combinations of scenario and observation periods: for the RCP 2.6 scenario in 2050, the RCP 2.6 scenario in 2070, the RCP 8.5 scenario in 2050, as well as the RCP 8.5 scenario in 2070. It becomes apparent that the temperature in Colombia will continue to increase, even if the Paris Agreement is met. In this case a temperature increase of more than 1°C is projected for 2050 and 2070. If global economies tend towards following the BAU scenario, temperatures will rise further: A temperature increase by almost 2°C in 2050 and almost 3°C in 2070 needs to be envisaged, then.
- The potential developments regarding annual and monthly precipitation are less straightforward, as depicted in figure 2.5. By and large, it can be stated that annual precipitation is projected to slightly increase in any scenario. Accordingly, the highest precipitation increase can be expected under RCP 8.5 in 2070. In that case, 60 mm more rainfall would occur within 12 months, which is 2.2 percent more than what has been observed most recently in the country (see figure 2.3). The changes throughout the year are even more interesting:

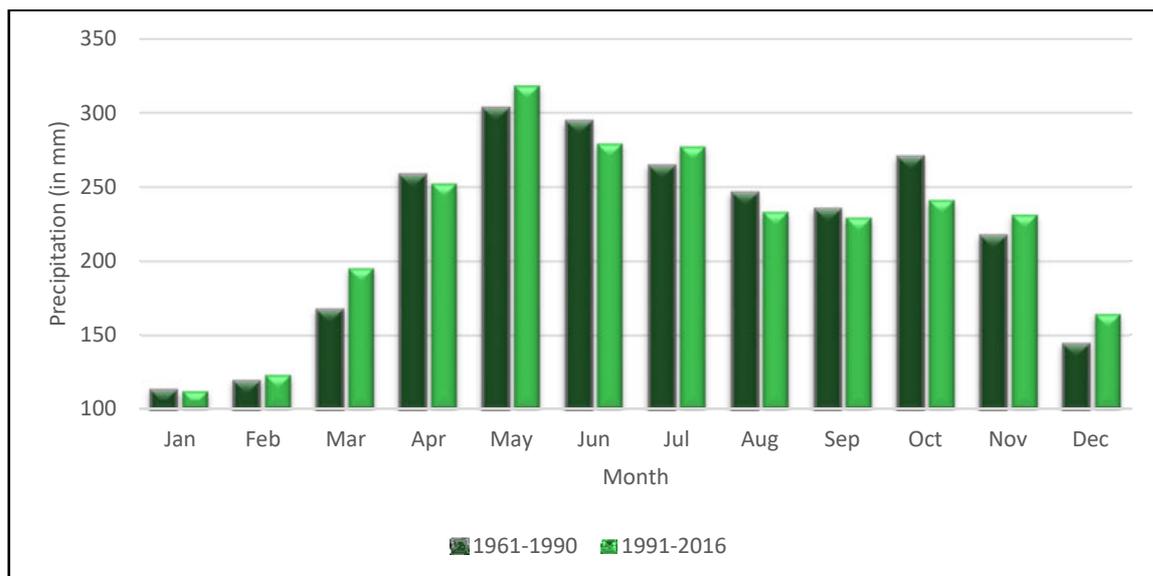
Apparently, rainfall in the months September, October and November will decrease in any scenario, whereas it will increase from around December to May.

**Figure 2.2:** Average monthly temperature of Colombia for the years 1961–1990 as well as 1990–2016



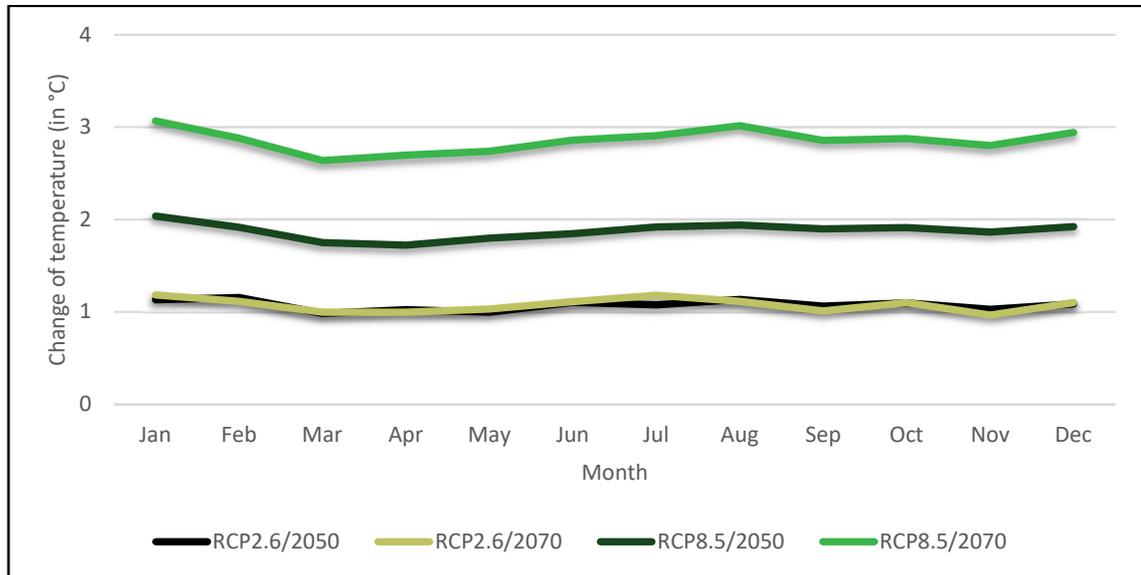
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.3** Average monthly precipitation of Colombia for the years 1961–1990 as well as 1990–2016



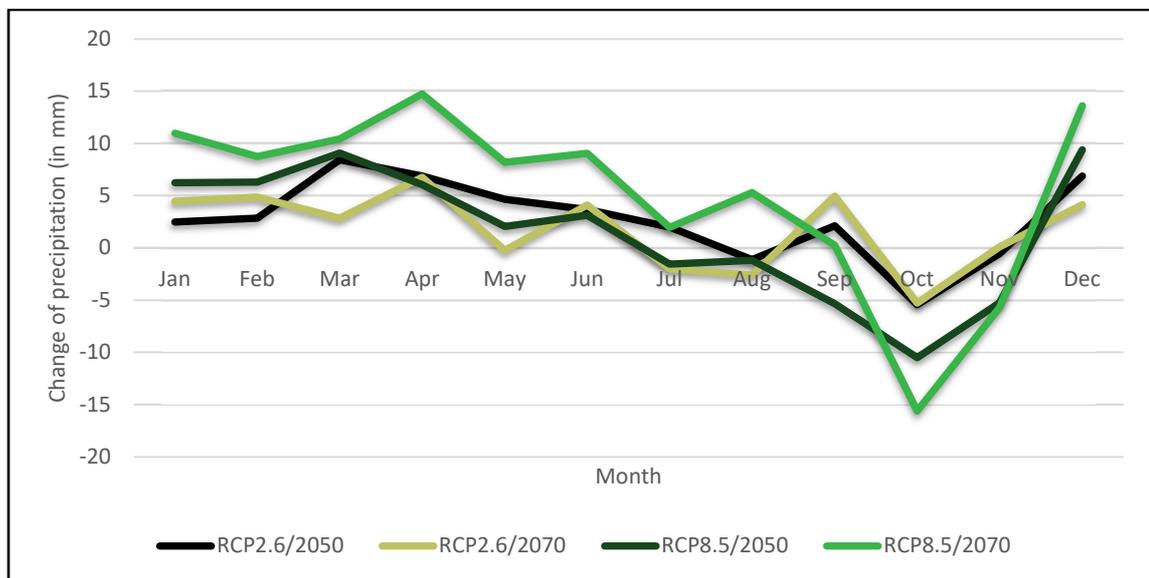
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.4:** Change of average monthly temperature of Colombia for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5



Source: Own figure based on The World Bank Group (2020b).

**Figure 2.5:** Change of average monthly precipitation of Colombia for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5



Source: Own figure based on The World Bank Group (2020b).

The figures 2.4 and 2.5 visualize the average for the ensemble of altogether 16 climate models. The various models, however, come to different conclusions. This implies uncertainty. To appropriately take into consideration this uncertainty aspect, i.e. to better cope with the – despite all scientific efforts – still vague projections, the 10-percent and 90-percent percentiles of available model data are additionally plotted in annex A of this report for temperature and precipitation, for 2050 and 2070, as well as for the RCP 2.6 and RCP 8.5 scenarios. Taking the RCP 8.5 and 2050 as an example, the graphs in annex A can be interpreted as follows: While the annual temperature is projected to rise on average by 1.9°C until 2050, it may as well increase anywhere between 1.4°C and 3.1°C; similarly, while annual precipitation is projected to increase on average by 18 mm, it may actually also decrease by 418 mm or increase by 588 mm.

Surely, the historically observed changes in climate have already had an impact on Colombian agriculture, and the projected future climate change will certainly continue to do so. According to USAID (2017a), major stressors related to climate change in Colombia are considered to be the following: increased temperatures, higher rainfall variability along with increased drought conditions and storms leading to higher risks in terms of an increased incidence of pests and diseases, reduced soil moisture, increased soil erosion (partly due to increases of floods and landslides) and desertification. All these factors act to damage agricultural crops and livestock production and subsequently reduce yields, further leading to additional food insecurity. And along with that, an expansion of the cultivation of highlands is considered an outcome posing risks to fragile and unique mountain ecosystems and contributing to the decline of rare species such as high-altitude flora and fauna (USAID, 2017a).

These rather general findings are partly mirrored by other experts and scientists. Fernandes et al. (2012), for instance, project a future decrease of the agricultural value added by up to 5 percent until 2050, and this outcome would mainly be triggered by decreasing yields in crop production. Substantial yield reductions are also predicted by Boshell et al. (2018), while looking at land productivity changes between 2000 and 2050, and by Thomas et al. (2018) similarly bridging the time horizon between 2010 and 2050<sup>5</sup>.

This may also affect banana production and harvestable yields of the crop. In fact, a remarkable yield decline should be anticipated. This follows from Varma and Bebbler (2019a) who predict that banana production in Colombia is generally at risk and banana yields may decline by more than 4 percent in 2050 compared to the average of the years 1970–2000 as figure 2.6 displays<sup>6</sup>. This equals a decrease of approximately 0.5 percent within a decade, or 0.05 percent per year.

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<sup>5</sup> In addition, Lachaud et al. (2017) estimated a negative effect of climatic variability on agricultural output in Colombia for the first decade after the millennium to be in the range of 3.6 percent (compared to 1961–1999 holding inputs constant at their mean values).

<sup>6</sup> Varma and Bebbler (2019a) calculate yield impacts for different climate change scenarios, for the RCP 8.5, as in this study, and in addition for the RCP 4.5. A scenario based on the RCP 2.6, however, is not part of the authors' study and could, therefore, not be displayed in the figure.

**Figure 2.6:** Predicted impacts of various climate change scenarios on banana yields in 2050 for Colombia in comparison with 1970–2000

Scenario	RCP 4.5	RCP 8.5
Yield impact	-3.70 % (+/-1.10 %)	-4.32 % (+/-1.16 %)

Source: Own figure based on Varma and Bebbler (2019a).

### 2.3 Climate change and its impacts on agriculture and banana production in Costa Rica

As in the case of Colombia, various studies deal with climate change in Costa Rica and allow to discuss past, current and future climate changes in the specific LAC country. Using mainly information provided by GFDRR and The World Bank (2011b), Hannah et al. (2017), Herrera (2015), Prager et al. (2020), and Sain et al. (2019) the following can be summarized:

- Costa Rica's climate displays generally well-defined annual patterns. While the lowlands of the country harbor a tropical and subtropical climate, a mountainous climate is experienced in the highlands. The mean annual temperature for Costa Rica is around 24 to 25°C, ranging from 26 to 28°C on the Caribbean and North Pacific coast to only 6°C on Cerro Chirripó, the highest peak in the country. The mean annual precipitation is around 3,000 mm, ranging from 1,300 mm in the dry climates of Guanacaste Province, to more than 7,000 mm in the Río Grande de Orosí watershed on the Caribbean slope. Monthly rainfall patterns vary widely across different regions as the country's topographic diversity creates a "rain shadow" effect, with the Caribbean slope experiencing rain practically all year round and the Pacific slope characterized by a prolonged dry season lasting approximately from November until April or May and a wet season during the rest of the year. Periodically, the El Niño phenomenon causes severe droughts on the Pacific coast of Costa Rica, while intense rains can cause flooding on the central Caribbean slope.
- The country is considered a primary "hot spot" for the already ongoing climate change in the tropics. An analysis of temperature and precipitation reveals many changes in the extreme values of these variables from 1961 onwards. Accordingly, temperatures have increased between 0.2 and 0.3°C per decade with a prolonged and hotter dry season. Similarly, temperature extremes have also increased. The number of warm days (nights) has increased by 2.5 percent (1.7 percent), while the number of cold nights and cold days has decreased by 2.2 and 2.4 percent per decade, respectively. Precipitation trends in the region, on the other hand, are highly spatially variable and usually statistically insignificant. Overall average annual precipitation in the region and the number of consecutive wet days do not show very significant changes although there has been a slight increase in volume and rainfall intensity. However, extreme precipitation has increased significantly. Trends over the last four decades suggest

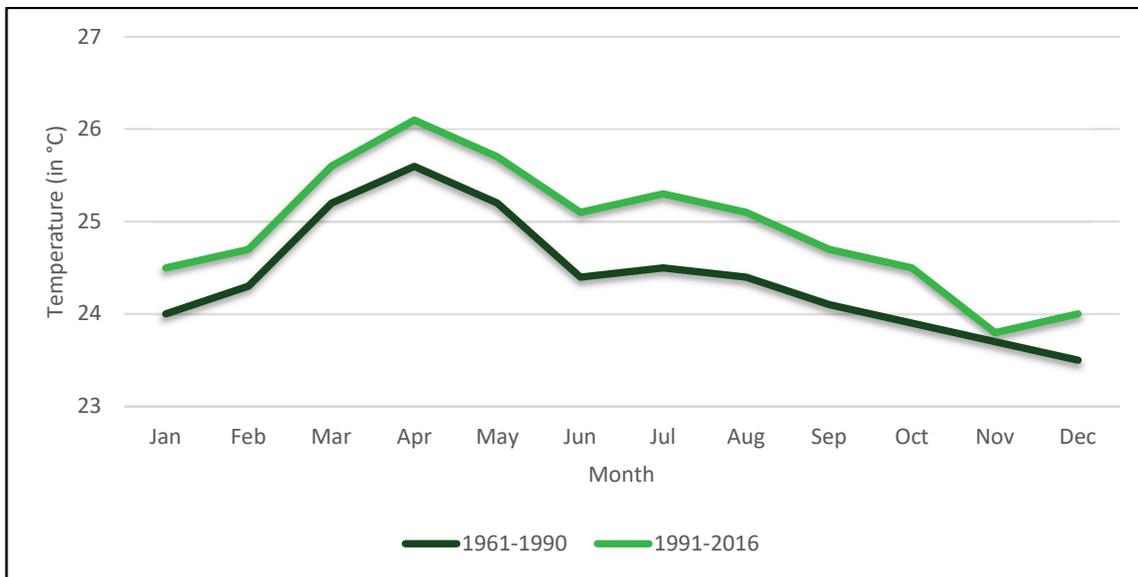
the occurrence of more intense rain during shorter periods of time that produce greater average precipitation per episode.

- Concerning future climate change, temperatures in Costa Rica are projected to increase by 1 to 2°C in 2050, and between 2 and 4°C in 2080, with increases happening particularly during May and June. Warming will be more pronounced in the lowlands than in the highlands, while temperature variance will be more pronounced at higher elevations than in the lowlands. The number of dry days is expected to increase as well, along with the frequency of more intense precipitation and extreme events such as storms and floods. Projected changes in precipitation vary by region and are highly uncertain. While rainfall is projected to decrease between 13 and 25 percent in the North Pacific Region, between 16 and 23 percent in the Caribbean Region, and between 7 and 56 percent in the Northern Region, projected increases in annual rainfall are expected in the Central Pacific Region and in coastal areas of the Central Region. The expected increase in climate variability may lead to a shift in the height of the orographic cloud base of tropical montane forests, increasing the altitude of cloud formation in the region and seriously affecting the moisture supply to the montane forests during the dry season.

More details of the past, current and future climate in Costa Rica can be obtained from the following four figures which, again, use data from The World Bank Group (2020b):

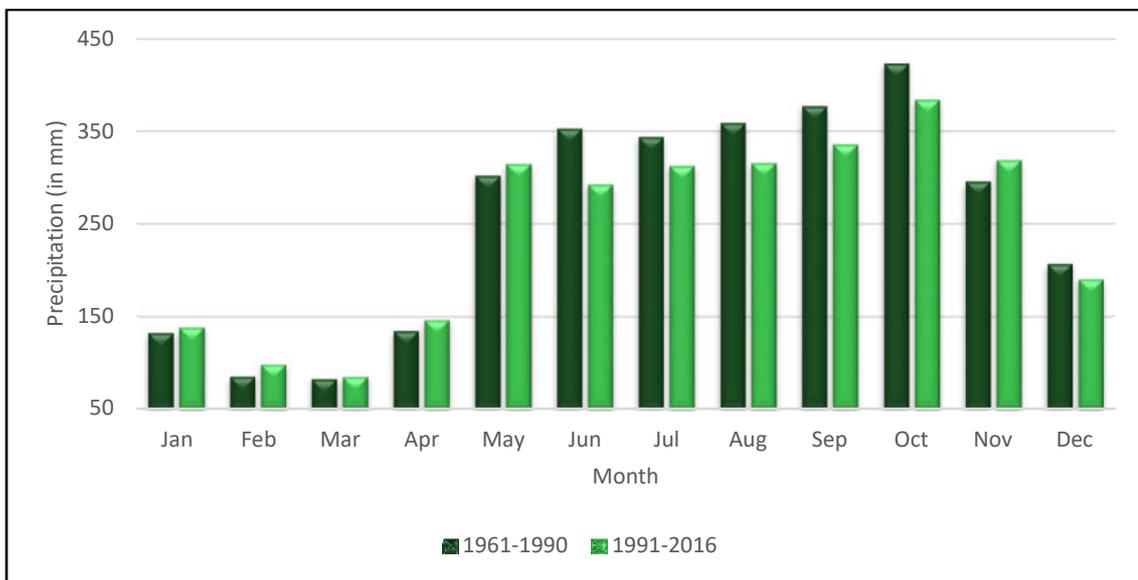
- Since the year 1990 marks the starting year of our ex-post analysis below, figure 2.7 displays the monthly temperature for the time periods 1961-1990 and 1991-2016. This allows to better distinguish the time before and after that starting year. Comparing both time periods, a temperature increase of at least 0.5°C becomes obvious. The increase is more pronounced for summer and autumn months than for winter and spring months.
- Similarly, figure 2.8 visualizes the monthly precipitation for the two time periods 1961-1990 and 1991-2016. On average, overall rainfall increased by just 13 mm per month. Apart from that, inter-annual change is obvious: Rainfall seems to increase between November and May, whereas it slightly decreases between June and October.
- In terms of tendency, the temperature rise is projected to continue. Figure 2.9 shows this for the monthly temperature and various scenarios. It becomes apparent: If the Paris Agreement (the RCP 2.6 scenario) is met, temperature will increase by less than 1°C in 2050 and 2070. But if the Paris Agreement fails and the emissions pathway follows the BAU scenario, temperatures will increase much more: by almost 1.5°C in 2050 and by more than 2.2°C in 2070.
- The prediction of precipitation is less straightforward as displayed by figure 2.10. By and large, it can be stated that changes in annual precipitation are projected to be only minimal if RCP 2.6 is considered. However, under RCP 8.5 summer and autumn months would become a bit dryer while during winter and spring no remarkable change in monthly rainfall should be expected.

**Figure 2.7:** Average monthly temperature of Costa Rica for the years 1961–1990 as well as 1990–2016



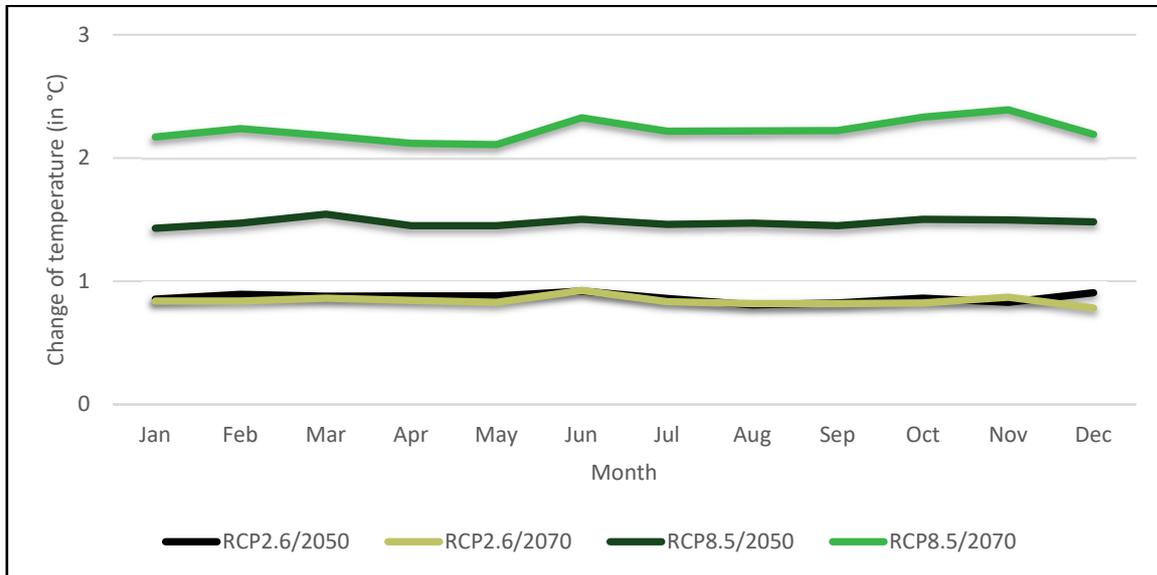
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.8** Average monthly precipitation of Costa Rica for the years 1961–1990 as well as 1990–2016



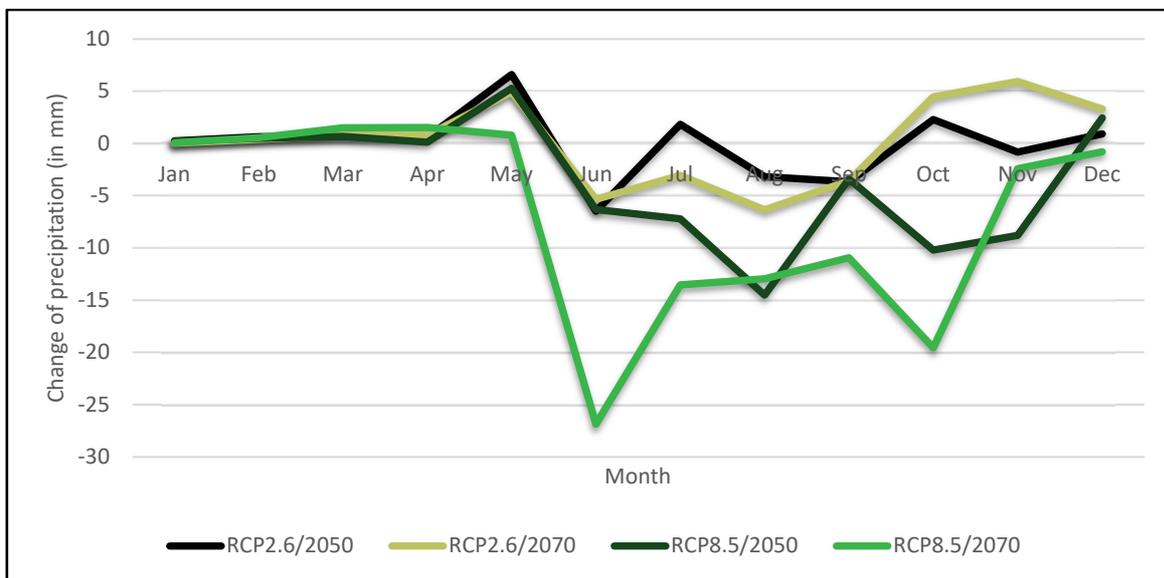
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.9:** Change of average monthly temperature of Costa Rica for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5



Source: Own figure based on The World Bank Group (2020b).

**Figure 2.10:** Change of average monthly precipitation of Costa Rica for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5 (in mm)



Source: Own figure based on The World Bank Group (2020b).

The figures 2.9 and 2.10 visualize the average for the ensemble of altogether 16 climate models. Each of these models, however, comes to its own conclusion. To appropriately take into consideration the model-specifics as well as the associated uncertainty, the 10-percent and 90-percent percentiles of available model data are additionally plotted in annex B of this report for temperature and precipitation, for 2050 and 2070, as well as for the RCP 2.6 and RCP 8.5 scenarios. Taking the RCP 8.5 and 2070 as an example, the graphs in annex B can be interpreted as follows: While the annual temperature is predicted to increase by 2.2°C on average, it realistically may increase between 1.7 and 3.6°C; similarly, while annual precipitation is projected to decrease on average by 83 mm, it may as well decrease by 642 mm or increase by 525 mm.

Global climate change is already a reality throughout most of Central America including Costa Rica. Consequently, it is already affecting the regions' agricultural production systems. Considering this and according to The World Bank, CIAT and CATIE (2014), the country's agricultural sector faces immediate risks from climate change, including increased frequency of extreme weather events, rising temperatures, and abnormal weather patterns. The increasingly erratic and unpredictable patterns of seasonal rainfall are of particular concern. Also, the spread of pests and diseases associated with long-term climate warming is considered a problem for the agricultural sector. These rather general findings are also supported by other authors. For instance, Hannah et al. (2017) see agriculture in the Central American region as particularly vulnerable to climate change, since production of many of the region's principal crops is expected to decrease significantly with rising temperatures. Moreover, most farmers are smallholders with limited adaptive capacity and there is high dependency on ecosystems and biodiversity for both on-farm (e.g. pollination, water provision) and off-farm (e.g., tourism) income. In fact, all the changes mentioned above will pose negative implications for the country's ecosystems and endemic species, which are all too often dependent on a narrow range of temperatures and precipitation (Hannah et al., 2017).

Lachaud et al. (2017) already estimated the negative effect of climatic variability on agricultural output in Costa Rica for the first decade after the millennium to be in the range of 14.5 percent (compared to 1961–1999 holding inputs constant at their mean values). Apart from that, negative agricultural impacts for the future are expected by Ovalle–Rivera et al. (2015) and Läderach et al. (2013). Consequently, climate change may also affect banana production and harvestable banana yields. A moderate climate-driven yield decline is anticipated by Varma and Bebbler (2019a) who predict that banana production in Costa Rica could see yield declines of up to 3.0 percent by 2050, as displayed in figure 2.11. This equals a decrease of slightly more than 0.3 percent within a decade, or around 0.03 percent per year.

**Figure 2.11:** Predicted impacts of various climate change scenarios on banana yields in 2050 for Costa Rica in comparison with 1970–2000

Scenario	RCP 4.5	RCP 8.5
Yield impact	-1.03 % (+/-2.02 %)	-2.97 % (+/-2.24 %)

Source: Own figure based on Varma and Bebbler (2019a).

## 2.4 Climate change and its impacts on agriculture and banana production in the Dominican Republic

The Dominican Republic shares the Caribbean island of Hispaniola with Haiti occupying the eastern two thirds of the island. Using information provided by USAID (2017b), Caffrey et al. (2013), Prager et al. (2020), and The World Bank Group (2020) the following can be summarized in terms of climatic change and its impacts in the Dominican Republic:

- Average annual temperature is around 24°C, but it varies with time of the year and altitude. Monthly temperatures are highest between July and September, reaching 26 to 28°C close to sea level, and lowest from December to February, when they average between 23 and 25°C. Average annual precipitation for the Dominican Republic is about 1,400 mm with two peaks during the year around May and October. The spatial distribution of rainfall is determined by trade wind direction and the orientation of the mountains from northwest to southeast. The heaviest precipitation occurs in the northeast, where it exceeds 2,500 mm per year, while the far western and southwestern valleys of the country remain relatively dry with less than 760 mm of annual precipitation. Inter-annual variability in climate is strongly influenced by the ENSO: Between June and August, El Niño (La Niña) episodes bring warmer (colder) and drier (wetter) than average conditions. In addition, the Dominican Republic is in the center of a hurricane belt, with cyclone and hurricane landfall frequencies averaging one every two years, but sometimes occurring as often as two per year or as little as every five to ten years.
- Several climatic changes have already been observed in the country over the past decades. From 1960 to 2015 average annual temperatures slightly increased in the order of around 0.05°C per decade. The increase in the number of hot days (and nights) was more pronounced with increases of more than 17 percent (13 percent) between 1960 and 2003<sup>7</sup>. The trend in average annual precipitation points towards a slight increase of 4 to 5 percent from 1960 until 2015. However, this trend is not statistically significant. Also, data to determine the trends in daily rainfall extremes has found to be insufficient.
- Projected changes for the future can be obtained based on historic observations and additional modelling. For the Dominican Republic, it is expected that by 2050 average annual temperatures will increase by 1 to 1.5°C accompanied by a slight decrease in average annual rainfall. Consequently, an increase in the number of consecutive dry days is also expected. Shifts in seasonal rainfall patterns are also predicted, with a decrease in rainfall in May (a particularly rainy month in all regions of the country) and an increase in December (a rather dry month in all the regions). Uncertainty remains about the changes in extreme rainfall as well as in the frequency of hurricanes hitting the country. However, an increase in the global average intensity of tropical storms is predicted by the year 2100.

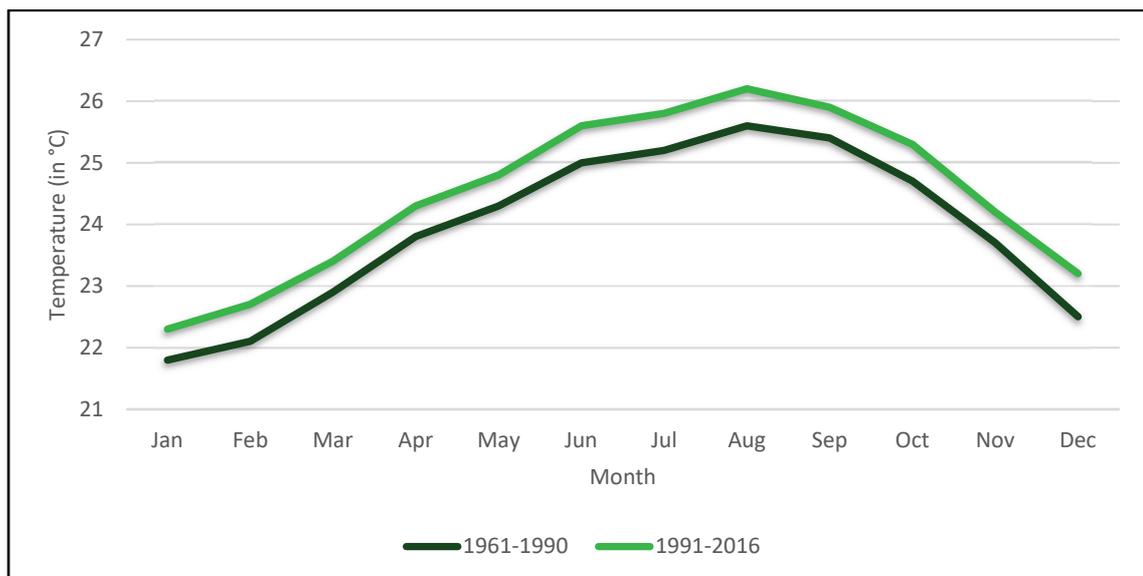
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<sup>7</sup> The highest rates of increase thereby occurred from June to August.

Again, more details of the past, current and future climate (change) in the country can be obtained from data provided by The World Bank Group (2020b) and the following inserted four figures:

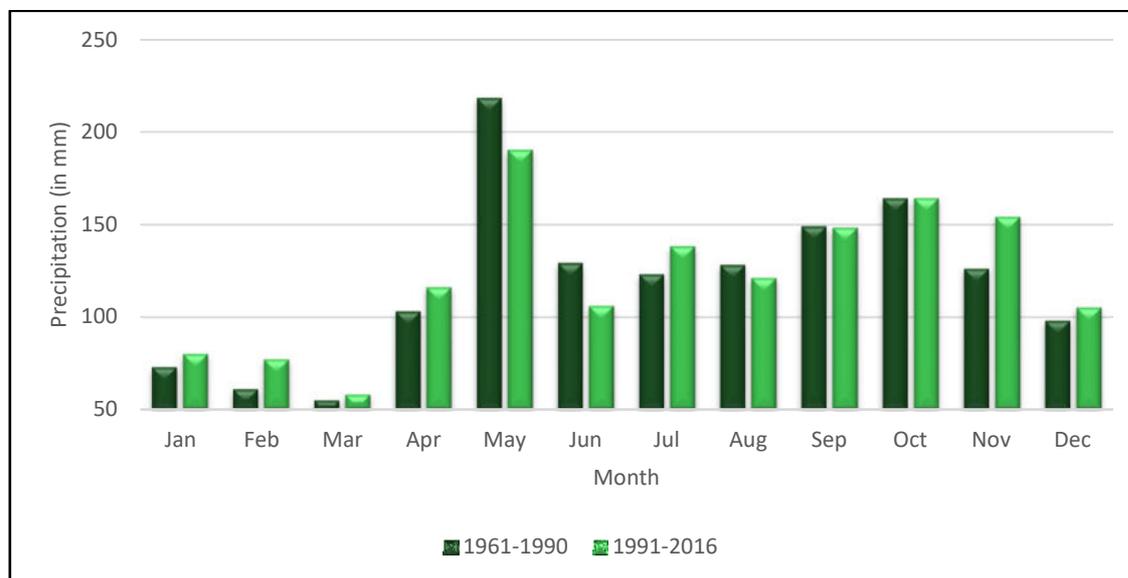
- Figure 2.12 displays the average monthly temperature for 1961–1990 and 1991–2016. This allows to better distinguish the time before and after the starting year of our ex-post analysis, i.e. 1990. Comparing both time periods, a temperature increase of 0.6°C can be observed. The increase is almost similar for all months of the year, but highest for December with 0.7°C.
- Similarly, figure 2.13 visualizes the monthly precipitation for the two time periods, i.e. 1961–1990 and 1991–2016. On average, overall rainfall increased by less than 2 mm per month. However, inter-annual change is obvious: Rainfall sharply decreased in May and June, whereas it (slightly) increased in most of the other months.
- The temperature rise is projected to continue. Figure 2.14 shows this for the monthly temperature and the selected four scenarios. Accordingly, it becomes obvious that temperature will increase by 0.8°C in 2050 and 0.9°C in 2070 if the Paris Agreement is met. However, if the Paris Agreement fails and the future emissions pathway follows the RCP 8.5 scenario, temperatures will increase much more: by almost 1.4°C in 2050 and 2.1°C in 2070.
- The projection of precipitation is less uniform as visualized by figure 2.15. It can be stated that annual precipitation is projected to stay the same if RCP 2.6 is considered. Monthly changes will be in the range of less than +/- 5 mm. However, a remarkable change should be taken into account under RCP 8.5. In this specific case, any month of the year will experience a loss in precipitation accumulating to more than 50 (60) mm per year in 2050 (2070).

**Figure 2.12:** Average monthly temperature of the Dominican Republic for the years 1961–1990 as well as 1990–2016



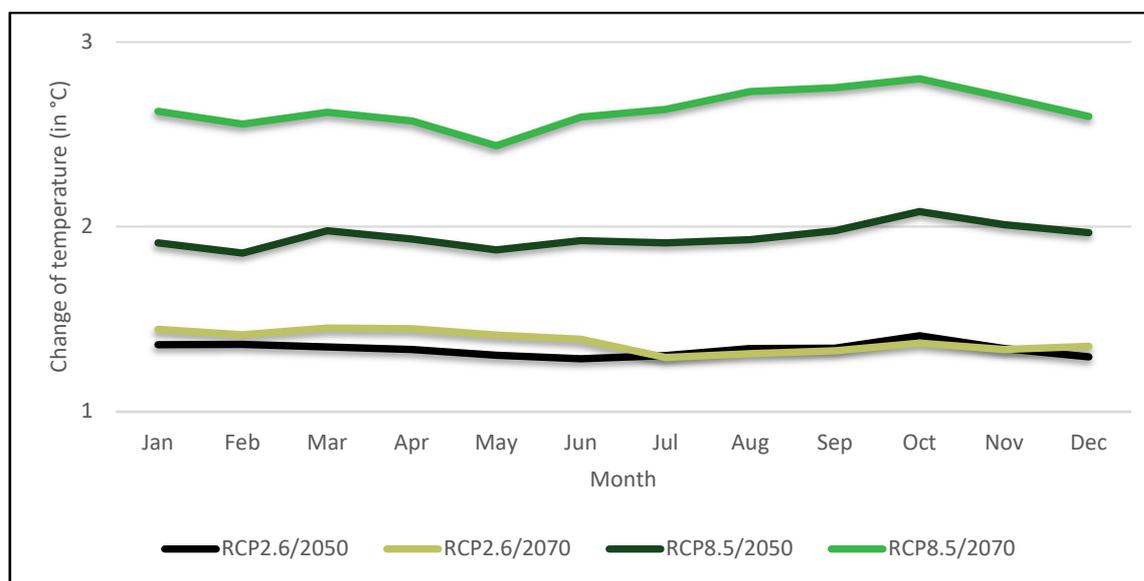
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.13** Average monthly precipitation of the Dominican Republic for the years 1961–1990 as well as 1990–2016



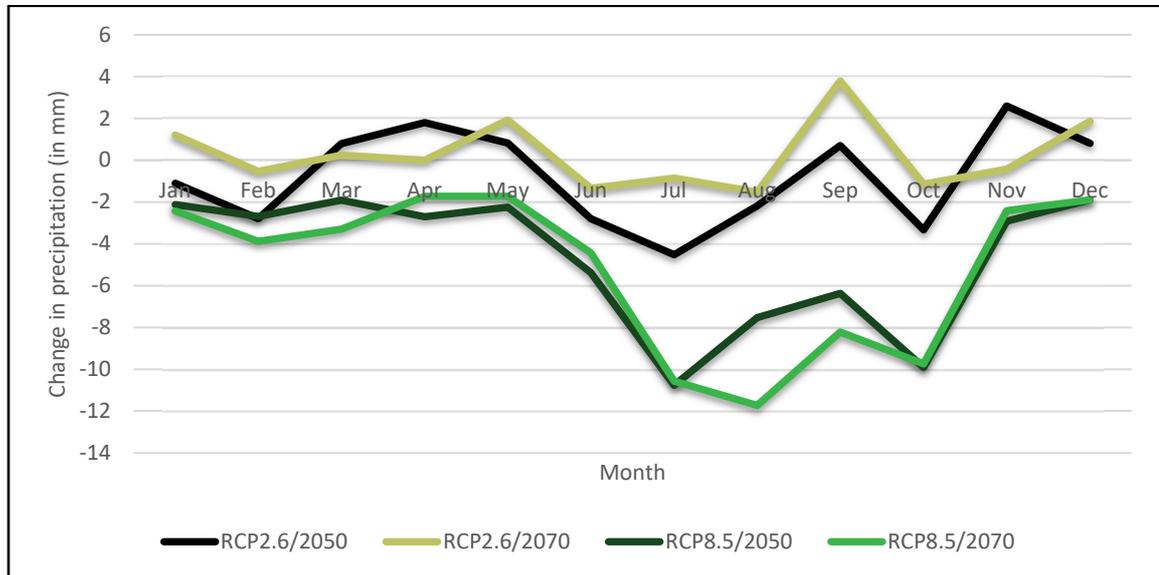
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.14:** Change of average monthly temperature of the Dominican Republic for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5



Source: Own figure based on The World Bank Group (2020b).

**Figure 2.15:** Change of average monthly precipitation of the Dominican Republic for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5



Source: Own figure based on The World Bank Group (2020b).

To appropriately take into consideration the various models leading to average values as depicted in figures 2.14 and 2.15 and the herewith associated uncertainty, the 10-percent and 90-percent percentiles of available model data are additionally plotted in annex C of this report. Taking the RCP 8.5 and 2070 as an example, the graphs in annex C should be interpreted as follows: The annual temperature is predicted to increase by 2.1°C on average (ranging from 1.7 to 3.2°C); and annual precipitation is projected to decrease on average by 62 mm ranging from a decrease by 386 mm to an increase by 163 mm.

It is evident that the historically observed climate change has already had an impact on agriculture in the Dominican Republic, and the projected future climate change will certainly continue to do so. According to USAID (2017b), major stressors for agriculture related to climate change are considered to be the following: rising temperatures, changes in the seasonality of precipitation along with increased drought conditions and storms leading to higher risks in terms of an increased incidence of pests and diseases, increased waterlogging of fields, increased soil erosion and loss of soil fertility as well as increased storm damage to crops and livestock. All these factors act to damage agricultural crops and livestock production and subsequently reduce yields further leading to additional food insecurity. In addition, the projected sea level rise leads to seawater intrusion of aquifers, subsequently leading to the salinization of coastal aquifers that will considerably reduce freshwater quality and supply for irrigation of agricultural crops under dryer conditions. Such negative effects of climate change on the agricultural sector are also described by Caffrey et al. (2013). Interestingly, Lachaud et al. (2017) estimate the negative effect of climatic variability on agricultural output in

the Dominican Republic in the first decade post the millennium to be only relatively small, namely at 0.02 percent, pointing to the fact that the agricultural sector might have been able to cope relatively well with the climatic changes observed during that period.

While the effects of climate change on the agricultural sector might be negative overall, neutral, or somewhat positive impacts of climate change are expected by some authors. In particular, a slightly positive to slightly negative climate-driven yield effect is anticipated by Varma and Bebbler (2019a) who predict that banana production in the Dominican Republic could alternatively see average yield increases of less than 1.0 percent or declines of approximately 0.5 percent by 2050 compared to the years 1970–2000 as displayed in figure 2.16.

**Figure 2.16:** Predicted impacts of various climate change scenarios on banana yields in 2050 for the Dominican Republic in comparison with 1970–2000

Scenario	RCP 4.5	RCP 8.5
Yield impact	0.84 % (+/-1.69 %)	-0.50 % (+/-1.80 %)

Source: Own figure based on Varma and Bebbler (2019a).

## 2.5 Climate change and its impacts on agriculture and banana production in Ecuador

Based on GFDRR and the World Bank (2011c), Marengo et al. (2014), Moran-Tejeda et al. (2016), Prager et al. (2020), and The World Bank Group (2020b), the following can specifically be summarized for past, current and future climate change in Ecuador:

- Ecuador has two major seasons that are differentiated by the distribution of rainfall: a rainy and a dry season. On average, the mean annual precipitation is around 2,100 mm. However, the country's topography is very diverse, and consequently, the climate differs strongly depending on the region.
- The coastal region, for instance, has a tropical climate and a rainy season extending from end of December to May, with an average annual temperature of around 21 to 22°C. In opposite to that, the inter-Andean valleys have a temperate climate with average temperatures of only around 14 to 15°C. In this region, the rainy season runs from October to May and a dry season is experienced from June to September. In the Amazon region, located in the eastern part of the country, the average temperature is around 21°C during most months, and rainfall is also continuously experienced throughout the year. Finally, on the Galapagos Islands in the Pacific Ocean, the climate is similar to that of the coastal region, with average temperatures of around 25 to 26°C during the rainy season (December to May) and between 21 and 22°C during the dry season (June to November), mainly owing to the influence of the cold

Humboldt current. As in other LAC countries, the inter-annual variability of the country's climate is strongly influenced by the ENSO.

- Climatic changes have also been observed in Ecuador in the recent decades. A trend towards rising temperatures has been identified across the country. In the rural highland zone consistent trends point to changes in the mean temperature of 1.5°C between 1930 and 1990, while in the urban coastal zones mean temperatures have "only" increased between 0.5 and 1°C<sup>8</sup>. At the same time, increasing trends of cold nights have been observed along the coastline too. In addition, there is no clear trend in precipitation changes at the national level, but a greater inclination towards a decline in rainfall has been observed, especially in the coastal regions. Positive trends in extreme rainfall have been observed too, as well as an increase in the frequency and maximum length of dry spells along the coastline.
- In terms of climatic changes to be expected in Ecuador in the future, projected temperature increases are substantially higher than the global average. Mean annual temperatures are projected to rise by 2 to 3°C in the period 2030–2049 as compared with 1980–1999, while annual precipitation is expected to increase by around 3 percent in the same period. Precipitation levels are also projected to increase in the periods from December to February and from March to May by 3 percent and 5 percent, respectively, while for the period from June to August, precipitation levels are likely to decrease by 3 percent. Following from the already observed positive trends in extreme rainfall events, the frequency and intensity of these extreme events are projected to increase in the coastal region.

More details of the past, current and future climate in Ecuador can be obtained from the following four figures 2.17 to 2.20 which, as in the case of the other three LAC countries, again use data from The World Bank Group (2020b):

- Figure 2.17 displays the average monthly temperature for the two time periods 1961–1990 and 1991–2016. Comparing both time intervals before and after the starting point of our analysis reveals that a temperature increase has already happened. However, with on average "only" 0.2°C this increase in temperature is rather small compared to the other three LAC countries analyzed in this study (see above).
- Similarly, figure 2.18 visualizes the monthly precipitation in the country for the two time periods 1961–1990 and 1991–2016. Accordingly, it can be stated that on average overall rainfall increased by 14 mm per month. However, real increases can only be observed from February until July and for November, while the other five months of the year experienced rainfall losses.

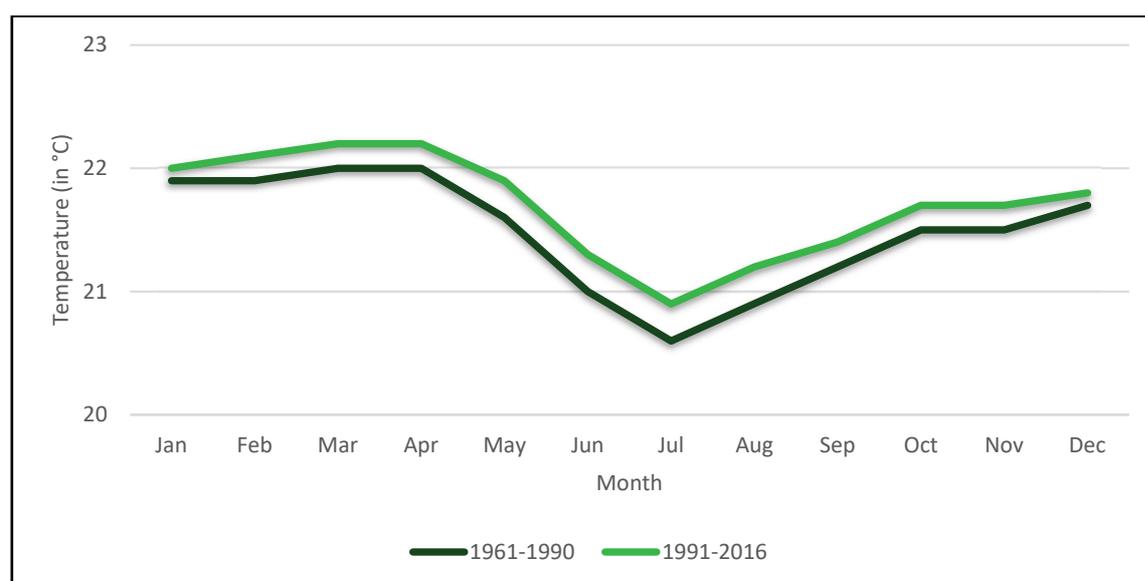
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<sup>8</sup> At the same time, the rural coastal zones do not seem to show any clear positive trends in terms of temperature.

- In terms of tendency, the temperature rise for Ecuador is projected to continue. Figure 2.19 shows this for the average monthly temperature and the four scenarios in the focus of this study. It becomes apparent that the temperature will increase, even if the Paris Agreement is met. In this case a temperature increase of around 1.0°C is projected for 2050 and 2070. If the Paris Agreement fails, i.e. if global economies tend towards following the BAU scenario, temperatures will further increase. In this case, a temperature rise by 1.7°C in 2050 and 2.6°C in 2070 shall be envisaged.
- The potential developments regarding annual and monthly precipitation are less straightforward as depicted in figure 2.20. By and large, it can be stated that annual precipitation is projected to slightly increase in any scenario. Accordingly, precipitation will increase the highest (lowest) under RCP 8.5 in 2070 (RCP 2.6 in 2050). In this case, more than 180 mm (less than 40 mm) additional rainfall would occur within twelve months. However, the changes throughout the year are also interesting: Apparently, rainfall in October will decrease in any scenario whereas it will increase the most during winter and spring if the two RCP 8.5 scenarios are considered.

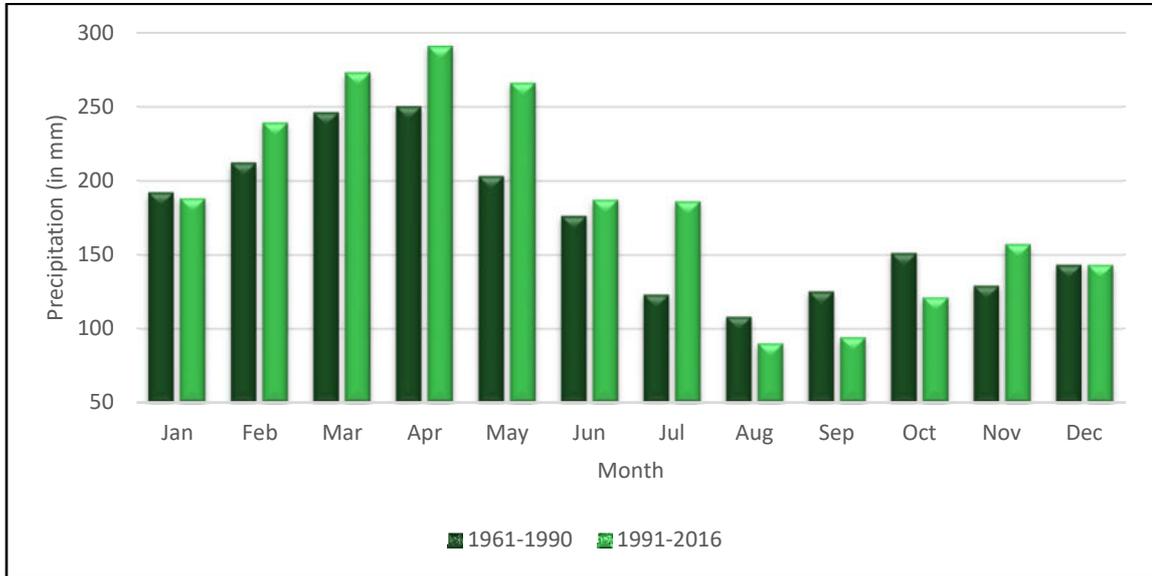
As in the case of the other three LAC countries analyzed in this study, the figures 2.19 and 2.20 visualize the average for the ensemble of altogether 16 climate models. The various models, however, come to different conclusions, subsequently implying uncertainty. To take into consideration this uncertainty, the 10-percent and 90-percent percentiles of available model data are additionally plotted in annex D of this report for temperature and precipitation, for 2050 and 2070, as well as for the RCP 2.6 and RCP 8.5 scenarios.

**Figure 2.17:** Average monthly temperature of Ecuador for the years 1961–1990 as well as 1990–2016



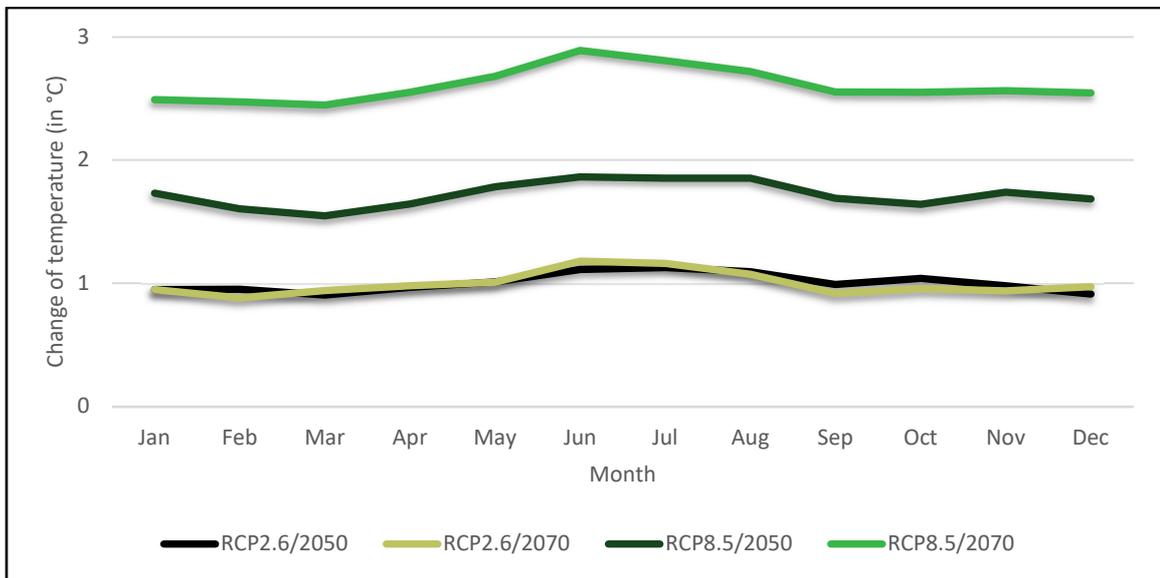
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.18** Average monthly precipitation of Ecuador for the years 1961–1990 as well as 1990–2016



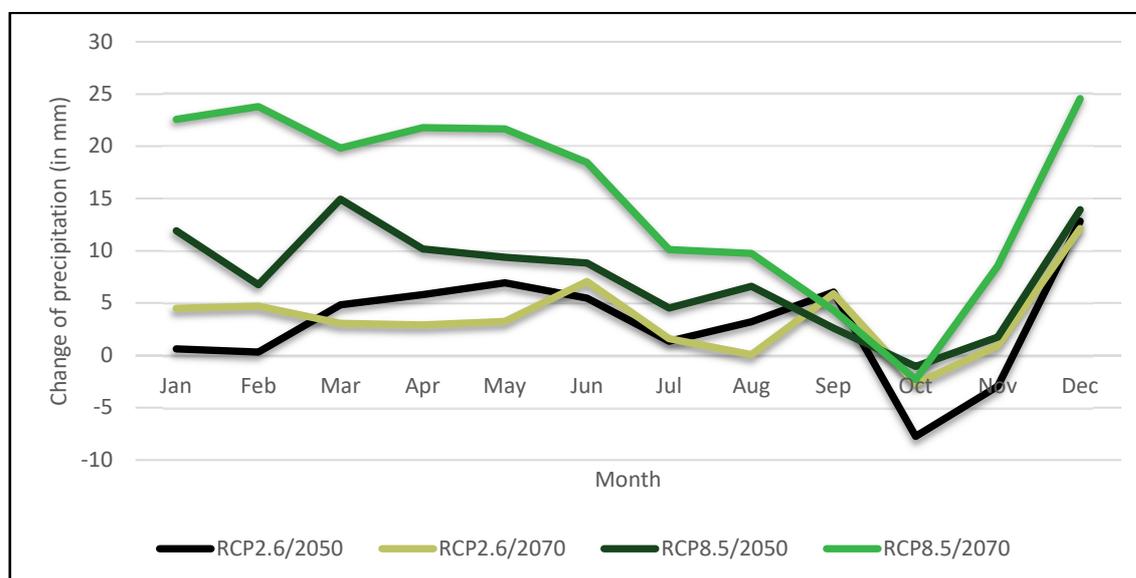
Source: Own figure based on The World Bank Group (2020b).

**Figure 2.19:** Change of average monthly temperature of Ecuador for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5



Source: Own figure based on The World Bank Group (2020b).

**Figure 2.20:** Change of average monthly precipitation of Ecuador for the years 2050 as well as 2070 and the climate change scenarios RCP 2.6 and RCP 8.5



Source: Own figure based on The World Bank Group (2020b).

Taking the RCP 8.5 and 2070 as an example, the graphs in annex D can be interpreted as follows: While the annual temperature is projected to rise on average by 2.6°C until 2070, in reality it may as well increase between 2.0°C and 4.2°C; similarly, while annual precipitation in Ecuador is projected to rise on average by 183 mm, it may actually decrease by 326 mm or increase by 917 mm.

As outlined above, climate change in Ecuador is expected to increase the variability and incidence of extreme weather events, such as droughts, floods, and intense rainfall events (GFDRR and The World Bank, 2011c). This variability can be expected to negatively impact crop production, particularly because agriculture is already vulnerable to current fluctuations in climate. Increasing temperatures will also cause greater evapotranspiration, which will lead to drier soil conditions in many areas. The increasing demand for water will likely decrease water availability even with an increase in precipitation. Apart from these more general findings, climate change is expected to affect agriculture in different ways depending on the specific crops. According to GFDRR and The World Bank (2011c), rice production will probably be negatively affected if no adaptation measures are pursued. For potatoes, different (less or more optimistic) scenarios predict both, a deficit as well as a surplus in production. Similarly, soybeans would also be adversely affected by climate change, while corn production would benefit from it. While estimating the effect of climatic variability on agricultural output in Ecuador in the decade from 2000–2012<sup>9</sup>, Lachaud et al. (2017) found for Ecuador that the

<sup>9</sup> The authors estimated the percentage change in agricultural production over the period 2000–2012 relative to 1961–1999 holding inputs constant at their mean values.

accumulated effect was positive, at around 10 percent. Although these results need to be interpreted with caution, they could suggest that the agricultural sector in the country might have been able to cope relatively well with the climatic changes observed during that period.

In fact, relatively neutral to positive impacts of climate change are also expected by some of the few available studies analyzing the potential impacts of climate change on the country's banana production. For instance, a study published by Elbehri et al. (2016) concluded that climate change between today and the middle of this century is unlikely to present a major challenge to Ecuador's capacity to produce bananas, although the authors also point out that climate change in the medium to long term will likely require adjustments in certain banana production practices. Positive climate-driven yield effects are also anticipated by Varma and Bebbler (2019a) who predict that banana production in Ecuador could see yield increases of (more than) 6.2 percent by 2050 compared to 1970-2000, as displayed in figure 2.21<sup>10</sup>.

**Figure 2.21:** Predicted impacts of various climate change scenarios on banana yields in 2050 for Ecuador in comparison with 1970-2000

Scenario	RCP 4.5	RCP 8.5
Yield impact	6.20 % (+/-1.89 %)	6.27 % (+/-2.18 %)

Source: Own figure based on Varma and Bebbler (2019a).

## 2.6 Brief summary on the findings so far

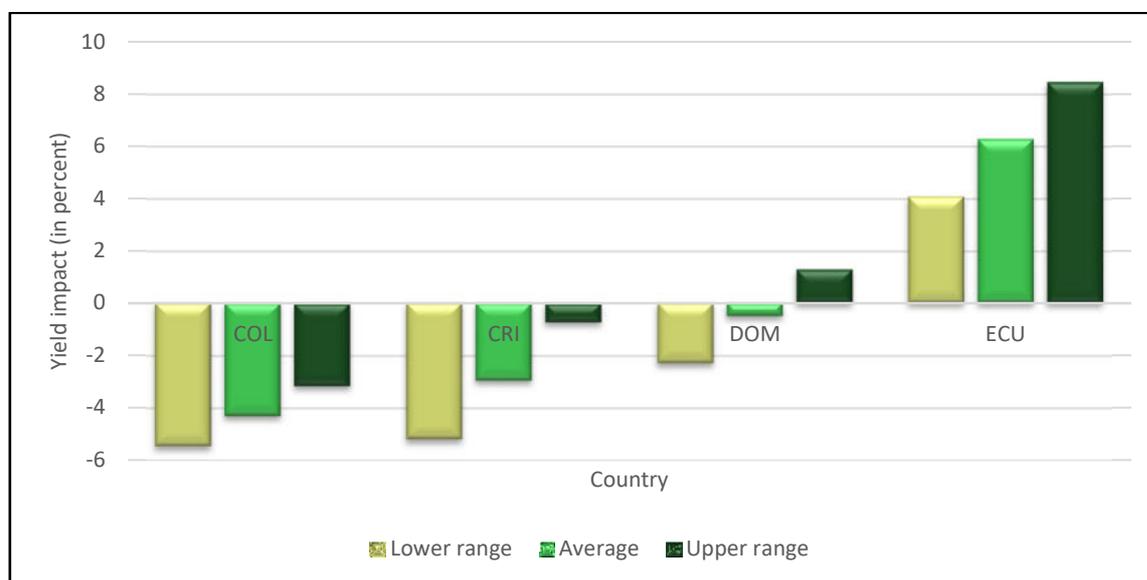
The current state of knowledge shows that a temperature increase is already happening in the selected countries, and that a future rise of temperatures is projected. The developments regarding precipitation quantities and distribution are less uniform. Climate change often has negative effects on agricultural production, and banana production in the four LAC countries is predicted to be affected as well. However, the direction and magnitude of potential banana yield changes seem to be different for each country as figure 2.22 summarizes for the RCP 8.5 scenario and the year 2050:

- Within the group of countries that we are focusing on, Colombia and Costa Rica will potentially suffer the most while
- the Dominican Republic may experience smaller losses and
- Ecuador could even benefit from climate change in terms of banana yields.

Comparing both climate change scenarios used in this study, smaller losses can be expected for the RCP 2.6 scenario, while larger losses are most probable for the RCP 8.5 scenario in the longer term.

<sup>10</sup> This equals a yield increase of more than 0.7 percent per decade.

**Figure 2.22:** Predicted banana yield impacts of the RCP 8.5 climate scenarios in 2050 for Colombia, Costa Rica, the Dominican Republic, and Ecuador compared to 1970–2000



Source: Own figure based on Varma and Bebbler (2019a).

It is important to point out, however, that the available information on potential climate change-related banana yield losses or gains at the national scale should not be overestimated at this point. Climate projections always entail a considerable degree of uncertainty (as is also shown in annexes A to D of this study), and this uncertainty tends to become even more pronounced as projections extend further into the future. In addition, climate projections may differ within a country. It also needs to be taken into account that, apart from climate, yield is also influenced by several other factors, such as available agricultural technology and management options, the occurrence of pests and diseases, efforts in plant breeding and availability of improved varieties, access to irrigation infrastructure, and many more. And of course, as an economic sector agriculture is also embedded into the broader socio-political context of a country, and often indirectly influenced by developments and political decisions primarily directed at other sectors of the economy. Therefore, yield projections will naturally only have a limited validity, and will often be based on modelling the effects of a few influencing variables, while the totality of influencing factors cannot be considered to their full complexity.

In fact, the yield effects at national scale presented in figure 2.22 are based only on average climatic conditions, and explicitly do not account for other factors such as the climate-driven increase in the frequencies of extreme events, or the risk posed by established and emerging diseases (Varma and Bebbler, 2019a). In addition, the changes displayed in figure 2.22 are predicted to happen over a period of around 65 years. Hence, the average change for Colombia equals a yield decrease of 0.5 (0.05) percent per decade (year). And in the case of Ecuador, a yield increase of less than 0.75 (0.075)

percent per decade (year) can be anticipated. To compare, during the past three decades, banana yields in LAC increased on average by 1.3 percent – per year (FAO, 2020b). Therefore, and as is also pointed out by Varma and Bebbler (2019a) in their study, the dimension of the climate-related yield effects projected for the four countries by 2050 suggests that decreasing climate-related yield trends could potentially be compensated by technology- and management-driven yield increases, as long as changes in climate remain within certain “manageable” thresholds<sup>11</sup>.

Apart from the points mentioned above, a limitation of the discussion so far is that the overview has focused merely on the national level of the selected LAC countries, thereby displaying average values for the countries and not taking into account some of the differences in climate and banana yields found in the different geographic regions within these countries. For instance, differences in altitude, latitude, and other topographic peculiarities may be very large and, thus, will certainly affect the countries' regional natural conditions including regional and even very localized weather patterns. To improve our understanding of climate change impacts on banana production, it is therefore necessary to zoom into the most important banana producing regions within these countries. This will be done in the following sections of the study.

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<sup>11</sup> Of course, depending on the climate scenario, a compensation of climate-related negative yield effects through technology and management options will only be possible up to a certain point, as adaptation of banana cultivation to a changing climate might no longer be feasible once certain tipping points in the atmospheric concentration of GHG are reached (Hoegh-Guldberg et al., 2018; IPCC, 2014; Lenton, 2013).

### 3 Observed and projected climate developments in selected banana producing regions of Latin America and the Caribbean

For the selected banana producing regions in the focus of this study and additionally for the overall LAC region, the following discussion distinguishes an analysis of observed climate (sub-chapter 3.1) from an analysis of projected climate change, i.e. the climate expected in the future (sub-chapter 3.2). Major target variables are temperature, precipitation, number of dry months, and potential evapotranspiration (PET). Methodological and data aspects of the analysis are discussed in annex E.

#### 3.1 Observed climate in the regions

To describe the climate of the broader LAC region and in the selected seven regions, we average and compare the chosen climate variables over a 29-year period by using historical/observed climate information from 1990 until 2018. By and large, it can be stated that the climate of the seven LAC regions analyzed in this study is tropical (Beck et al., 2018) with rather high temperatures and precipitation values. For the temperature variable, this also becomes evident when looking at figure 3.1, which visualizes the observed average temperatures between 1990 and 2018 in the entire LAC region as well as in the selected seven sub-national regions. The observations for the seven regions (Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde) as well as for specific banana producing areas located within these seven regions are additionally displayed in annexes F and G<sup>12</sup>.

In coastal and rainforest regions, the average temperatures lie between 20 and 30°C, while it is considerably colder in mountainous regions. The lowest temperatures of the region are found in the Andes. For example, average temperatures in the Ecuadorian Andes are below 10°C. With respect to the selected seven regions, the following can be highlighted:

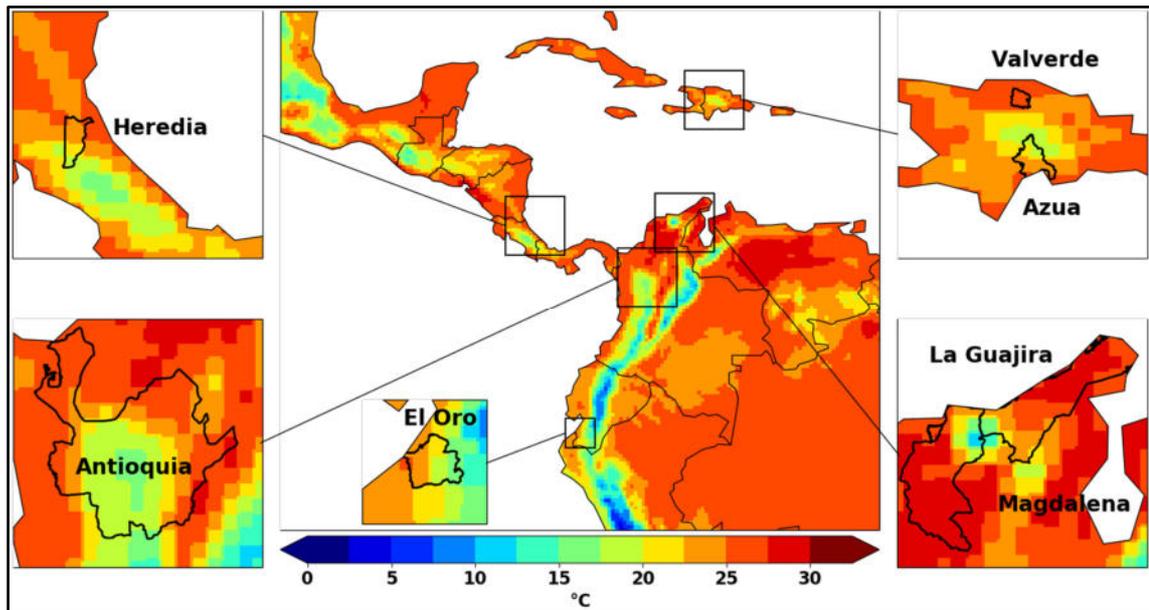
- Due to its location between the Andes and the coast of Ecuador, El Oro shows a steep east-west gradient in temperature ranging from around 15°C in the east to around 25°C in the west.
- In contrast, the Costa Rican region of Heredia displays a north-south gradient ranging from temperatures of less than 20°C in the south to more than 25°C in the north.
- In the Dominican Republic, temperatures in Valverde are on average between 25 and 27.5°C, while temperatures in the more southern region of Azua range from 17.5 to 25 °C.
- In comparison with the other regions of this study, the Colombian regions show the largest temperature range: Antioquia covers the tail of the Andes with temperatures between 15 and 17.5°C as well as lowlands and coastal regions where temperatures range from 25 to 27.5°C;

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<sup>12</sup> Exactly this set of annual temperature and precipitation (see below) observations will also constitute an important dataset for modelling the climate-yield impact in chapter 4 and chapter 5 of the study.

and the most northern Colombian regions of Magdalena and La Guajira display average temperatures ranging from 10°C in the Sierra Nevada de Santa Marta to 30°C at lower altitudes.

**Figure 3.1:** Observed near-surface temperature (at 2 m) averaged over the period from 1990 to 2018 in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

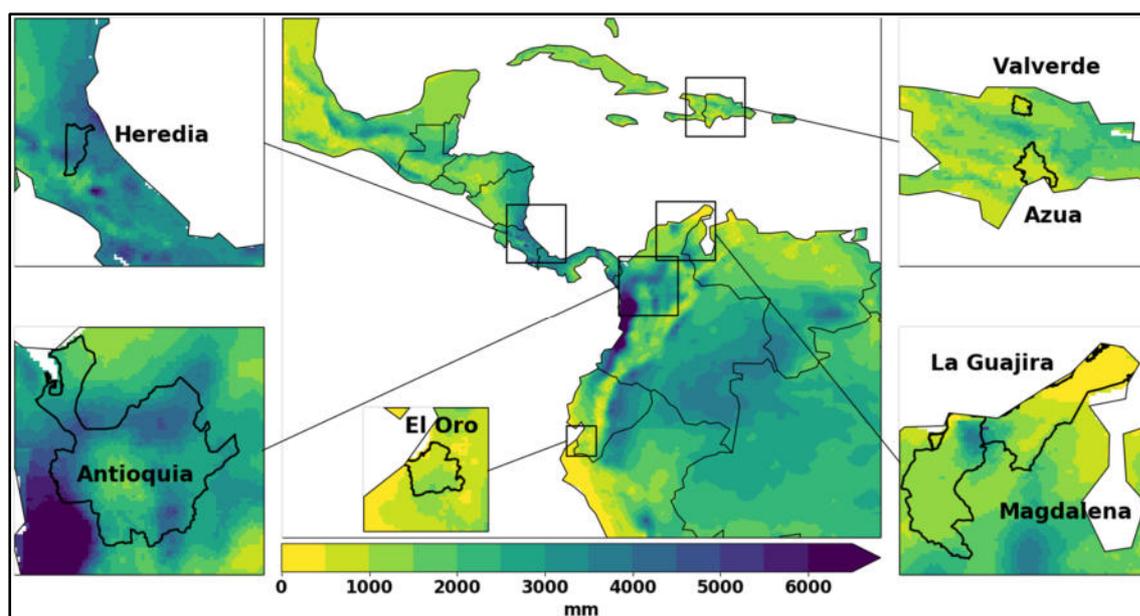
Observed annual precipitation in the broader LAC region has a large range as well. This is displayed in figure 3.2<sup>13</sup>. Accordingly, average precipitation from 1990 to 2018 was between less than 250 mm precipitation per year in deserts of coastal areas in Colombia and Ecuador and more than 6,500 mm in tropical rainfall regions at the Pacific coast of Colombia. The seven regions in the focus of this study also show quite high precipitation ranges:

- La Guajira in Colombia does not only show the largest temperature range, but also the largest precipitation range of all the regions considered here. In fact, the driest sub-region can be found in northern Colombia: The northeast of the region is desert, and a wide area receives less than 500 mm precipitation per year. In contrast, in the western parts of La Guajira precipitation rates of up to 3,000 mm are found.

<sup>13</sup> For the seven regions of Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde as well as for the specific banana producing areas within these seven regions, the annual observations are again displayed in annexes F and G and constitute another important dataset for modelling the climate-yield impact.

- El Oro in Ecuador as well as Valverde and Azua in the Dominican Republic receive moderate precipitation of around 500 to 1,500 mm per year.
- Magdalena in Colombia receives similar precipitation amounts of around 1,000 to 1,500 mm in most of the region, except for the Sierra Nevada de Santa Marta, where annual precipitation rates of up to 4,000 mm are found.
- Antioquia shows a large precipitation range with a drier center, where annual rainfall is around 1,000 to 1500 mm, while most precipitation is experienced on the western slopes of the Andes with up to 6,000 mm.
- Climatic conditions in Costa Rica are overall rather wet. Thus, the region of Heredia experiences an annual precipitation of 3,000 to 4,500 mm on average.

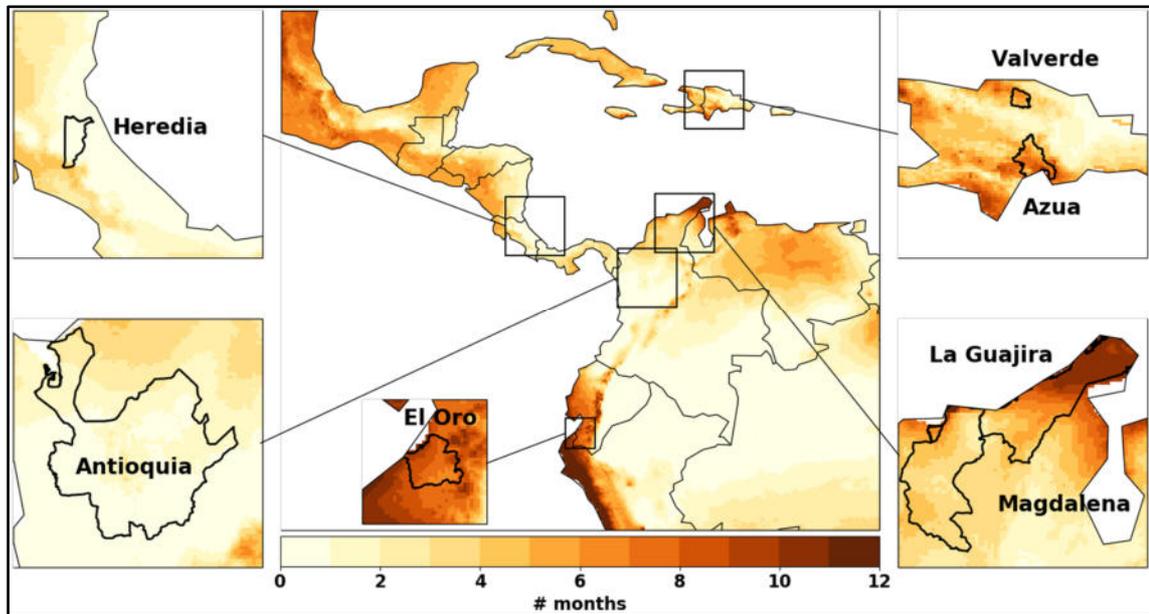
**Figure 3.2:** Observed annual precipitation averaged over the period from 1990 to 2018 in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

As banana growth is not only influenced by average precipitation but also by dry spells, we analyze the number of annual dry months too. Dry months are defined as months with less than 60 mm of precipitation (see also Calberto et al., 2015). The observed number of annual dry months in the broader LAC region, averaged for the period from 1990 to 2018, is presented in figure 3.3.

**Figure 3.3:** Observed annual number of dry months averaged over the period from 1990 to 2018 in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



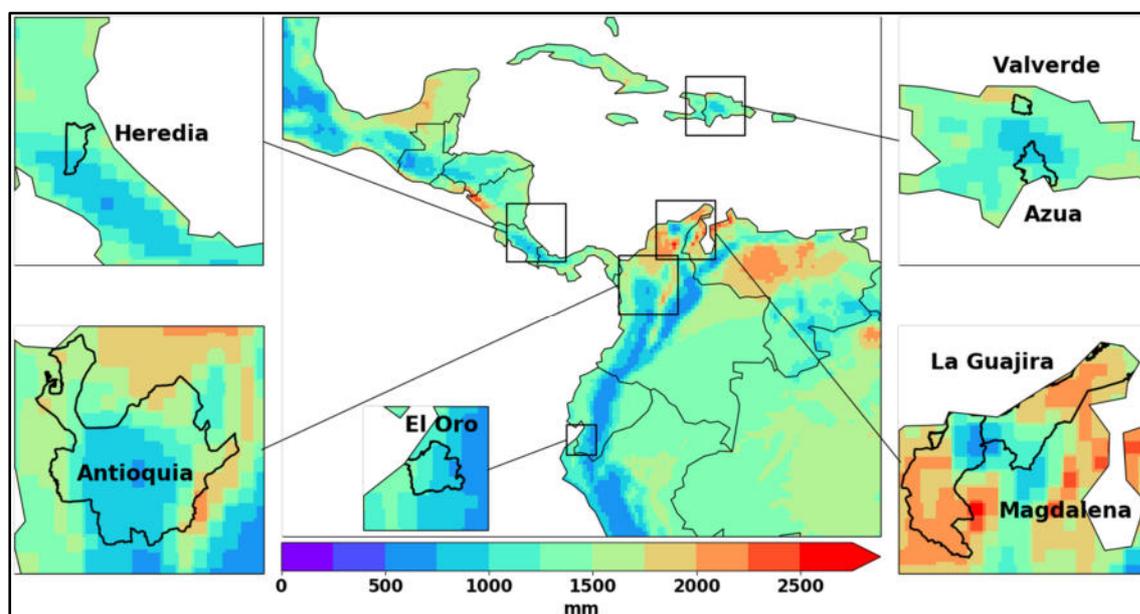
Source: Own figure.

Evidently, the observed number of annual dry months reciprocally reflects the distribution of precipitation as can be seen for instance by looking at the northwestern parts of Colombia. Again, remarkable differences between the selected seven regions in Colombia, Costa Rica, the Dominican Republic, and Ecuador exist:

- El Oro at the Ecuadorian Pacific Coast has between six and ten dry months per year.
- Northern La Guajira even has ten to eleven dry months per year on average, while the east displays fewer dry spells – locally even just one month on average.
- The bordering region of Magdalena has similarly low numbers in dry months with most of the region staying below the value of six months per year.
- The third Colombian banana producing region, Antioquia, locally has a maximum of two dry months per year.
- In Costa Rica, the number of dry months is also low, and in Heredia the average is below one month per year.
- In the Dominican Republic, however, conditions locally vary strongly. The number of dry months in Azua and Valverde ranges from two to eight months in most areas.

While precipitation as a climate variable gives information on the input of moisture into the local system, the future water availability for agriculture will also be limited by the increased water demand of the warming atmosphere. This water demand is expressed by PET, which is the maximum rate of evapotranspiration, if enough water is available<sup>14</sup>. Against this background, the average annual sum of PET in the broader LAC region as well as in the selected seven regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador is shown in figure 3.4.

**Figure 3.4:** Observed annual sum of potential evapotranspiration averaged over the period from 1990 to 2018 in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

As PET is a non-linear function of temperature, the spatial distribution strongly resembles the temperature distribution, but the spatial variability is stronger. Lower values of 500 to 750 mm per year are found in the Andes and the Sierra Nevada de Santa Marta, while the lower regions of Colombia show annual sums between 2,000 and 2,500 mm. In regions like the deserts of northern La Guajira, the soil and rainfall clearly do not provide enough moisture to ever reach evapotranspiration rates close to this theoretical upper limit. Between the seven regions, remarkable differences exist:

<sup>14</sup> The actual evapotranspiration is usually lower than the PET as the actual evapotranspiration is determined by the water input, i.e. the precipitation, and the soil characteristics. In this respect, an increased atmospheric water demand due to rising temperature must be considered when it comes to providing sufficient water – for instance via irrigation – for the banana production.

- The Colombian regions La Guajira, Magdalena and Antioquia show the largest range in annual PET from 500 to 2,250 mm.
- The annual PET sum of the Ecuadorian region of El Oro is comparatively low with values between 500 and 1,500 mm; and an almost similar range can be observed in Heredia in Costa Rica. Here, the annual PET sum is between 750 and 1,500 mm locally.
- The same PET range can also be seen in the Azua region, while Valverde, also in the Dominican Republic, has 1,250 to 1,500 mm per year.

In addition to the climatic factors already presented above, which influence banana production, wind and temperature extremes are also of importance. However, an analysis of observed wind conditions is problematic due to the poor data situation. There is little agreement on past wind variability between datasets. And particularly gridded datasets, which give the necessary coverage needed in this study, tend to underestimate wind speed peaks (Hartman et al., 2013). To cover these wind peaks, high spatial resolution data, with a higher resolution than the grid level scale of the climate models used in this study (see annex E), and with a much higher temporal resolution would be necessary<sup>15</sup>. In addition, as there is little agreement between models the confidence in future changes in wind conditions is also very low (Seneviratne et al., 2012). In the LAC region, however, wind speeds related to tropical cyclones are projected to increase (Christensen et al., 2013).

Since extreme temperatures are increasing and projected to further increase globally (Seneviratne et al., 2012), an additional analysis of the highest annual temperatures as well as of consecutive dry days would strongly resemble an analysis of the status quo and of the pattern of increase of mean temperatures (see above), and the observations and projected changes of maximum temperatures would merely highlight the same regions. By and large, it can be stated that the magnitudes of the projected changes in maximum temperatures are similar to the projected changes in mean temperatures. In this respect, Annex H provides more details on regional maximum temperatures and covers all the information that has been discussed in sub-chapter 3.1, and which will additionally be considered in sub-chapter 3.2 for the other climate variables.

### 3.2 Projected climate change for the regions

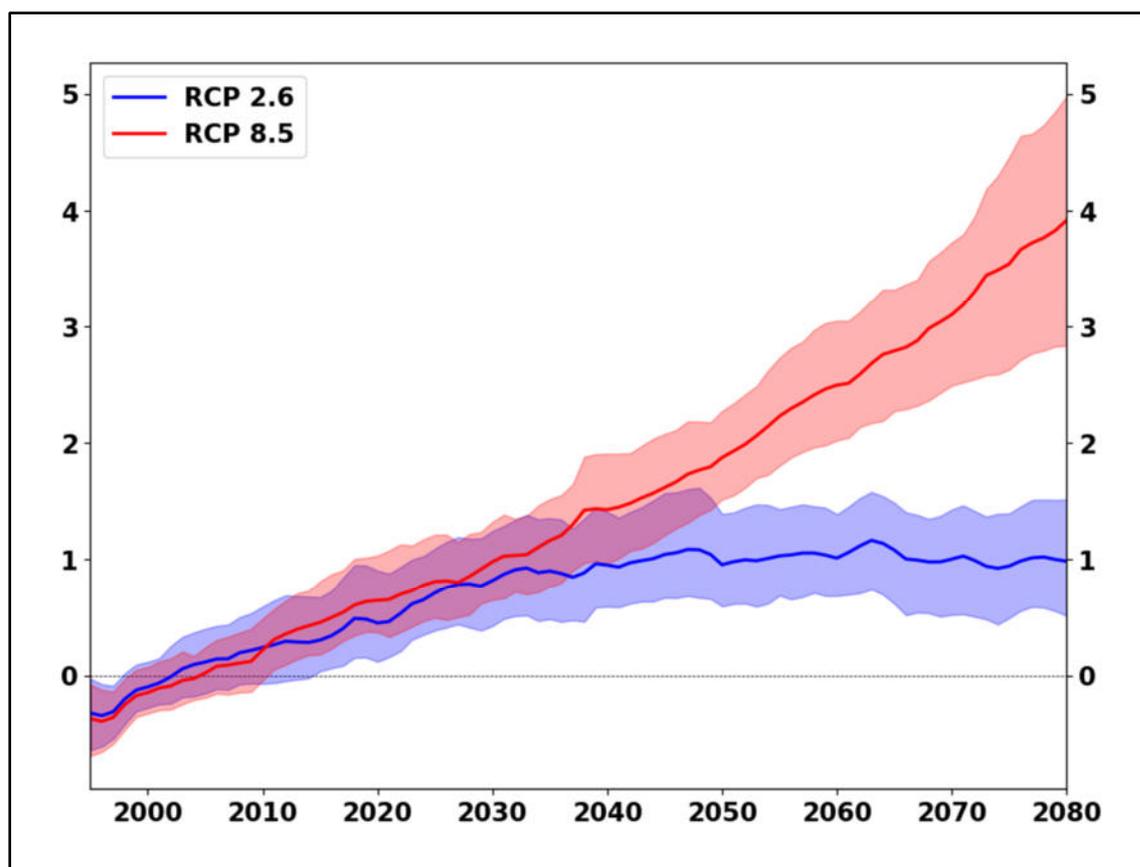
In the following, the climatic changes projected for the broader LAC region and for the selected seven regions will be described. To do so, we average and compare the climate variables discussed in the previous chapter over 29-year periods. This is done by using model data for the two time periods ranging from 2036 to 2064 to analyze the climate for 2050, and from 2056 to 2084 to analyze the climate for 2070. These data will be compared to model data for the years from 1990

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<sup>15</sup> In this study we used daily weather and climate data, but for capturing the wind peaks, hourly observations would be needed, which, in turn, could not be projected to future periods at the end of the 21<sup>st</sup> century.

to 2018. Regardless of the time horizon, the climate models strongly agree that the earth will continue to warm (Kirtmann et al., 2013). Consequently, the temperature in the broader LAC region is also projected to increase as figure 3.5 displays. In this figure, we compare the evolution of near-surface temperature averaged over the whole region using climate projections from 1990 to 2085<sup>16</sup>.

**Figure 3.5:** Projected evolution of near-surface temperature (as 11-year running mean) averaged over the whole LAC region being in the study focus, 1990–2080 (in °C)



Source: Own figure.

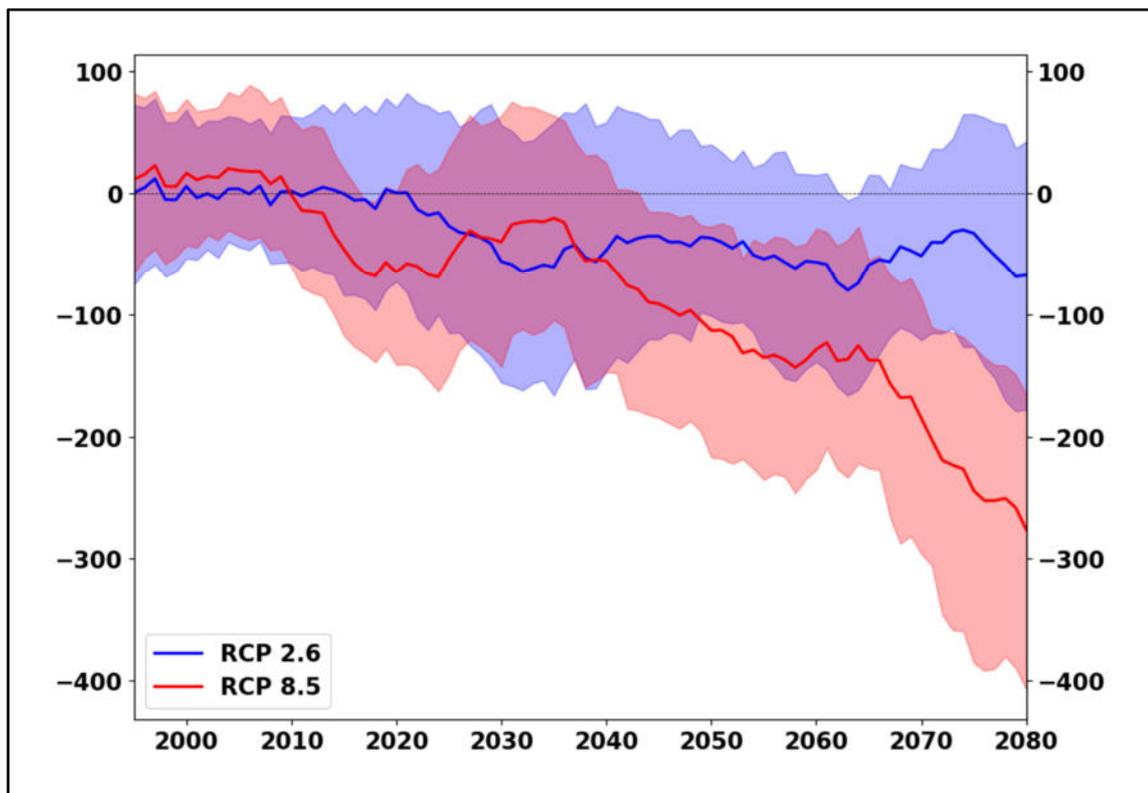
More particularly, we show the model mean as well as the model range under the two most extreme of the RCP scenarios, namely RCP 2.6 (representing strong mitigation efforts) and RCP 8.5 (representing no mitigation efforts). All the climate models we use in this study (see again annex E) project a temperature increase under both scenarios:

<sup>16</sup> Note: As we show the 11-year running means of temperature change in the figure to reduce inter-annual variability, the time series displayed covers the years from 1995 until 2080 only.

- Under RCP 2.6, the model average shows a temperature increase of about 1°C in comparison with historic conditions (1990–2018) by the middle of the century and then temperature stabilizes over time. Also, the model range is about 1°C in the RCP 2.6 scenario.
- Under RCP 8.5, temperature increases continuously and hits the 4°C mark around the year 2080. Around 2050, the increase arrives at approximately 2°C, and for 2070, an increase of more than 3°C should be expected. Also note that the model range is expanding with increasing temperature under RCP 8.5 to about 2°C by 2080.

In contrast to that clarity regarding projected temperature increases, precipitation projections are generally much more uncertain (Kirtmann et al., 2013). This is displayed in figure 3.6, which similarly to figure 3.5 shows the evolution of average annual precipitation over the whole LAC region considered here.

**Figure 3.6:** Projected evolution of annual precipitation (as 11-year running mean) averaged over the whole LAC region being in the study focus, 1990–2080 (in mm)



Source: Own figure.

Over time, the model mean for annual precipitation in the broader LAC region shows a decrease under both RCP scenarios. Following the RCP 2.6 trajectory, the model mean precipitation decreases

by around 50 mm by 2080 in comparison with the 1990–2018 average. However, the model range is around 200 mm, therefore one of the three models even projects a slight increase in precipitation. Following the RCP 8.5 trajectory, the model mean precipitation decreases by around 250 mm by 2080 with a similar model range of about 200 mm.

These values visualized in figures 3.5 and 3.6 are, however, only the average of the very diverse climatic changes projected for a rather large geographic region. To account for this diversity within the LAC region, we will present the values of projected changes for each individual region in the following. Our analysis will focus on all the climate variables discussed in the previous chapter and present the model ensemble means for each of these variables and for each of the seven regions by 2050 and 2070, respectively. For this purpose, several figures will be presented and discussed in this chapter, each focusing on the projection of a specific climate variable for one specific time period (i.e. for 2050 and 2070) and for one defined RCP scenario (i.e. RCP 2.6 and RCP 8.5).

Starting with an analysis of the projected changes in temperatures in the regions, the essential outcomes are presented in figure 3.7. The figure displays the calculated absolute temperature difference by 2050 and by 2070, compared to 1990–2018, for the seven selected regions and the two RCP scenarios (see also annex I<sup>17</sup>).

In addition, figures 3.8 and 3.9 show the modelled absolute mean temperature increases as geographic maps by 2050 for the RCP 2.6 scenario and RCP 8.5 scenario, respectively. Similarly, figures 3.10 and 3.11 depict the modelled mean temperature changes by 2070 for the two defined RCP scenarios.

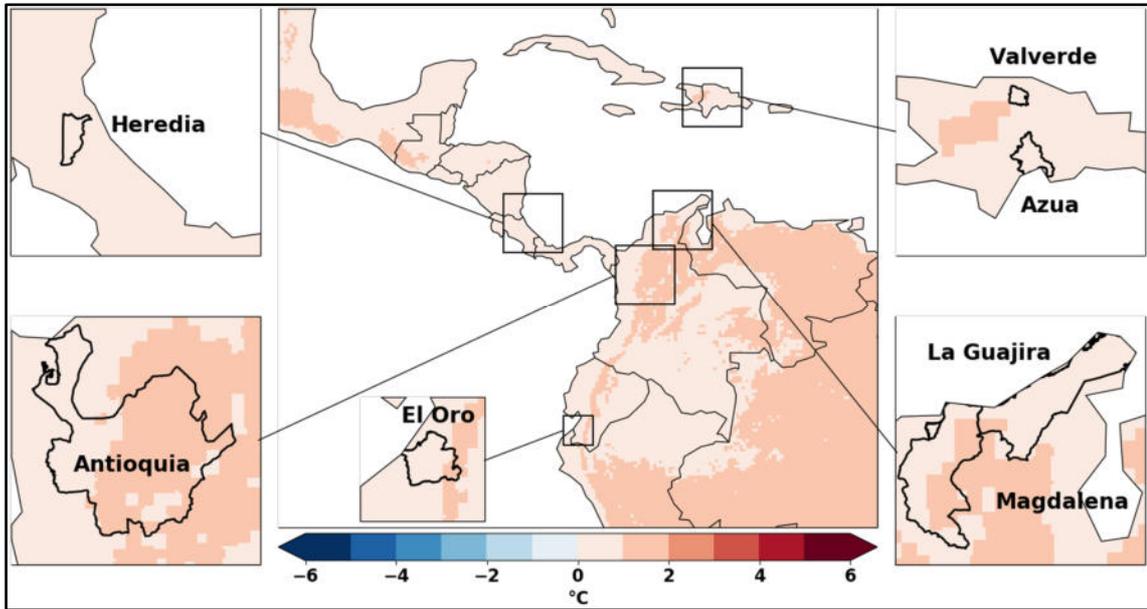
**Figure 3.7:** Calculated difference of the near-surface temperature, compared to 1990–2018, for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Region	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	0.99°C	1.98°C	1.13°C	3.20°C
Azua	0.87°C	1.74°C	0.90°C	2.82°C
El Oro	0.94°C	1.75°C	1.04°C	2.81°C
Heredia	0.78°C	1.43°C	0.81°C	2.26°C
La Guajira	0.88°C	1.60°C	0.93°C	2.55°C
Magdalena	0.97°C	2.00°C	1.16°C	3.30°C
Valverde	0.97°C	1.84°C	0.97°C	2.95°C

Source: Own figure.

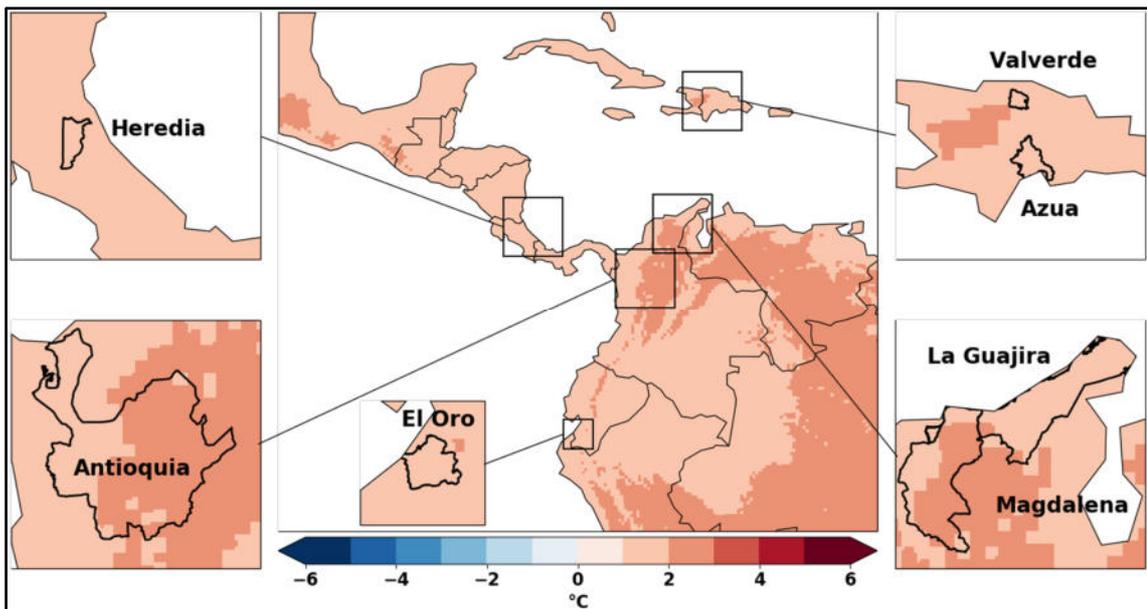
<sup>17</sup> Annex I displays similar information as figure 3.7 for specific banana production areas located within the seven regions. The data are needed to later perform a more detailed climate-yield impact analysis.

**Figure 3.8:** Projected change in near-surface temperature by 2050 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



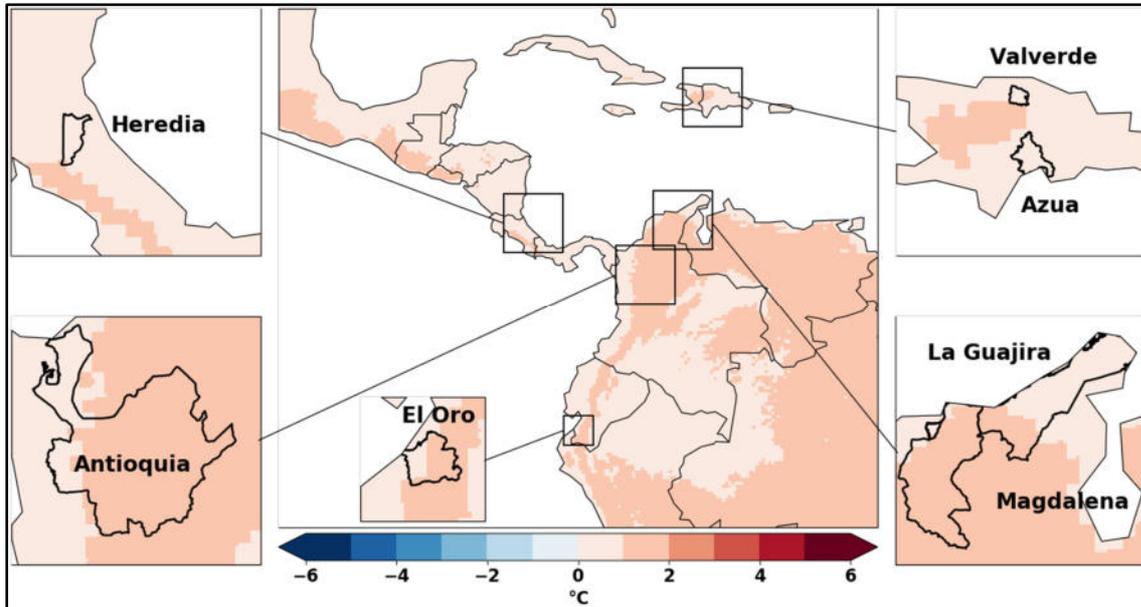
Source: Own figure.

**Figure 3.9:** Projected change in near-surface temperature by 2050 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



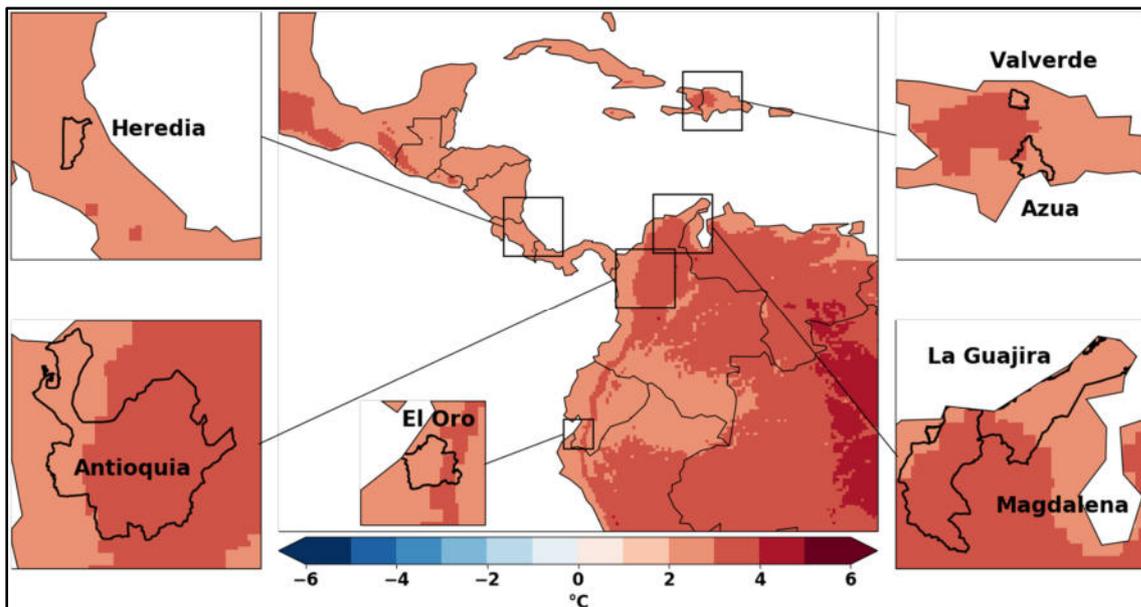
Source: Own figure.

**Figure 3.10:** Projected change in near-surface temperature by 2070 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

**Figure 3.11:** Projected change in near-surface temperature by 2070 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

Accordingly, it can be stated that by 2050 temperatures are expected to increase everywhere in the LAC region. Under the strong mitigation scenario RCP 2.6, this increase ranges from 0 to 2°C as figure 3.8 displays. In all of Costa Rica, i.e. also in Heredia, in the banana producing regions of the Dominican Republic and of Ecuador, as well as in La Guajira in northern Colombia temperature is projected to increase by up to 1°C. And for much of Antioquia as well as for the east of Magdalena, both in Colombia, a warming of 1 to 2°C is even predicted for specific locations. However, when averaged for each of the seven regions, the warming rates for the banana producing regions only differ slightly from each other and are between 0.76°C in Heredia and 0.99°C in Antioquia (see figure 3.7 and annex I). Under the no-mitigation scenario RCP 8.5, the warming distribution in 2050 looks strikingly similar, but warming rates are roughly doubled everywhere in the seven regions as shown by figure 3.7, annex I and figure 3.9.

By 2070, conditions will not substantially change from those predicted for 2050 under the RCP 2.6 scenario: the details are shown in figure 3.10. Accordingly, the further increase in temperature is most notable in El Oro, which by 2070 is projected to be locally about 1 to 2°C warmer than in the historic period. However, the average temperature difference will only increase by 0.1°C from the value projected for 2050 (see figure 3.7 and annex I). The difference in temperature changes between 2070 and 2050 for RCP 2.6 in Heredia, La Guajira, Valverde, and Azua are (also) negligibly small. In contrast to that, the warming areas within Antioquia and Magdalena will have extended, which leads to a further increase in the regional average temperature of these regions by more than 0.1°C. In contrast, there is a strong further increase of temperatures under RCP 8.5 by 2070. While the warming pattern is the same by 2070, the regional warming will range between 2.16°C in Heredia and 3.30°C in Magdalena (see figure 3.11 and, again, figure 3.7 as well as annex I).

The projected changes for precipitation show different wetting and drying trends throughout the selected regions. Figure 3.12 shows the details in terms of the calculated relative difference of the annual precipitation by 2050 and 2070, compared to 1990–2018, for the seven selected regions and the two RCP scenarios<sup>18</sup>).

In addition, figures 3.13 and 3.14 show the modelled mean relative precipitation change as geographic maps by 2050 for the RCP 2.6 scenario and RCP 8.5 scenario, respectively. Similarly, figures 3.15 and 3.16 depict the modelled mean precipitation change for 2070 and the two defined RCP scenarios.

By 2050, the projected changes in precipitation under RCP 2.6 will generally be small but already show a large spread as figure 3.13 and annex I visualizes. In Ecuador, there is no clear wetting or drying pattern throughout the country and the changes in El Oro are negligible, with a decrease by less than 5 percent in specific locations and a decrease of around 1 percent on average. In Heredia, there is a slight increase in precipitation of up to 10 percent locally and of around 4 to 5 percent

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<sup>18</sup> Again, annex I displays similar information as figure 3.12 for specific banana production areas located within the seven regions. The data are also needed to perform a more detailed climate-yield impact analysis hereafter.

on average. Instead, in the Dominican Republic, a low decrease in precipitation of up to 10 percent locally and of 3 to 5 percent on average is projected for Valverde, whereas a negligible increase of precipitation of less than 5 percent locally and of slightly more than 2 percent on average is projected in Azua. In the Colombian banana producing regions, changes in Magdalena are also negligible amounting to less than 5 percent locally and close to 1 percent on average, while central Antioquia shows a reduction in precipitation of up to 15 percent locally. In contrast, western Antioquia shows an increase in precipitation of up to 15 percent, which brings the regional average change to near minus 2 percent as well. The strongest relative change is found in the northern part of La Guajira, with an increase in precipitation of up to 30 percent. However, since annual precipitation in this region is very low, the absolute change is also low. Therefore, precipitation in La Guajira will only increase by 5 percent on average.

**Figure 3.12:** Calculated difference of the annual precipitation, compared to 1990–2018, for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Region	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	-2.02 %	-6.61 %	-3.02 %	-12.06 %
Azua	2.07 %	-8.09 %	-0.48 %	-18.69 %
El Oro	-0.75 %	-0.86 %	-0.64 %	2.86 %
Heredia	4.11 %	1.78 %	1.58 %	4.93 %
La Guajira	5.37 %	-5.90 %	-3.98 %	-18.75 %
Magdalena	0.91 %	-8.89 %	-4.61 %	-17.92 %
Valverde	-4.72 %	-11.78 %	-5.10 %	-22.61 %

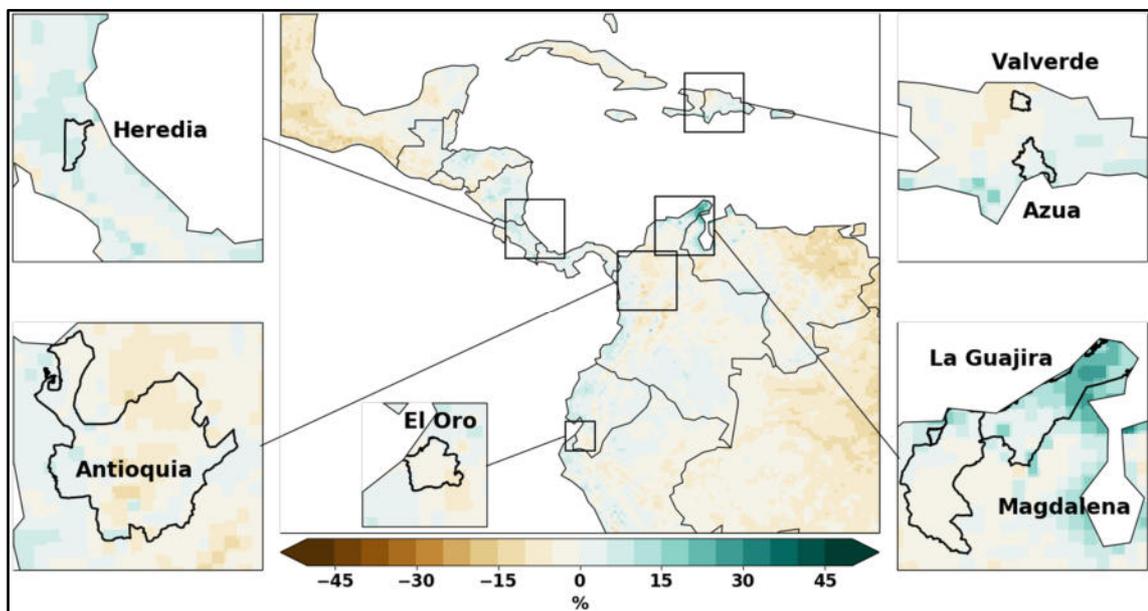
Source: Own figure.

As for the RCP 8.5 scenario, annual precipitation changes projected for 2050 are – on average – slightly stronger and not everywhere consistent with the direction of the changes projected for the RCP 2.6 scenario in the same period as figures 3.12 and 3.14 as well as annex I reveal. For the RCP 8.5 by 2050, the Dominican Republic, for instance, now shows a decrease in precipitation with the changes amounting to up to 15 percent in specific areas of both, Valverde and Azua. The average change in annual precipitation in these two regions will be minus 12 percent and minus 8 percent, respectively. The change in Heredia is similar to the RCP 2.6 scenario with increases of still up to 10 percent locally and with an average increase of now 2 percent. The precipitation changes in El Oro are again negligible, as they already were under the RCP 2.6 scenario. A decrease of 1 percent on average can be projected in this region. In turn, for RCP 8.5 Colombia shows a stronger drying than for the RCP 2.6 scenario. Central and eastern Antioquia are projected to be drier by up to 25 percent locally and by 7 percent on average, and Magdalena shows a drying of up to 15 percent throughout much of the region resulting in an annual precipitation decrease of 9 percent on

average. The direction of precipitation changes in La Guajira is reversed going from an increase to a slight decrease in precipitation of up to 10 percent locally and of 6 percent on average for the whole region<sup>19</sup>.

By 2070, projected changes for annual precipitation under the strong mitigation scenario RCP 2.6 are still only small, as figure 3.15 shows. The most obvious difference to 2050 is that precipitation changes in La Guajira move from positive to negative, but as the changes displayed in figure 3.15 are relative, the change in this region is disproportionately strong compared to the other regions. On average, precipitation in La Guajira is projected to decrease by approximately 4 percent. Most of the Colombian banana producing regions show a clear drying. In Magdalena, for instance, the change is up to 10 percent locally and around 5 percent on average, while in Antioquia, it is up to 20 percent locally and 3 percent on average. In contrast, the changes in Heredia and El Oro are negligible with less than 5 percent locally and 1 to 2 percent on average. In the regions of the Dominican Republic, there is also a comparatively slight drying projected, with a 5 percent average decrease in precipitation in Valverde, but almost no change in the average precipitation projected for Azua (see also annex I).

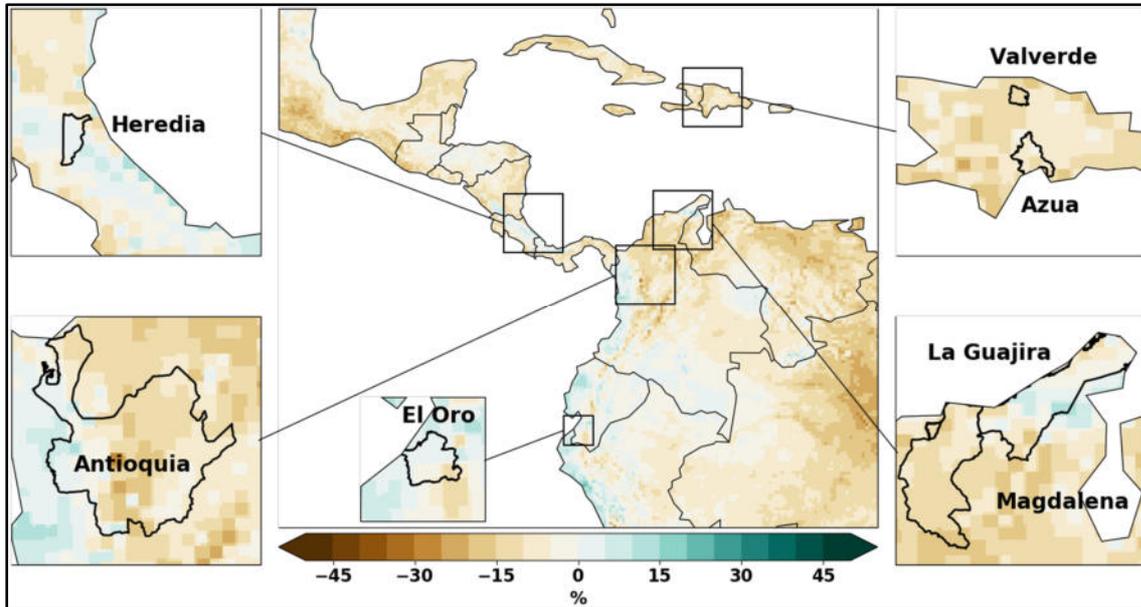
**Figure 3.13:** Projected change in annual precipitation by 2050 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

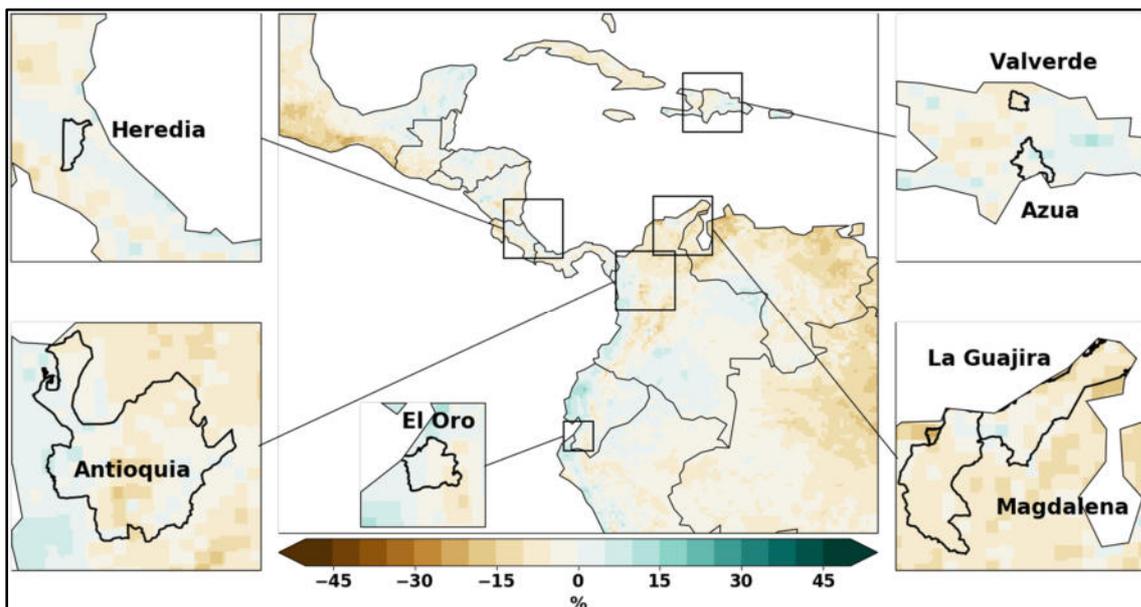
<sup>19</sup> For some specific and more differentiated data zooming into the specific banana production areas of this and the other seven regions, see again annex I.

**Figure 3.14:** Projected change in annual precipitation by 2050 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



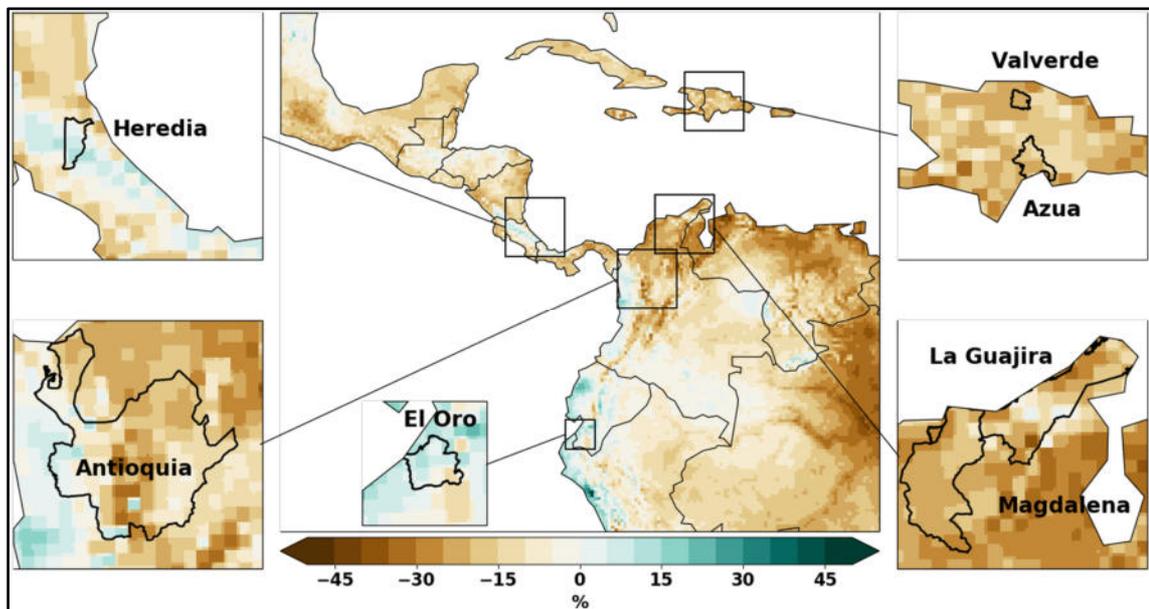
Source: Own figure.

**Figure 3.15:** Projected change in annual precipitation by 2070 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

**Figure 3.16:** Projected change in annual precipitation by 2070 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

Precipitation changes for the RCP 8.5 scenario by 2070 are projected to be much stronger, but similar in direction to those projected for 2050, as is visualized in figures 3.12 and 3.16 as well as in annex I. Accordingly, the Colombian banana producing regions show an overall drying, with precipitation being reduced by up to 40 percent locally and by 12 percent on average in Antioquia and, again, by 40 percent locally but by 19 percent on average in La Guajira. Magdalena, under this scenario, shows a 25 percent decrease of precipitation locally and a decrease of 18 percent on average. The two regions located in the Dominican Republic also show local precipitation decreases of up to 25 percent. Precipitation decreases on average by 23 percent in Valverde and by 19 percent in Azua. In contrast, Heredia in Costa Rica and El Oro in Ecuador display a mix of slightly wetting and drying across the two regions. In both regions, precipitation is shown to increase by up to 15 percent locally, but while El Oro also shows an average increase of 3 percent in precipitation, the change in Heredia postulates a weak increase of around 5 percent on average.

The projected annual precipitation changes are also reflected in the projected changes of the number of dry months per year, i.e. months with less than 60 mm rainfall. Figure 3.17 shows the details comparing projections for 2050 and 2070 with the period of 1990–2018, again for the seven selected regions and the two RCP scenarios. In addition, figures 3.18 and 3.19 show the modelled mean changes in dry months by 2050 for the RCP 2.6 scenario and RCP 8.5 scenario, respectively, whereas figures 3.20 and 3.21 depict the same information for 2070.

**Figure 3.17:** Calculated change of annual dry months, compared to 1990–2018, for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Region	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	0.16 months	0.37 months	0.22 months	0.72 months
Azua	0.07 months	0.56 months	0.17 months	1.06 months
El Oro	0.08 months	0.29 months	0.16 months	0.42 months
Heredia	-0.22 months	-0.32 months	-0.17 months	-0.42 months
La Guajira	-0.09 months	0.26 months	0.24 months	0.71 months
Magdalena	0.09 months	0.36 months	0.27 months	0.82 months
Valverde	0.07 months	0.55 months	0.02 months	1.01 months

Source: Own figure.

Accordingly, it can be stated that the changes vs. the reference situation differ per scenario and are as follows:

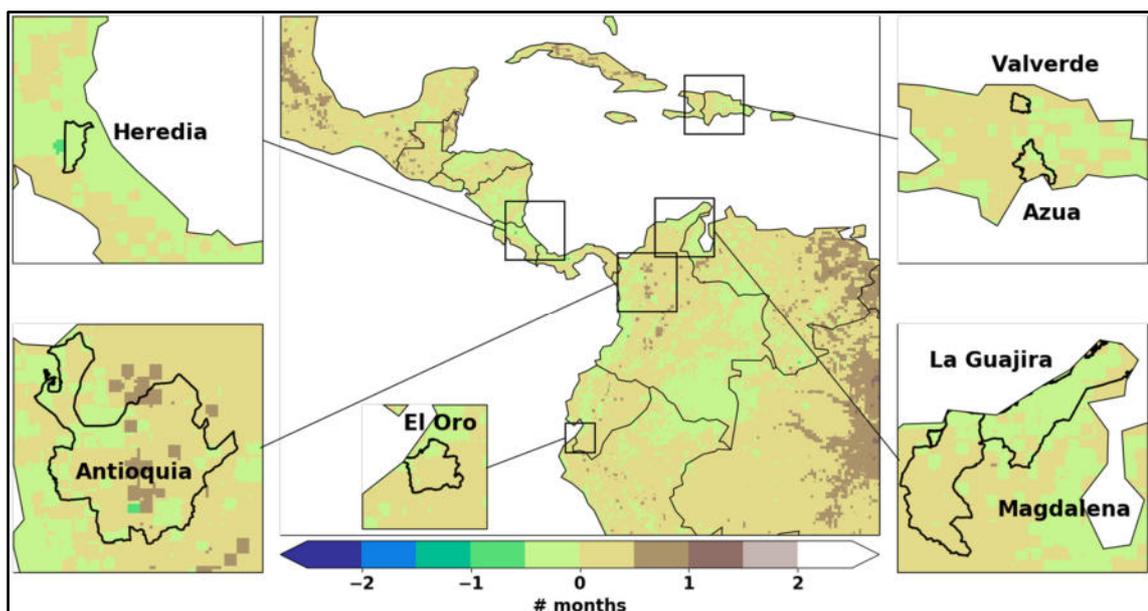
- For the RCP 2.6 scenario in 2050, only certain areas in Antioquia show up to one dry month more per year locally as displayed in figure 3.18. However, the regional average change for Antioquia is still only 0.16 months per year. In contrast, dry months in Heredia decrease by 0.22 months per year. In the other banana producing regions, the average changes are negligible, i.e. less than plus/minus 0.1 months per year.
- For the RCP 8.5 scenario, the projected changes by 2050 are slightly stronger as is visualized in figure 3.19. Some smaller areas of El Oro in Ecuador, of Valverde in the Dominican Republic and of Magdalena in Colombia show an increase in dry months of up to one month per year. In some small areas of the Colombian regions of La Guajira and Antioquia, there is even a projected increase of dry months of up to 1.5 months per year. In contrast, northern Heredia in Costa Rica shows a decrease in dry months of up to 1 month per year. The average changes range from a decrease of 0.32 months per year in Heredia to an increase of 0.56 months per year in Azua<sup>20</sup>.
- Looking at the RCP 2.6 scenario again, the changes projected by 2070 are only slightly stronger than those projected by 2050 (see figure 3.20). The drying in central Antioquia is slightly more prominent than what is expected for the two decades before. Generally, the Colombian banana producing regions show the strongest further increase of dry months in comparison with 2050, with projected increases of 0.22 months per year for Antioquia, 0.24

<sup>20</sup> Only Heredia in Costa Rica shows a projected decrease in dry months under the RCP 8.5 scenario in 2050 and continues to do so in the other scenarios.

months per year for La Guajira and 0.27 months per year for Magdalena. Changes in Valverde in the Dominican Republic are, in contrast, still negligible, while Azua shows a projected average increase in dry months of 0.17 per year. Heredia in Costa Rica and El Oro in Ecuador show a decrease of 0.17 months per year and an increase of 0.16 months per year on average, respectively.

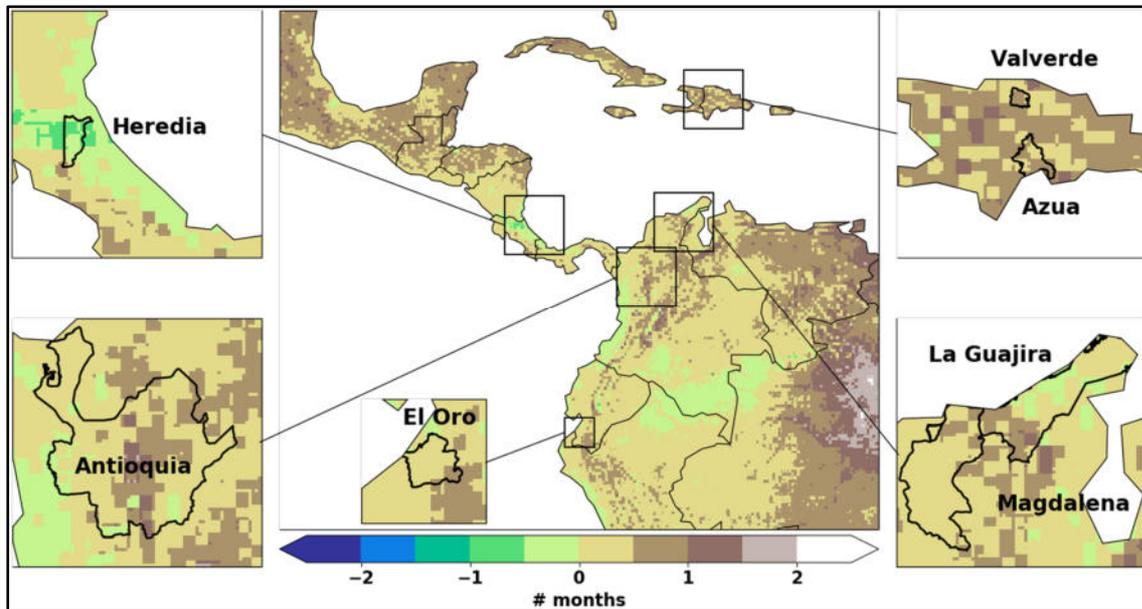
- In line with temperature and precipitation, the changes projected for 2070 are much stronger under the RCP 8.5 scenario (see figure 3.21). Generally, the selected regions show a tendency towards more dry months. The strongest increases in dry months are predicted to be in the Colombian regions. Locally, in central Antioquia, as well as southern La Guajira, the models project an increase of more than two months per year. The projected average change in both regions is an increase of 0.72 months per year in Antioquia and 0.71 months per year in La Guajira. Throughout most of Magdalena, the increase is up to one month per year locally and 0.82 months per year on average. The Dominican Republic is also projected to suffer an increase in dry months. Valverde shows an increase of up to one month per year locally and on average, and Azua will most probably face an increase of up to 1.5 months per year locally and 1.06 months per year on average. The changes in El Oro are still weak, with only a small area in the east of the region showing an increase in dry months of up to one month per year, while the other regions show an average increase of 0.42 dry months per year. In contrast to most of the broader LAC region, the north of Heredia in Costa Rica, again, shows a decrease in dry months of up to one month locally and 0.42 months per year on average.

**Figure 3.18:** Projected change in number of dry months by 2050 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



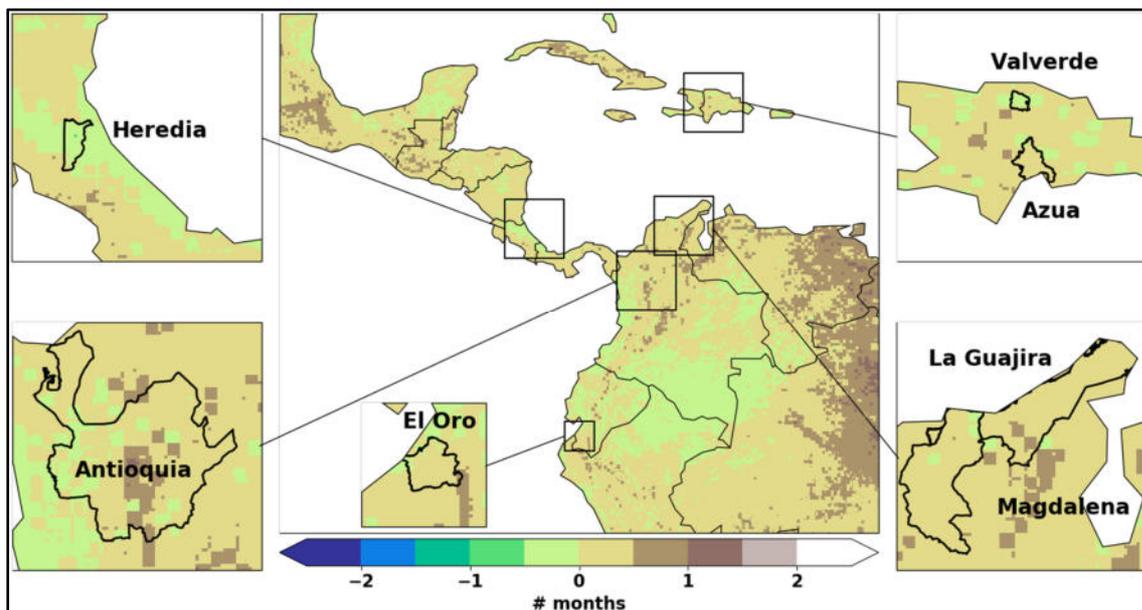
Source: Own figure.

**Figure 3.19:** Projected change in number of dry months by 2050 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



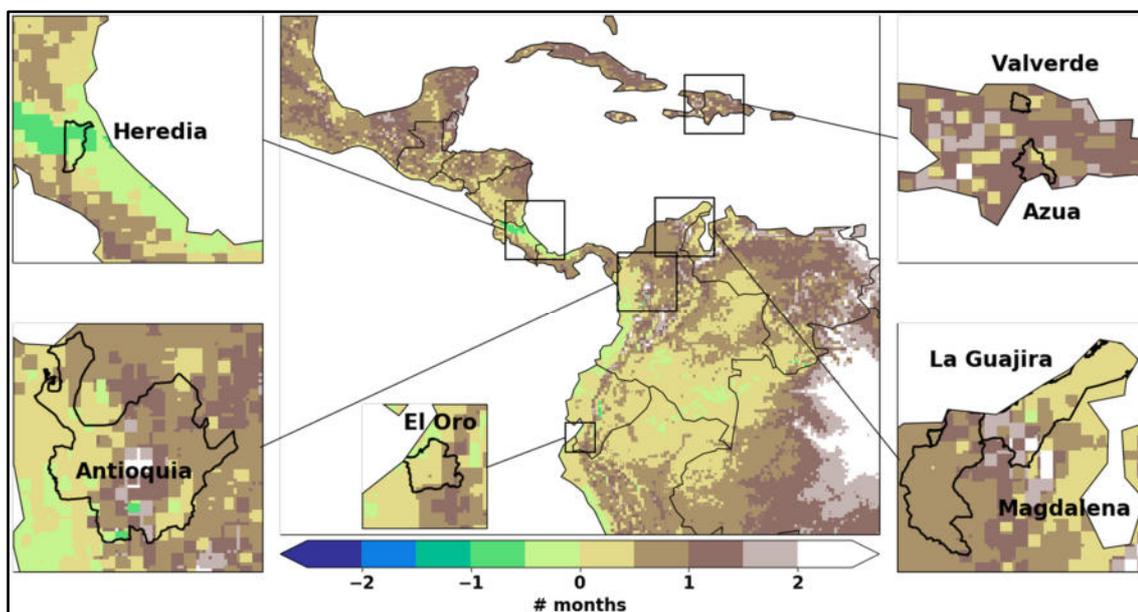
Source: Own figure.

**Figure 3.20:** Projected change in number of dry months by 2070 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

**Figure 3.21:** Projected change in number of dry months by 2070 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

Finally, we will now analyze the potential changes in atmospheric water demand, i.e. in PET. As visualized in figure 3.22, the regions selected for this study show an increase in PET for both future time periods, and under both RCP scenarios due to the temperature dependence of PET.

**Figure 3.22:** Calculated change of annual potential evapotranspiration, compared to 1990–2018, for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Region	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	15.55 %	37.05 %	18.21 %	65.67 %
Azua	11.71 %	26.44 %	12.01 %	45.26 %
El Oro	12.68 %	26.26 %	13.99 %	44.40 %
Heredia	10.19 %	20.26 %	10.51 %	33.22 %
La Guajira	13.92 %	28.16 %	14.59 %	47.65 %
Magdalena	18.93 %	48.68 %	23.29 %	90.59 %
Valverde	14.85 %	32.02 %	14.65 %	55.02 %

Source: Own figure.

Additionally, this becomes apparent by looking at figures 3.23 and 3.24. which show the modelled mean changes in PET by 2050 for the RCP 2.6 scenario and RCP 8.5 scenario, and figures 3.25 and 3.26, which present the same information for the two RCP scenarios in 2070. The following can be highlighted:

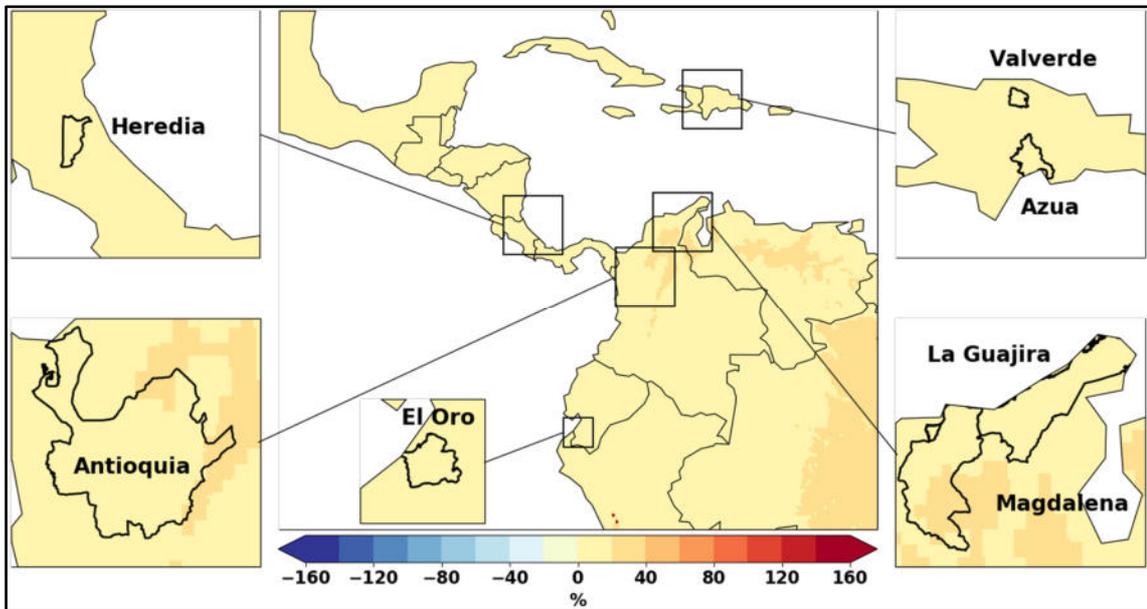
- Figure 3.23 shows the projected changes in PET by 2050 for the RCP 2.6 scenario. Almost for the whole LAC region the changes are lower than 20 percent<sup>21</sup>. Within the seven selected regions the changes range from 10 percent in Heredia to 19 percent in Magdalena.
- Under the RCP 8.5 scenario, the projected PET changes in 2050 are slightly stronger as figure 3.24 displays. The change in Heredia, Costa Rica, is between 0 and 40 percent locally. In the other regions, the projected change is mostly between 20 and 40 percent locally. In most of Magdalena, Colombia, the PET increase, however, is even up to 60 percent. Consequently, the average changes within the regions are roughly twice as high compared to the changes projected for the RCP 2.6 scenario in 2050 (see also figure 3.22), which again shows the strong dependence on temperature changes being more or less similar in ratio. More particularly, changes under this scenario range from 20 percent in Heredia to 50 percent in Magdalena.
- By 2070, changes under the RCP 2.6 scenario are expected to have stayed rather constant in comparison with 2050 (see figure 3.25). Within the seven selected regions, the average projected PET changes only show very small differences bridging the two decades. The change in Magdalena is most notable ranging from 19 percent in 2050 to 23 percent in 2070.
- Under the RCP 8.5 scenario for 2070, finally, the climate models project a strong further increase in annual PET. This is clearly visible in figure 3.26. The strongest changes are found for the western Amazon region with up to 160 percent and the Colombian lowlands south of the Sierra Nevada de Santa Marta, where PET is projected to increase by up to 140 percent. Within the seven regions the range is large. In Heredia, Costa Rica, the projected PET change is still only between 20 and 40 percent locally and 33 percent on average. In the regions of the Dominican Republic as well as of Ecuador the local changes range from 20 to 60 percent with average changes of 55 percent in Valverde, 45 percent in Azua and 44 percent in El Oro. And the Colombian banana producing regions show a local range of 20 percent increase in, for instance, central Antioquia and up to 140 percent increase in southeastern Magdalena. The averages of the projected annual PET increases are 48 percent in La Guajira, 66 percent in Antioquia and more than 90 percent in Magdalena.

All this additional atmospheric water demand has to be compensated by higher precipitation – which is not projected to increase in most of our case study regions in the future as has been discussed earlier – or by irrigation to assure a water supply situation as it currently is.

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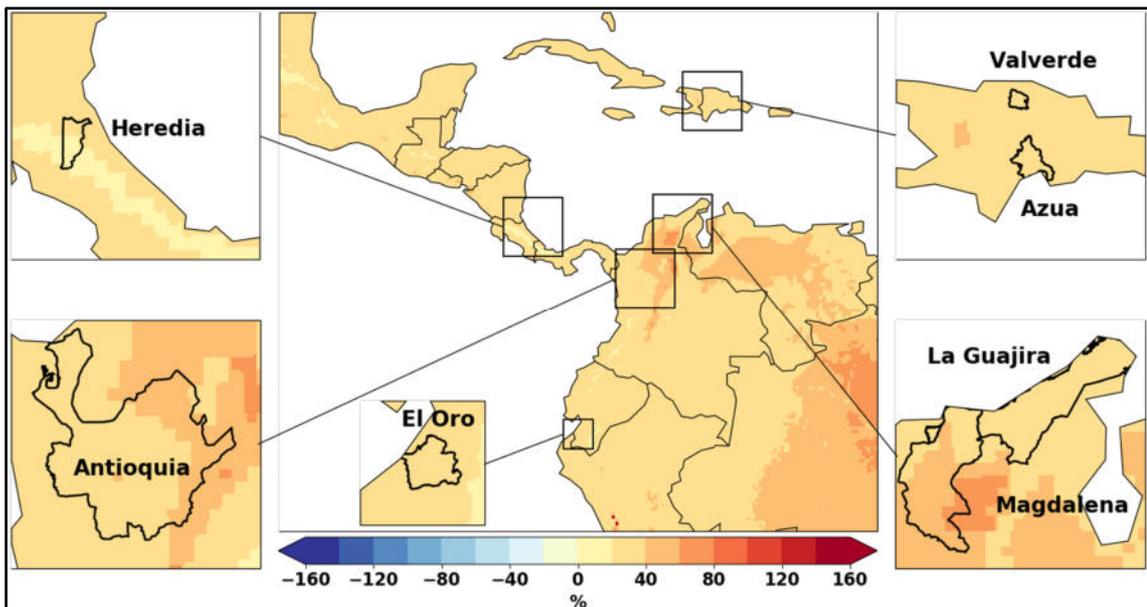
<sup>21</sup> This should already be considered a strong change, but it is the "best case scenario" in comparison with changes under the RCP 8.5 to be discussed hereafter.

**Figure 3.23:** Projected change in annual potential evapotranspiration by 2050 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



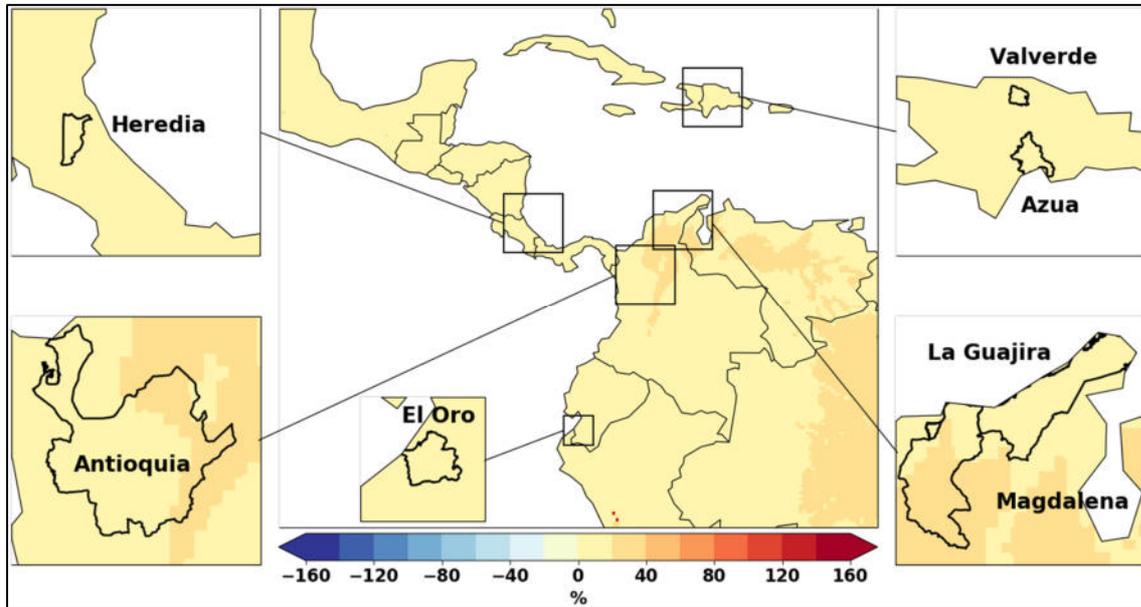
Source: Own figure.

**Figure 3.24:** Projected change in annual potential evapotranspiration by 2050 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



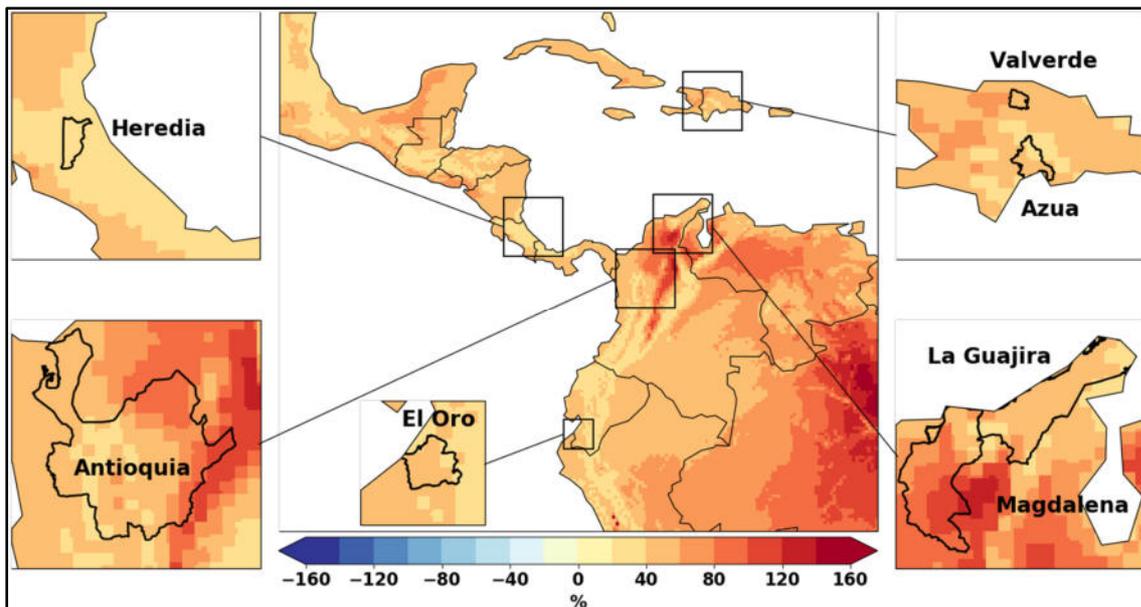
Source: Own figure.

**Figure 3.25:** Projected change in annual potential evapotranspiration by 2070 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

**Figure 3.26:** Projected change in annual potential evapotranspiration by 2070 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

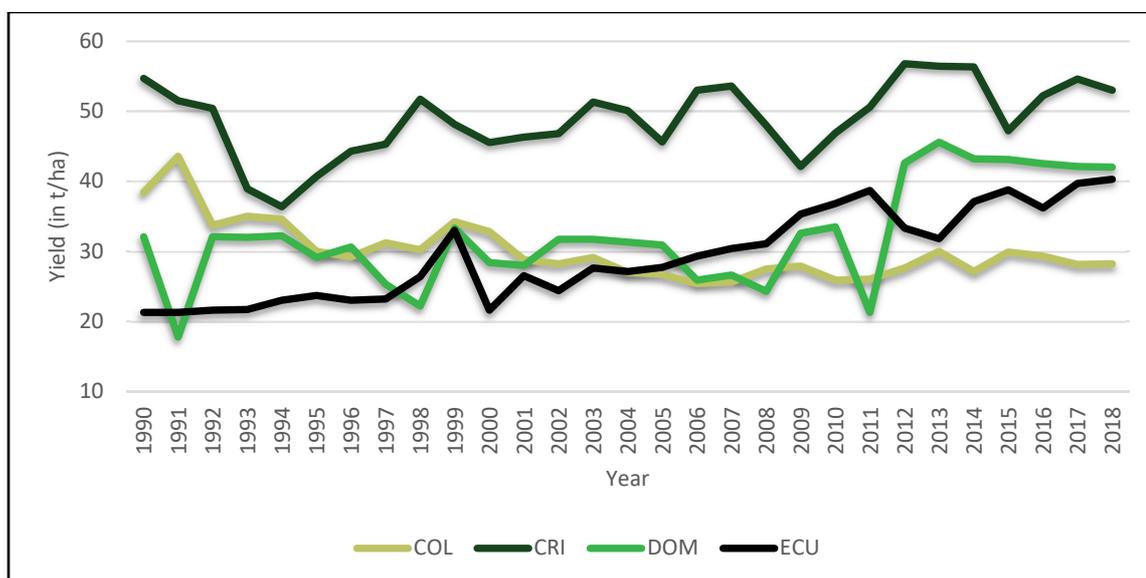


Source: Own figure.

## 4 Ex-post assessment of climate change impacts on banana yields in selected regions of Latin America and the Caribbean

In the following, climate change impacts on banana yields are analyzed ex-post (in chapter 4) and ex-ante (in chapter 5). Before starting with the analysis, it is, however, important to note that banana yields are always a multifactorial outcome. Therefore, changing weather patterns (or climate change) constitute only one component and cannot totally explain yield developments and variability. Since the turn of the millennium, banana yields in LAC have increased by 35 percent, or the equivalent of 1.7 percent per year, on average (see FAO, 2020b). In contrast, with less than 0.01 percent per year, or less than 1.0 percent per decade, the climate change-induced impacts on yields predicted by Varma and Bebber (2019a) for the four LAC countries appear to be relatively small (see figures 2.6, 2.11, 2.16, and 2.21). In fact, the use of new technologies, improved inputs and mechanization, as well as several other factors have been very important drivers of land productivity across the globe leading to considerable yield improvements in agricultural production also in the LAC region (Avila and Evenson, 2010; Fuglie, 2012). The resulting development of banana yields in Colombia, Costa Rica, the Dominican Republic, and Ecuador from 1990 onwards is visualized in figure 4.1.

**Figure 4.1:** Banana yield development in Colombia, Costa Rica, the Dominican Republic, and Ecuador, 1990–2018



Source: Own figure based on FAO (2020b).

It becomes evident from figure 4.1, for instance, that Ecuador has experienced a strong increase of crop-specific land productivity in the past three decades. On average, banana yields in this country have increased by 2.4 percent per annum. This cannot be explained by the observed rather small

temperature and rainfall increases alone (see figures 2.17 and 2.18). A relatively small temperature and rainfall increase was also observed in Colombia (see figures 2.2 and 2.3). Here, however, yields declined by approximately 1.0 percent per year during the same period. Between 1990 and 2018, banana yields in Costa Rica and the Dominican Republic annually increased by 0.6 and 1.5 percent, respectively. Also, the considerable difference in terms of yield levels between Costa Rica and the other three countries cannot simply be explained by different climatic conditions. Consequently, it becomes evident that yield developments cannot be discussed in terms of climate (change) only, and that factors other than climate did apparently have a much larger influence on yields during this period.

Before analyzing the specific climate change impacts on banana yields, it is therefore necessary to have a better understanding of the totality of factors that actually influence banana yields, as well as to gain an understanding of how the impacts of (changing) weather conditions (may) affect banana yields in comparison with other major yield determinants. Consequently, the following sub-chapter 4.1 will more generally discuss such factors before the specific climate change impact is then analyzed in sub-chapter 4.2. In the latter, we will also zoom into the seven selected banana production regions and also into specific banana production areas located within these regions going from the national to the regional and further to the local level because, as was already highlighted in chapter 3, climate change manifests itself in different ways at the various scales and will therefore continue to have different impacts on the selected regions and areas in the future.

## 4.1 Overview on determinants of banana yield and its development

The bulk of banana production in the overall LAC region is of the Cavendish type produced in large plantations for the export market. Taking this as a point of departure and based largely on Gonçalves and Kernaghan (2014), Dita et al. (2013), and Evans et al. (2020a), some basic elements of banana cultivation in the major banana producing regions of LAC will briefly be described in the following:

- From a morphological perspective, bananas are tree-like perennial herbs: After the fruit-bearing stem is harvested and cut down, shoots arising from lateral buds on the rhizome – called suckers – take over and develop into the next fruit-bearing stems. Accordingly, banana production is not seasonal, and the natural cycle of each individual banana plant begins when the sucker that grows alongside the main or mother plant appears at the ground level. After the mother plant dies, the shoot grows to become the next mother plant emitting leaves until flowering, and then the inflorescence develops forming the banana bunch. When the bunch is harvested the mother plant is usually cut down and dies and the next sucker, which always appears next to the mother plant, will replace the dead tree, thereby maintaining the process on a continuous basis. The whole cycle from the appearance of the sucker at the ground level until the harvesting of the bunch takes approximately one year. Each banana tree produces a single bunch that is formed by many banana fruits (or “fingers”) and clustered in several “hands”.

- According to their morphological characteristics, bananas are generally cultivated in tropical and subtropical regions with plenty of water, heat, air humidity and light. As the most important tropical fruits, bananas are grown between approximately 30°N and 30°S of the equator (FAO, 2020c). Commonly, bananas for commercial purposes are cultivated in areas where rainfall is around (and above) 1,200 mm per year and temperature is around 25 to 27°C; soils must be nutrient-rich as well. Under such natural conditions, bananas grow during the whole year, although the growth of the plants is somewhat slower during colder seasons.
- If temperatures become too low, bananas might start to show chilling injuries around day/night temperatures of 17/10°C, while heat damages start to occur at day/night temperatures of 37/30°C (Turner and Lahav, 1983)<sup>22</sup>. In addition to requiring a specific temperature range, bananas prefer not to be exposed to stronger winds. In fact, wind is not tolerated well by banana plants, as their large leaves are quickly damaged reducing the capacity of the plant to make photosynthesis<sup>23</sup>.
- In terms of humidity, bananas prefer values above 60 percent. In fact, the continuous availability of plenty of water is indispensable to assure high yields. In rainfed cropping systems, an average – well distributed – rainfall of more than 2,000 mm per year is desirable. However, the crop will also grow with lower amounts of water and may develop high yields if irrigated (FAO, 2020c). Although bananas need plenty of water, saturated or flooded areas are not well tolerated by this crop, and soils need to be well drained.
- The soil conditions are indeed an important factor. Soil depth, drainage and water holding capacity as well as salinity and humus content will determine the land productivity to a remarkable extent (FAO, 2020c).
- Apart from the natural conditions, it is the specialized management of the crop that will lead to successful banana growth and production. Different methods are used for establishing conventional banana plantations depending on the purpose of the farm. While smallholder farmers often accomplish land preparation by hand with the help of a sickle, commercial plantations often employ mechanized soil tillage to clear existing vegetation from the ground before planting. Herbicides are commonly used in small and large-scale production systems to eliminate and suppress undergrowth. Insecticides for the initial control of pests, especially nematodes, are also commonly used. Depending on the purpose of the farm, the planting material is either taken directly from established banana plantations (i.e. by getting freshly cut suckers from neighboring farmers) or produced from seedlings that are propagated in

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<sup>22</sup> According to FAO (2020c), a minimum temperature for adequate growth of 16°C is required. Below this level, growth is checked and shooting delayed. However, only temperatures below 8°C for longer periods are considered to cause severe damage. The maximum temperature for adequate growth in accordance with FAO (2020c) is about 38°C.

<sup>23</sup> A wind speed of already more than 16 km per hour is considered to cause initial crop losses (FAO, 2020c).

laboratories from tissue cultures. Before planted in the field, the seedlings first need to be transferred to a nursery until they reach a size suitable for transplanting.

- Potential yields also depend on planting distances. Plants in commercial plantations are often spaced at grids of 2.0 x 2.0 meters to 2.0 x 3.0 meters, thus, generating a density ranging from 1,800 to 2,100 plants per hectare<sup>24</sup>.
- In highly land-productive and large-scale commercial plantations, fertilizer is applied regularly during the whole life cycle of the plant, with applications often taking place every two weeks all year round. Especially the demands for nitrogen (N) and potash (K) are very high during the phase of planting as well as while developing the ratoon crop and require short intervals of fertilizer application to later account for high yields (FAO, 2020c). Fertilizer use, thus, often exceeds 400 kg of N and 700 kg of K per year. Organic fertilizer is also often applied. In addition to controlling nematodes (with up to four applications per year), chemical plant protection is also used to combat black leaf streak or Black Sigatoka (with applications ranging from 15 to 60 per year depending on total rainfall and the number of dry months). At the same time, insects and diseases of the bunch are increasingly controlled through biological means or indirectly with protective bags and cultural practices such as deflowering.
- After establishing, banana plantations can remain productive for several decades: In some regions it is even possible to find banana plantations more than 50 years old. However, on commercial banana plantations the plants are commonly renewed after a period of between seven and ten years with the main purpose of controlling the appearance of pests and diseases. In this respect, the very aggressive fusarium wilt disease, more specifically the Tropical Race (TR) 4 strain (García-Bastidas et al., 2014; Lambert, 2019), is considered by many as the biggest threat to global banana production with the potential to even eliminate all banana plantations worldwide (Ploetz, 2006; Evans et al., 2020a)<sup>25</sup>.

If planted, nurtured, and protected that way or by other means, bananas are harvested at full-mature (green) stage<sup>26</sup> and may produce more than 60 tons of fruits per hectare under very good production conditions. It becomes obvious, then: Many factors contribute to ensuring high banana yields. And – as was tried to illustrate in this sub-chapter – weather patterns and climatic conditions are but one of these, while proper crop management and technologies play an essential role.

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<sup>24</sup> Some management options include a 5.0 x 5.0 meters grid allowing to plant 400 plants per hectare.

<sup>25</sup> In addition, the economic impact of the Black Sigatoka disease is significant for producers due to the cost of protection measures, such as regular fungicide applications, that have been found to raise production costs by 25 percent or more (see below, as well as FAO, 2013).

<sup>26</sup> Bunches are usually hung in a shaded and cool place for up to two weeks after the harvest to improve flavor development. Afterwards, bananas undergo different stages of ripening, the fruits going from dark green to yellow with brown freckles. During ripening, different physiological, biochemical, and organoleptic changes lead to a soft and edible ripe fruit. Depending on variety and final use, bananas are shipped to markets at their optimal ripening stage or at full-mature green stage. Postharvest losses are common if the harvested fruit is not stored and transported at optimal temperature conditions.

## 4.2 Analysis of the climate change impact on regional banana yields

As has been shown in chapter 3, climate change is already manifesting itself in the LAC region, but so far, its impacts in terms of absolute changes in the most important climate variables are still relatively moderate. Therefore, the comparably rather broad climate niche suitable for banana growth and production paired with the important effects of factors other than climate on banana yields (such as the managerial and technological factors highlighted in sub-chapter 4.1), allow us to formulate the following working hypothesis to be "tested" hereafter: Climate change certainly – but only partly – influences current banana yields, in addition to other drivers.

Thus, measuring the impacts of climate change on banana yields is obviously a considerable challenge. In fact, very few scientific studies that have attempted to conduct such an analysis have been published so far. Two of these studies are the research conducted by Calberto et al. (2015) and the study by Elbehri et al. (2016) focusing on Ecuador. Both studies use a methodological concept that discusses banana yields as a variable determined by agroecological zones which are characterized by meeting certain ranges of temperature (13–18°C, 18–24°C, 24–35°C, and more than 35°C), precipitation (less than 900 mm, 900–1,500 mm, 1,500–2,500 mm, and more than 2,500 mm) and duration of dry months (less than 3 months and more than 3 months). Hence, banana yields are discretely distributed and cannot be set in relation to continuously changing variables such as temperature and precipitation in terms of a non-interrupted mathematical function. Moreover, yield effects cannot be calculated directly in terms of percent or tons per hectare but more indirectly in terms of the so-called leaf emission rate<sup>27</sup>.

Varma and Bebbler (2019a) also calculate banana yields as a function of climate variables such as temperature and precipitation. In opposite to Calberto et al. (2015) and Elbehri et al. (2016), however, their approach allows for the calculation of a functional relationship between the banana yield on the one hand and two distinct climate variables – namely annual temperature and annual precipitation – on the other hand. More precisely, in this approach banana yields are affected by two yield coefficients which "measure" the distance of an observed annual temperature and precipitation from the optimal values of these two climate variables for banana production.

Accordingly, the yield coefficient for temperature  $R_t$  is derived by the following equation (1):

$$(1) \quad R_t = ((T_{max} - T_{obs}) / (T_{max} - T_{opt})) * ((T_{obs} - T_{min}) / (T_{opt} - T_{min}))^{((T_{opt} - T_{min}) / (T_{max} - T_{opt}))}$$

With  $R_t$  = Yield coefficient for temperature,  
 $T_{max}$  = Maximum temperature for banana growth and production,  
 $T_{obs}$  = Observed annual average temperature,  
 $T_{opt}$  = Optimal temperature for banana growth and production, and  
 $T_{min}$  = Minimum temperature for banana growth and production.

<sup>27</sup> Simply speaking: The higher the leaf emission rate, the more photosynthesis will take place in a banana plant, and subsequently a higher accumulation of carbohydrates in banana fruits will be possible.

And similarly, the yield coefficient for precipitation  $R_p$  is defined in equation (2):

$$(2) \quad R_p = ((P_{max} - P_{obs}) / (P_{max} - P_{opt})) * ((P_{obs} - P_{min}) / (P_{opt} - P_{min}))^{((P_{opt} - P_{min}) / (P_{max} - P_{opt}))}$$

With  $R_p$  = Yield coefficient for precipitation,  
 $T_{max}$  = Maximum precipitation for banana growth and production,  
 $T_{obs}$  = Observed annual precipitation,  
 $T_{opt}$  = Optimal precipitation for banana growth and production, and  
 $T_{min}$  = Minimum precipitation for banana growth and production.

In addition, the conditions in formulas (3) and (4) shall apply:

$$(3) \quad T_{min} \leq T_{opt} \leq T_{max}$$

$$(4) \quad P_{min} \leq P_{opt} \leq P_{max}$$

Following Varma and Bebbler (2019a), the (mathematical) product of the two yield coefficients for temperature  $R_t$  and precipitation  $R_p$  is equal to the quotient of an observable yield in a particular year (numerator) and an achievable yield given perfect climate conditions for banana production for that particular year (denominator) holding all other production conditions constant. Therefore, equation (5) applies:

$$(5) \quad Y_{obs} / Y_{ach} = R_t * R_p$$

With  $Y_{obs}$  = Observable yield at a particular point in time and  
 $Y_{ach}$  = Achievable yield given optimal temperature and precipitation.

Consequently,  $R_t$  and  $R_p$  – as well as the product of both individual coefficients – are without a unit and must be larger than 0.0 and smaller than 1.0 to display realistic yield manifestations<sup>28</sup>. From equation (5) it stringently follows that in a non-static but dynamic environment the product “ $R_t * R_p$ ” must be interpreted as the percentage value of an observed or potentially observable yield for a specific year vs. the climate-optimal yield for that same specific year (holding all other yield determinants constant).

In the following, this product describing the relative partial impact of annual temperature and yearly precipitation on yield is named the “climate-yield coefficient”. For example, a climate-yield coefficient of 0.8 means that given the observed or observable temperature and precipitation at a specific time (year) and location, 80 percent of the achievable yield – under the production settings given at that time – have been or can potentially be reached. Thus, changes in the trend and variation of the product “ $R_t * R_p$ ” over time will be a signal for climate change impacts on banana yields. This is because an impact of other variables subject to change, such as managerial and technological

<sup>28</sup> If  $T_{obs}$  ( $P_{obs}$ ) was equal to  $T_{min}$  ( $P_{min}$ ) or  $T_{max}$  ( $P_{max}$ ), a  $R_t$  ( $R_p$ ) value of 0.0 would result. If  $T_{obs}$  ( $P_{obs}$ ) was equal to  $T_{opt}$  ( $P_{opt}$ ), a  $R_t$  ( $R_p$ ) value of 1.0 would be the outcome. If  $T_{obs}$  ( $P_{obs}$ ) was lower than  $T_{min}$  ( $P_{min}$ ) or larger than  $T_{max}$  ( $P_{max}$ ), negative yields – not observable in reality – would be calculated.

factors, as well as other natural conditions can be excluded and do not cause a bias<sup>29</sup>. In other words: The climate–yield coefficient precisely measures the partial impact of annually changing average temperature and precipitation<sup>30</sup> on yield in relative terms<sup>31</sup>.

In the following we will make use of this sophisticated methodological concept known as a dynamic process-based model<sup>32</sup> to determine the yield impacts of observed climate change (initially being defined as a change in annual temperature and yearly precipitation) in the selected seven regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador, as well as in specific banana production areas within these regions.

As specified above, the observed annual average temperature and observed annual precipitation are needed to calculate a percentage climate–yield coefficient. In addition, the minimum, optimum and maximum temperature and precipitation values describing the suitable climatic ranges for banana production are needed<sup>33</sup>. Observations for temperature and precipitation were already discussed in chapter 3 as well as in the annexes F and G and can, thus, easily be integrated into our dynamic process-based climate–yield model. However, data on the two suitability ranges still have to be determined. In this respect, our literature review provided the values suggested by different authors that are shown in Figure 4.2.

It becomes apparent that the suggested ranges suitable for banana production are not uniform across the different studies and regions, what implies uncertainty for further analyses. In the following, we will use the center values of the displayed intervals. Two aspects shall be highlighted in this respect:

- The values to be used in our calculations are based both on profound statistical analyses<sup>34</sup> as well as on condensed expert wisdom. Due to the overall weak information base, especially

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<sup>29</sup> The coefficient will be calculated for each year. The other – over time but not within a year also changeable – factors are included twice. They are congruently an integral part of  $Y_{ach}$  as well as of  $Y_{obs}$ . Mathematically speaking, both factors would be cut out (see once more equation (5)) and, hence, do not alter the development of the calculable climate yield coefficient over time.

<sup>30</sup> Note: Climate is, of course, much more than only annual average temperature and precipitation. Our analysis of yield impacts due to climate change will appropriately discuss this complexity below.

<sup>31</sup> Therefore, precise yield information is not necessary since the coefficient value directly measures the ratio of an observed or observable yield vs. the achievable yield (see, again equation (5)). Such precise yield data would only be needed if the analysis aimed at providing an absolute yield impact (see below).

<sup>32</sup> Varma and Bebbler (2019a) were not the first authors who have used the concept. In fact, earlier versions of such a process-based climate–yield model were already suggested, established and/or used by, for instance, Archontoulis and Miguez (2015), Thomas et al. (1998), Turner and Lahav (1983), and Yin et al. (1995).

<sup>33</sup> To calculate an absolute yield impact, yield observations are necessary too. Here, we will concentrate on the relative impact of climate and climate change on yields. Findings with respect to absolute yield implications will be discussed further below.

<sup>34</sup> For more information see Varma and Bebbler (2019b).

with regards to precipitation, we have opted to combine both approaches. This will also allow for a more profound stress testing of our analytical results later.

- The specific minimum and maximum values proposed by Varma and Bebbler (2019a) for the LAC region, which at first glance might be considered preferable to use, are, however, too narrow for our sub-regional assessment. This means that the observed temperature and precipitation levels in the seven regions are sometimes beyond the LAC-specific frontiers defined by Varma and Bebbler (2019a) and, therefore, would not allow us to use the mathematical algebra discussed above.

**Figure 4.2:** Recommended ranges of temperature and precipitation suitable for growing and producing bananas

Author	Region	Variable	Minima	Optima	Maxima
Calberto et al. (2015)	Global	Temperature	13°C	27°C	38°C
FAO (2020c)	Global	Temperature	16°C	27°C	38°C
Ikisan (2020)	Global	Temperature	10°C	23°C	40°C
Turner and Lahav (1983)	Global	Temperature	10°C	25°C	37°C
Varma and Bebbler (2019a)	Global	Temperature	10°C	27°C	35°C
Varma and Bebbler (2019a)	LAC	Temperature	20°C	27°C	30°C
Varma and Bebbler (2019a)	Global	Precipitation	0 mm	1,673 mm	7,997 mm
Varma and Bebbler (2019a)	LAC	Precipitation	85 mm	2,646 mm	5,307 mm

Source: Own figure based on Calberto et al. (2015), FAO (2020c), Ikisan (2020), Turner and Lahav (1983), and Varma and Bebbler (2019a).

Accordingly, the minimum, optimum and maximum values used in our calculations hereafter are as follows:

- 15°C, 25°C and 35°C, respectively, for annual average temperature, and
- 43 mm, 2,160 mm and 6,652 mm, respectively, for annual average precipitation.

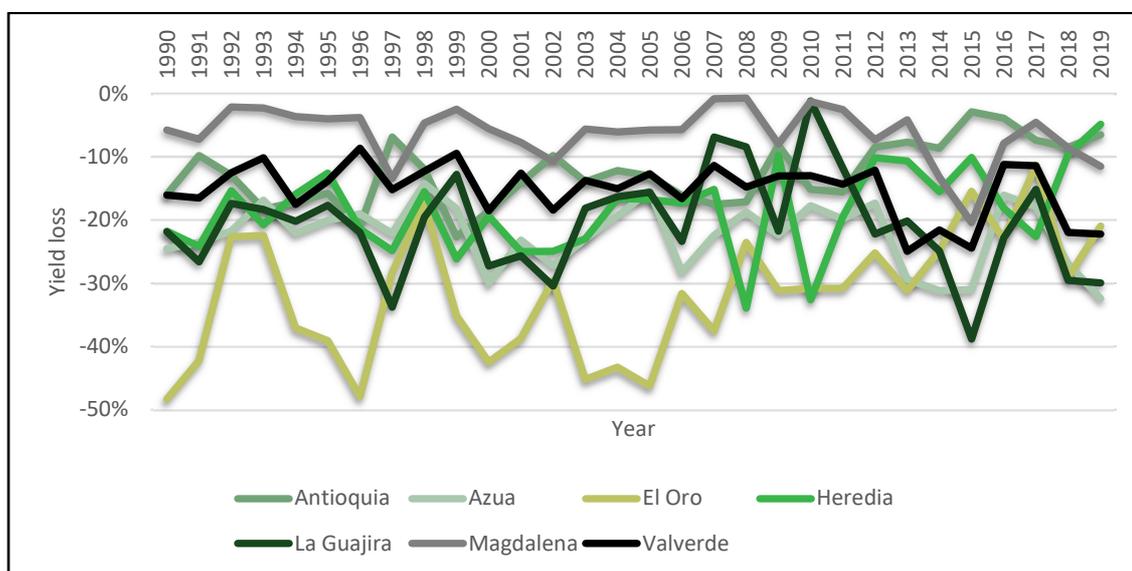
Using the above values results in the outcomes detailed in the following, which consist of two different data sets for annual average temperature and precipitation. In fact, average data hide complexity, and this is also the case for climate data. Consequently, the larger the region under consideration, the more complexity is hidden by the average values used, and the more details or complexity will get lost in the process. While Varma and Bebbler (2019a) looked at Colombia, Costa Rica, the Dominican Republic, and Ecuador at the country level, our aim is therefore to go one step further and look at specific regions and areas within these countries. A stepwise concept is applied hereafter:

- First, we will look at regional data, i.e. we consider Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde as target regions of our analysis. By doing so, we zoom from the national level to the regional level.
- Second, we duplicate the approach by looking into specific banana production areas within Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde. Hence, we also zoom from the regional level to the local level.

The analysis starts with the regional level and the interesting question now is: Is there already a trend observable which affects banana production of the selected regions and is driven by past long-term shifts of annual average temperature and yearly precipitation (i.e. climate change) besides the annual weather variability? And has this trend contributed to a worse (or better) situation for banana production subsequently leading to lower (or higher) yields over the years at the regional level?

To answer this question, the values of the climate–yield coefficient resulting from observed annual average temperatures and yearly precipitation in the single regions between 1990 and 2019 must be analyzed. Accordingly, figure 4.3 shows the relative yield loss per year caused by annually observed temperature and precipitation vs. optimal temperature and precipitation<sup>35</sup>.

**Figure 4.3:** Yield losses based on climate–yield coefficients for selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador, 1990–2019



Source: Own figure and calculations.

<sup>35</sup> Following equation (5), this implies a slight enlargement of the underlying algebra. For proper recalculation, the mathematical term " $-1 * (1 - Y_{obs} / Y_{opt}) = -1 * (1 - R_t * R_p)$ " applies and leads to the results displayed in figure 4.3.

Not much can be seen at first glance, apart from the fact that the annual regional climate defined in terms of average temperature and precipitation is very variable<sup>36</sup> and never optimal<sup>37</sup> leading to partly considerable yield losses per year and region vs. the annually achievable yield. Throughout the years, the annual average climatic conditions seem to have been rather favorable in Magdalena, but also in Antioquia and Heredia, whereas they were for instance rather unfavorable in El Oro and Azua. In any case, a uniform trend is not apparent:

- There are regions (Antioquia in Colombia, Heredia in Costa Rica, and El Oro in Ecuador), where a (small) decrease of annual yield losses (increase of the climate–yield coefficient) can be identified over the past three decades.
- In opposite to that, there are regions (Azua and Valverde in the Dominican Republic as well as La Guajira and Magdalena in Colombia), where a (small) increase of yield losses (decrease of the climate–yield coefficient) over time becomes evident.

The specific findings for the seven regions as a whole pass a stress test: In their study, Varma and Bebbler (2019a) argue that in the past five and a half decades prior to 2016, the climate-related impact on banana yields in the entire region was still very small, but not uniform. Marmai et al. (2016) also state that the underlying recent temperature and precipitation trends have been found to impact crop yields only to a small extent. Nevertheless, our results should be interpreted with caution and considered to be merely an indicative climate change signal. Why? Three additional aspects shall be especially kept in mind in this respect:

- The analyzed period in our study is rather short as 30 years are not a suitable time horizon when it comes to – for instance statistically – analyzing climate change impacts. To take an example, the model runs displayed in chapter 3 (see, again, figures 3.5 and 3.6) cover almost 100 years<sup>38</sup>.
- The first two years in our analysis period (i.e. 1990 and 1991) show rather low values in the case of El Oro. This “bias” acts to push the start value for the trend extremely downwards and, hence, has a tendency to contribute to a rather “positive” trend for that region.
- The approach behind our own calculations uses a temperature optimum of 25°C for banana production, which is still higher than the average observed temperature in some of the regions (see annex F and G, as well as sub-chapter 4.2 below). Thus, basically the obvious trend of past temperature increases tends to move climates in these regions towards the optimum

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<sup>36</sup> This is actually not unusual and similar to e.g. looking at annual temperature curves, where the annual variability is mostly much higher than any observable trend.

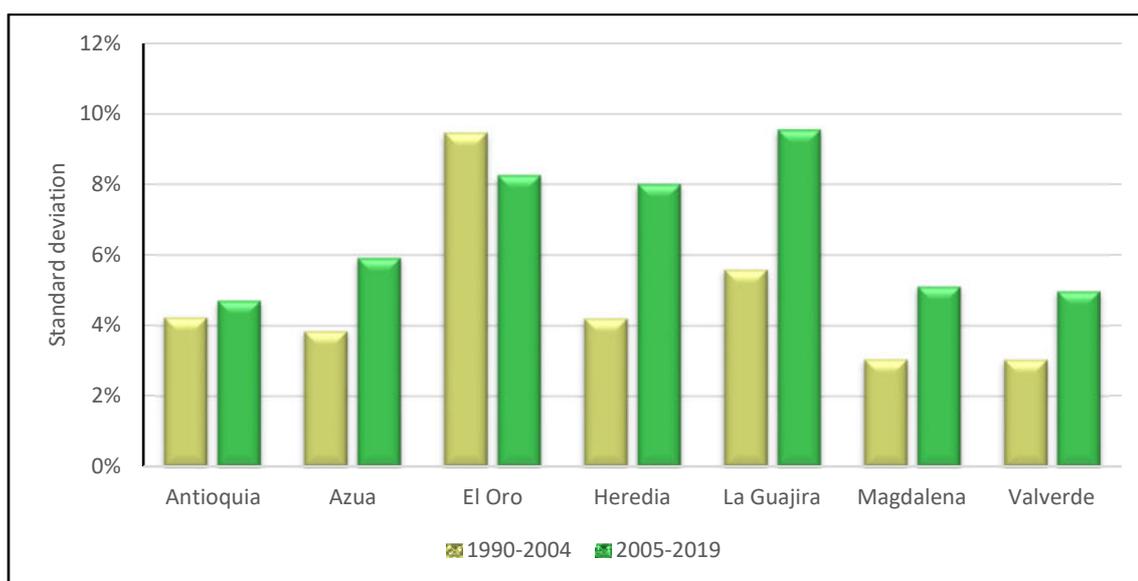
<sup>37</sup> In fact, the figure shows that although some years might have been very close to the optimum, none of the selected regions has ever had an optimal climate for banana production (which would require a climate–yield coefficient of 1.0 or 100 percent). Instead, the climate is always sub-optimal (i.e. the climate–yield coefficient is below 100 percent), and remarkable differences exist between regions.

<sup>38</sup> Marmai et al. (2016) and Varma and Bebbler (2019a) looked at more than 40, and almost 50 years, respectively.

conditions for banana production (positively influencing banana yields). Other regions face temperatures higher than 25°C already today. That means, further temperature increases tend to worsen the yield situation. In any case: the outcome of the analysis is in part also the result of the chosen ecological niche<sup>39</sup> and might look somewhat different if another niche was defined (see, again, figure 4.2).

The trends of the regional climate–yield coefficients for the past 30 years (which as stated above must be interpreted with caution due to the limited time horizon), however, are only one characteristic of yield responses to climate (change) – defined in terms of annual temperature and yearly precipitation. Another important aspect to look at is the annual variation of the climate–yield coefficients from what can be considered the trend of the climate–yield coefficient. In this respect, the picture is more uniform, as shown by figure 4.4, where the standard deviation of the calculated regional climate–yield coefficients for two consecutive 15-year periods are displayed.

**Figure 4.4:** Standard deviation of the climate–yield coefficients for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure and calculations.

All but one region (namely El Oro in Ecuador<sup>40</sup>) experienced an increase in annual fluctuation around the expected mean climate–yield coefficient. This can be considered as an initial indication of higher uncertainty due to already occurring climate change. In terms of the optimal climate for banana

<sup>39</sup> The results would have been (slightly) different if, for instance, the optimum temperature of 23°C suggested by Ikisan (2020) or of 27°C recommended by Calberto et al. (2015) (see also figure 4.2) had been used instead.

<sup>40</sup> The region is characterized by strong outliers especially at the beginning of the time series (see figure 4.3).

production, the number and/or intensity of "good" or close to optimal, but also of "bad" years is increasing. The annual yield is, thus, more often or more strongly influenced by changing annual temperature and yearly precipitation as well, and a first conclusion at this stage of the analysis is therefore that it is not so much the underlying trend of climatic changes (in terms of annual temperature and yearly precipitation) that should be an immediate cause for concern regarding banana production, but rather the uncertainty associated with climate change.

Having discussed the yield impacts at regional scale, we will now zoom into specific banana production areas that are located within the regions. By doing so, we intend to accentuate and substantiate our analysis and account for more complexity by including further details, while at the same time we aim at demonstrating the analytical capacities of the models applied. More specifically, we will discuss the information displayed in figures 4.3 and 4.4, but now for rather small and delimited banana production areas located within Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde. As our analysis is conducted on the finest spatial resolution of the climate datasets, namely a 0.05° grid<sup>41</sup>, we have selected a square of approximately 5 km times 5 km located within the banana production area of each of the seven selected regions to represent the conditions in a smaller sub-region. To identify such areas, appropriate information and detailed maps have been used<sup>42</sup>. In essence, this means we will now look at rather small and exemplary banana production areas, such as Urabá (Antioquia, Colombia) or near/east of Machala (El Oro, Ecuador)<sup>43</sup>.

The calculation of the climate-yield coefficient, resulting from observed temperatures and precipitation in the specific banana production areas within the selected regions between 1990 and 2019 (see annex G), results in figure 4.5. In comparison with figure 4.3, yield losses are lower and stay within a range of up to 40 percent, compared to a range of up to 50 percent when analyzing the larger regions. This is in line with the assumption that within larger regions banana production is concentrated in areas where temperature and precipitation are closer to the optimum<sup>44</sup> leading to higher coefficients. However, our other conclusion regarding the broader regions is also valid for the downscaled results: All but one local areas (i.e. the area in El Oro) experienced an increase in fluctuation around the expected mean climate-yield coefficient (see figure 4.6).

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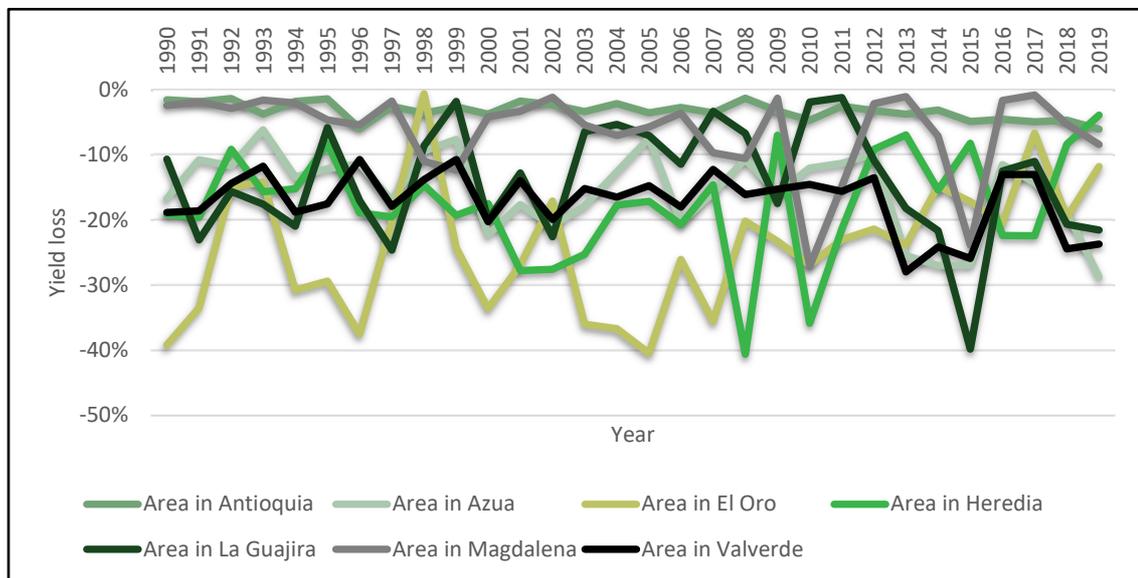
<sup>41</sup> All data was re-gridded to this resolution using first order conservative remapping (see also annex E).

<sup>42</sup> These have been provided by Blanco-Liberos (2009) for Antioquia, Damiani (2002) and FAO (2017b) for Azua, Voorend et al. (2017) for Heredia, Fresh Plaza (2019) for La Guajira, Hudson (2010) for Magdalena, and Varma et al. (2020) for Valverde.

<sup>43</sup> In principle, the following analysis can be carried out for any 0.05° grid of all banana production areas located in the seven regions. Such a detailed analysis is far beyond the scope of this study. However, the exemplary cases provided hereafter are considered to display some interregional complexity.

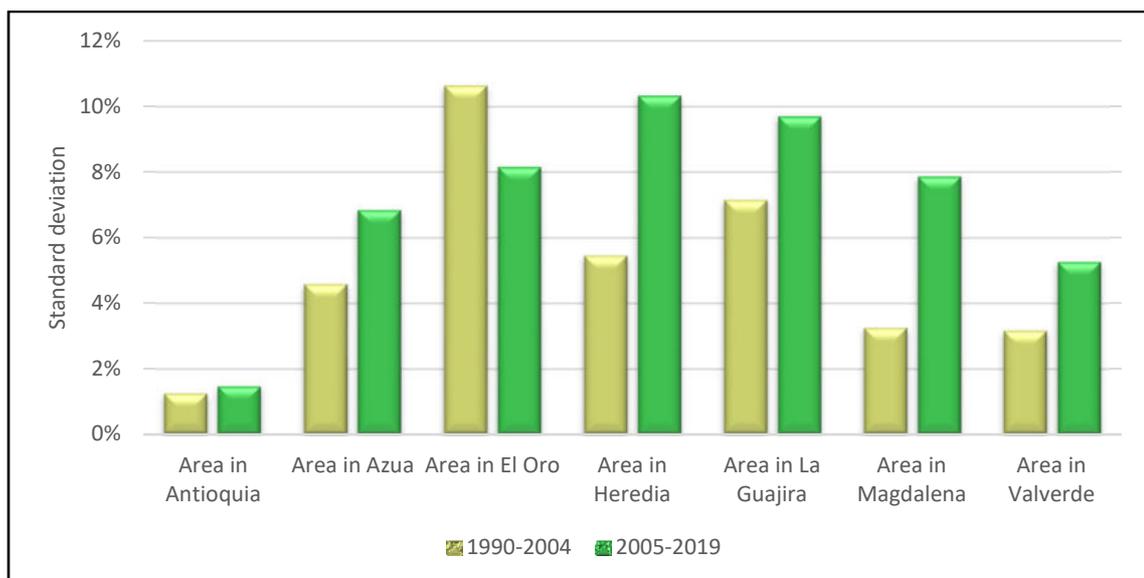
<sup>44</sup> The difference between the regional and downscaled analysis is most prominent in the case of (the area in) El Oro, and this change is mainly driven by altering temperature observations. In accordance to the applied climate observations and models, the specific banana production area near/east of Machala has an annual average temperature of 23.7 °C (instead of 21.0 °C for El Oro as a whole region), and this is obviously much closer to the defined optimum for banana production of 25 °C. In this respect, note that our value of 23.7 °C is in between observations provided by, e.g., The World Bank (2018) with 22.5 °C and Metzler (2020) with 25.5 °C.

**Figure 4.5:** Yield losses based on climate–yield coefficients for specific banana production areas in the selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador, 1990–2019



Source: Own figure and calculations.

**Figure 4.6:** Standard deviation of the climate–yield coefficients for specific banana production areas in the selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure and calculations.

It has already been stated above, that it is not so much the underlying trend of climatic changes (in terms of annual temperature and yearly precipitation) that should be a cause for concern regarding banana production, but rather the uncertainty associated with climate change. This is supported by figure 4.6 and will potentially lead banana growers to experience more frequent very good harvests, but also more frequent very low harvests, or even total losses. In other words:

- While the impacts of the "slower" changes in long-term temperature and precipitation trends on banana yields will probably become more significant at some point in the future,
- the observed increases in climate variability, also induced by climate change and so far not appropriately covered in this study, clearly have the potential to impact banana yields very strongly – today and most probably also in future.

In fact, the analysis of climate change impacts on banana production and yields should not only focus on changes in the mean values of weather variables such as annual temperature and yearly precipitation, but also on the probability, frequency, and severity of extreme events (see, for instance, Moriondo et al., 2011; Lesk et al., 2016; Marmai et al., 2016). The outcome of extreme events also affects the quantity (yields) and, in addition, the quality of agricultural raw materials such as banana bunches. This can partly be seen in annex J, which displays regional yield observations and relates them to the corresponding climate-yield coefficients. In essence, annex J shows that climate in terms of annual average temperature and yearly precipitation obviously has an impact on observable annual yields, but also that these yields must be determined by many more factors.

As we focus on climate change, the necessity to look at additional yield determining factors other than average annual temperature and yearly precipitation can and must certainly be substantiated for the occurrence of extreme weather events which have not been taken into consideration so far. In the case of bananas, this specifically refers – among others – to dry spells, winds, and floods. In fact, Calberto et al. (2018) project that climate change also increases the frequency of weather events with partially extreme deviations from average occurrences. So far, climate models – and hence, also climate-yield models – still have difficulties to project such extreme weather events (see, again, Caberto et al., 2018) and related impacts. This affects our analysis as well.

Nevertheless (and although the roughly 30 years of observations used in this study constitute a very small sample to conduct a meaningful analysis of extreme values), a few examples may illustrate the "hidden danger" posed by (very) short-term weather events and the "impact to be discovered" on banana yields in the selected regions. This is even more important, as this threat does not become evident by only looking at annual average temperature or precipitation data and at the subsequently resulting climate-yield coefficients, visualized for instance in figure 4.3. This will be shown by the following examples:

- The year 2017, for instance, marks a year when the climate-yield coefficient was rather high in the region of Valverde (see figure 4.3). Accordingly, one might argue that banana yields must also have been high that year. This is not true, however: In the same year, Maria, a

tropical hurricane of the highest category 5, heavily affected the north and east of the Dominican Republic bringing strong and damaging winds and leading to huge amounts of rainfall in just a few hours. Around 5,000 hectares of banana plantations were flooded. Many banana plants were bent and broken, and soils were waterlogged causing banana plants to suffer irreparable damage (Reay, 2019). Valverde was among the most heavily affected banana-growing areas (Produce Business UK, 2017). Some growers saw 80 percent of their plantations destroyed. In addition, the wet conditions and damaged plants provided a solid breeding ground for fungal diseases affecting harvests in terms of quality and quantity that year, i.e. in 2018 (Reay, 2019)<sup>45</sup>.

- According to the calculated climate-yield coefficients (see again figure 4.3), yield drops of only a very few percent might have occurred in Magdalena and La Guajira, the two northern Colombian regions, in 2014 compared to the year before. However, in early 2014, a severe drought took place leading to an actual banana yield decrease of up to 30 percent in the two regions (see Fresh Plaza, 2014).
- A serious drought also affected the Azua region around the turn of the millennium. This is partly mirrored in figure 4.3 as climate-yield coefficients at that time were below the climate-yield coefficients in the early and mid-nineties. However, the full extent of the drought-related problems is not visible in Figure 4.3: Not only were banana yields affected (i.e. the production volume), but the drought also had severe impacts on the production quality and, hence, on the marketable banana yield (Damiani, 2002).
- The situation in Magdalena in 2010 was totally different. During this year, Colombia experienced one of the most intense episodes of La Niña in recent history, and a lot of agricultural land was flooded or affected by excess soil humidity. Total losses were often recorded for crops in flooded areas, whereas crops in areas with excess soil humidity had lower yields because of an increase in phytosanitary problems (Romero and Molina, 2015). Again, this extreme weather event is not detectable via figure 4.3.
- Looking at the average annual temperature and precipitation data, the year 2010 marks a rather normal year for banana production in El Oro (as figure 4.3 depicts). However, the banana harvests in this region may have dropped by 40 to 60 percent due to temporarily low temperatures and lack of sun (Lara, 2010). A similar drop in harvests was observable in 2001, when a severe dry spell hit El Oro (Oñate-Valdivieso et al., 2020); however, figure 4.3 soothes this drop out.

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<sup>45</sup> Following Reay (2019), warmer seas have the potential to increase the energy of storms and result in more powerful hurricanes, but changing wind shear (the difference in speed and direction of winds in the upper and lower levels of the atmosphere) may actually reduce their number. It is likely that the kind of extreme rainfall and flooding risks posed by these storms have already become more pronounced and will be even greater in the coming decades.

- In accordance to figure 4.3, the year 2014 marks a rather favorable year for Antioquia when it comes to assess banana yields in terms of observable annual temperature and precipitation. However, a strong windstorm in that particular year caused yield losses to many farmers. 25 percent of banana growers and more than 15 percent of the planting area were negatively affected (Baquero-Melo, 2014).
- Heredia experienced a remarkable banana yield drop (of approximately 20 percent) in 2013 although the climate-yield coefficient for that year was rather favorable (see, again, figure 4.3). In 2013, banana production was affected by mealybugs and scale insects (Cassidy, 2013). A slightly higher temperature and short-term changes in rain patterns favored weather conditions under which these insects could better reproduce. More particularly, the weather conditions shortened the bugs' reproduction cycle by about one-third in that year. Subsequently, the high number of insects considerably weakened the banana plants and lowered regional land productivity.

The cause of these partly devastating weather events is most probably climate change (Calberto et al., 2018) as rising temperatures are considered to increase the frequency and/or severity of several types of weather events already today, particularly leading to more droughts, more intense but less frequent rains, cold snaps, heat waves, and more violent storms<sup>46</sup>. As detailed above, all of these events have the potential to temporarily but seriously impact local and regional banana productivity.

Including these specific findings on climate variables such as short-term droughts (dry spells), floods, winds (storms), and temperature anomalies, which substantiate and accentuate the discussion of the climate-yield coefficient, the entire analysis of climate change impacts on regional banana yields for the past decades can be summarized as follows<sup>47</sup>: Extreme weather events have had devastating impacts on local and regional banana production in the selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador in the past 30 years. Temporarily, temperatures that were too hot and/or too cold, or conditions that were too wet and/or too dry, often led to yield depressions at short notice that went (far) beyond the annual yield impacts resulting from the variability of average annual temperatures and yearly precipitation levels:

- Yield drops/surpluses of plus/minus 20 percent compared to the achievable yield (as suggested by the climate-yield coefficients displayed in figures 4.3 and 4.5) can be related to "normal" annual weather (i.e. average temperature and precipitation) fluctuations.
- In opposite to that, yield depressions of 80 percent and even more (up to a total loss) have been reported as the outcome of local/regional extreme events.

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<sup>46</sup> Having interviewed experts, Calberto et al (2018) summarize that in LAC the weather events that already occur more often are excess rain, drought, short-term critical temperature, wind, delayed start of the rainy season, and extended dry periods during the rainy season.

<sup>47</sup> More of such regional and even local events supporting this conclusion are reported in, for instance, Blake et al. (2018), as well as Toulkeridis et al. (2020).

## 5 Ex-ante estimation of climate change impacts on banana yields in selected regions of Latin America and the Caribbean

So far, it can be stated that in terms of past annual temperature and yearly precipitation developments, climate change has been relatively “kind” to banana producers in the selected LAC regions. This preliminary conclusion is also supported by Vaughan (2019), who additionally argues, however, that in the decades to come, the “friend” may turn to “foe” as temperatures are likely to become so hot that the annual production gains will begin to drop, meaning that banana yields will begin to decline in “some places” regardless of weather extremes. Where these places may be located has been analyzed by Varma and Bebbber (2019a). For the specific countries discussed in our study, the authors conclude the following:

- Varma and Bebbber (2019a) argue that in the future (by 2050) Ecuador might face an advantage compared to other banana production regions, meaning that even if no technology changes occur, the country may still experience yield increases – as these will be driven by climate change.
- In opposite to that, Varma and Bebbber (2019a) consider banana production in Colombia to be at risk, because the country might face decreasing banana yields due to climate change, while the rates of technological change experienced in Colombia in the past have been rather poor, and it is not evident that they will be able to compensate for climate-related losses in the future.
- In between these two extremes, the authors situate Costa Rica and the Dominican Republic. According to Varma and Bebbber (2019a), both countries are considered adaptable, meaning that yield declines due to climate change are projected, but could potentially be mitigated through climate-related technological improvements.

In this study, we aim at providing additional predictions of future climate change impacts on banana production not for the national level (as done by Varma and Bebbber (2019a)) but for the regional and even local level. In terms of banana yields, this means that potential changes in land productivity must be calculated, that can be traced back to predicted regional and local climatic developments. Hence, the question is whether the conclusions of Varma and Bebbber (2019a) can be supported or must be accentuated and/or substantiated. To answer this question, the following ex-ante analysis basically uses the same methodological concept which has been applied for the ex-post assessment in chapter 4, namely the concept of the climate-yield coefficient. The only difference is that instead of observed temperature and precipitation levels, projected temperature and precipitation levels are used for the ex-ante analysis<sup>48</sup>. As for the ex-post analyses, the subsequent (ex-ante) scenario analyses will be run for two data sets:

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<sup>48</sup> In this respect, it needs to be kept in mind that climate projections will always contain a (sometimes considerable) degree of uncertainty. This means that, although the different climate models generally

- First, we consider Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde as target regions of our analysis. By doing so, we zoom from the national level to the regional level.
- Second, we duplicate the approach by looking into specific banana production areas located within Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde. Hence, we also zoom from the regional level to the local level.

In both cases, the scenario analyses will concentrate on a comparison of the outcome in the reference scenario as displayed in chapter 4<sup>49</sup> with the outcomes of the two projected future scenarios, i.e. the RCP 2.6 and the RCP 8.5 at two different points in time, i.e. 2050 and 2070.

Again, the analysis starts with the regional level, and the additional inputs to be entered into the model are summarized in figure 5.1<sup>50</sup>. Looking at the values displayed and relating them to the optimum and range for proper banana production already allows us to identify some tendencies. Let us compare the temperature situation in the reference and RCP 8.5 scenarios for 2070 to get an initial impression:

- In some of the regions, the regional average temperature value for the reference period is lower than 25°C, i.e. below the optimum for banana production as defined above. This applies to Antioquia, Azua, and Heredia, where in some of the future scenarios the 25°C-level will be reached. It also applies to El Oro as a whole, where according to the two scenarios a rather huge increase of the annual average temperatures will most likely happen, although the 25°C-level will not be reached yet by 2070. The temperature rises predicted in these regions therefore mean that the climatic conditions will move closer to the defined optimum for banana production, and this will act to increase yields.
- In opposite to that, there are regions, where based on the regional average the optimum of 25°C has already been reached in the reference scenario, namely La Guajira, Magdalena, and Valverde. Increasing temperatures in these regions, hence, will move the climatic conditions away from the optimum, and this – *ceteris paribus* – will tend to lower banana yields.

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<sup>49</sup> show a high agreement in terms of projected temperature values, uncertainties do remain. This is even more the case for projections of future precipitation quantities as well as for their seasonal distribution. The reference scenario is defined by the observed temperature and precipitation values from 1990 to 2018 (see again sub-chapter 3.1 as well as annexes F and G).

<sup>50</sup> The input data are solely based on sub-chapter 3.2 and in particular on figures 3.7 and 3.12. This means that the average annual temperature and the average yearly precipitation for the seven regions as a whole are used as yield determining climate variables hereafter. This analytical perspective is certainly more detailed and focused than, for instance, the perspective applied by Varma and Bebbler (2019a). However, it is still an average and also rather partial perspective which hides some of the underlying complexity. This complexity can only be discovered by (a) zooming further into the local level (as will be done below), and (b) including the uncertainty of climate change and further climate change indicators such as the frequency and severity of extreme events to the analysis (see also the further discussion below).

**Figure 5.1:** Input data for the calculation of climate change impacts on yields in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Climate variable	Reference scenario	2050 RCP 2.6	2070 RCP 2.6	2050 RCP 8.5	2070 – RCP 8.5
<b>Antioquia</b>					
Temperature (in °C)	22.48	23.47	23.61	24.46	25.68
Precipitation (in mm)	3,126	3,063	3,032	2,919	2,749
<b>Azua</b>					
Temperature (in °C)	22.71	23.58	23.61	24.45	25.53
Precipitation (in mm)	876	894	872	805	712
<b>El Oro</b>					
Temperature (in °C)	20.96	21.90	22.00	22.71	23.77
Precipitation (in mm)	944	937	938	936	971
<b>Heredia</b>					
Temperature (in °C)	22.77	23.55	23.58	24.20	25.03
Precipitation (in mm)	3,638	3,787	3,695	3,703	3,817
<b>La Guajira</b>					
Temperature (in °C)	25.96	26.84	26.89	27.56	28.51
Precipitation (in mm)	863	910	829	812	701
<b>Magdalena</b>					
Temperature (in °C)	25.98	26.95	27.14	27.98	29.28
Precipitation (in mm)	1,517	1,531	1,447	1,382	1,245
<b>Valverde</b>					
Temperature (in °C)	25.45	26.42	26.42	27.29	28.40
Precipitation (in mm)	968	923	919	854	749

Source: Own figure.

The projections with respect to regional average precipitation changes are less straightforward. Considering a defined optimum of 2,160 mm rainfall (see above), the following can be noted (again initially comparing the reference scenario and the RCP 8.5 scenario for 2070):

- Two regions, namely Antioquia and Heredia, receive on average more rain than necessary for banana production. While the decreasing precipitation in Antioquia will therefore move climatic conditions closer to the optimum and will, thus, act to increase banana yields, the further increasing precipitation levels in Heredia will move climatic conditions even more away from the optimum, acting to decrease yields.
- The other regions are confronted with less rain than needed for optimal banana production in the reference scenario. Consequently, higher (or lower) precipitation in the future will tend to increase (or decrease) regional banana yields.

Using the data for temperature and precipitation as displayed in figure 5.1 for the reference scenario (the average of the years 1990 to 2018), the following climate–yield coefficients can be calculated:

- It is 0.88 for Antioquia. This means, the average climate has caused a banana yield which is 12 percent below the optimal yield using given production conditions.
- For Azua it is 0.79, what compares to an average yield drop vs. the optimal yield of 21 percent.
- In El Oro it is 0.71. Consequently, the average climate acted to lower regional yields by 29 percent compared to the achievable yield under an optimal climate and given other technologies and production management.
- Heredia faces better climate conditions. Here the resulting climate–yield coefficient is 0.82, what allows to state that climate since 1990 only has acted to lower yields by 18 percent vs. the optimal level.
- Looking at La Guajira, the coefficient is also 0.82, and the yield difference to the optimal (achievable) yield is 18 percent too.
- The climate was most favorable in Magdalena with a climate–yield coefficient of 0.95. This is close to the optimum since a drop of only 5 percent from the optimal yield occurred.
- Finally, Valverde has an average climate–yield coefficient of 0.86. Hence, the percentage yield drop is around 14 percent.

Combining the temperature and precipitation changes per scenario as displayed in figure 5.1 now allows to calculate potential climate–yield coefficients for 2070 and 2050, as well as the two RCP scenarios. The relative change of these coefficients subsequently shows the potential yield impact of longer lasting climate change (defined as the change in annual average temperature and yearly precipitation). The results of this calculation approach can be found in figure 5.2, which shows the banana yield change in 2050 and 2070 for the two RCP scenarios compared to the average yield of the years from 1990 until 2018.

**Figure 5.2:** Climate change impacts on yields in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador under various scenarios compared to 1990–2018

2050 RCP 2.6	2070 RCP 2.6	2050 RCP 8.5	2070 – RCP 8.5
Antioquia			
5.1 %	6.0 %	9.1 %	10.7 %
Azua			
4.1 %	3.3 %	2.1 %	-2.4 %
El Oro			
7.8 %	8.5 %	12.9 %	18.8 %
Heredia			
-0.2 %	1.9 %	3.2 %	1.3 %
La Guajira			
-0.7 %	-4.0 %	-7.7 %	-18.0 %
Magdalena			
-2.7 %	-4.5 %	-9.7 %	-21.1 %
Valverde			
-3.4 %	-3.5 %	-9.0 %	-19.0 %

Source: Own figure.

As can be seen, potential yield developments due to climate change (as defined above) are not uniform across the seven regions<sup>51</sup>:

- Regardless of the chosen scenario, climate change may apparently create a benefit in terms of yield for banana producers in Antioquia in Colombia and El Oro in Ecuador. In both regions the current regional average of annual temperature is still well below the defined optimum for banana production of 25°C (see figure 5.1). That means, the inherent temperature increase due to climate change is favorable. And precipitation changes are so small (as in the case of

<sup>51</sup> In this respect, it shall be repeated that this was already an outcome of the ex-post analysis provided in chapter 4.1. There were regions (Antioquia in Colombia, Heredia in Costa Rica, and El Oro in Ecuador), where a (small) increase of the climate-yield coefficient within the past three decades could be identified. In opposite to that, there were regions (Azua in the Dominican Republic, La Guajira and Magdalena in Colombia, as well as Valverde in the Dominican Republic), where a (small) decrease of the indicator over time became evident when using regional averages for annual temperature and yearly precipitation as explanatory variables of regional climate change.

El Oro) or even "positive" (as they move towards the optimum in the case of Antioquia) (see again figure 5.1) that the temperature-related trend is supported or at least not counteracted.

- In opposite to that, climate change will most probably be (very) unfavorable (in terms of land productivity) for banana producers in La Guajira and Magdalena, both in Colombia, as well as in Valverde in the Dominican Republic. These three regions currently face regional averages of annual temperature around the optimum. Further temperature increase (see again figure 5.1) tends to lower yields as the temperature moves away from the most comfortable situation. The trend will be supported by precipitation changes: In all three regions current precipitation is below the optimum for banana production and frequently projected to further decrease (see, once more, figure 5.1).
- Azua in the Dominican Republic and Heredia in Costa Rica are somewhere in between. On average, both regions are still below the temperature optimum for banana production and face increasing temperatures (as figure 5.1 shows). This tends to increase yields. However, both regions will most likely also see a worsening of the precipitation situation. In accordance with figure 5.1, annual rainfall might increase in Heredia, whereas the opposite should be considered a potential outcome of climate change in Azua. In any case, precipitation tends to move away from the optimal climate situation. Consequently, both trends act to further limit regional banana yields.

Again, we will now zoom into specific banana production areas within the selected broader regions. More specifically, we will repeat the analysis and information displayed in figures 5.1 and 5.2 for the specific banana production areas (i.e. the 0.05° grids already used in sub-chapter 4.2) located within Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde. In figure 5.3, the temperature and precipitation values for the reference scenario (which are the result of the downscaled analysis in the previous sub-chapter) are displayed, as well as the change rates of average annual temperature and yearly precipitation in accordance with annex I. The following shall be highlighted in comparison with the analysis of the broader regions and the reference scenario, i.e. the average climate situation in 1990–2018 (see also figure 5.1):

- In the specific banana production area of Urabá in Antioquia, temperatures are higher (now above the optimum) and precipitation is lower (closer to the optimum) than on average in the entire region.
- The climate of the banana producing area in Azua is also warmer and, in addition, wetter than the average climate of this region.
- Similar to the case of Urabá in Antioquia, the climate conditions near/east of Machala in El Oro also show a (considerably) higher temperature and (slightly) lower precipitation levels than the region on average.

- The specific banana production areas of La Guajira and especially of Magdalena also show higher precipitation levels, while temperatures do not differ too much from the regional average.
- The climate of the banana producing area in Valverde does not differ too much from the average climate of this rather small region of the Dominican Republic.

**Figure 5.3:** Input data for the calculation of climate change impacts on yields for specific banana production areas in selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Climate variable	Reference scenario	2050 RCP 2.6	2070 RCP 2.6	2050 RCP 8.5	2070 – RCP 8.5
<b>Area in Antioquia</b>					
Temperature (in °C)	26.30	27.12	27.22	27.89	28.87
Precipitation (in mm)	2,536	2,639	2,590	2,541	2,367
<b>Area in Azua</b>					
Temperature (in °C)	26.17	26.94	26.96	27.66	29.00
Precipitation (in mm)	1,017	1,068	1,015	913	794
<b>Area in El Oro</b>					
Temperature (in °C)	23.72	24.56	24.62	25.22	26.11
Precipitation (in mm)	780	763	803	802	861
<b>Area in Heredia</b>					
Temperature (in °C)	24.31	25.07	25.09	25.68	26.47
Precipitation (in mm)	3,804	3,996	3,946	3,983	4,143
<b>Area in La Guajira</b>					
Temperature (in °C)	25.99	26.83	26.94	27.58	28.58
Precipitation (in mm)	1,113	1,169	1,073	1,109	1,234
<b>Area in Magdalena</b>					
Temperature (in °C)	23.84	24.75	24.87	25.65	26.82
Precipitation (in mm)	2,547	2,576	2,573	2,362	2,118
<b>Area in Valverde</b>					
Temperature (in °C)	25.12	26.09	26.09	26.96	28.05
Precipitation (in mm)	903	861	854	796	698

Source: Own figure.

Although differences of "just a few" degrees Celsius and/or mm resulting from a comparison of local vs. regional temperature and precipitation data might be considered negligible at first sight, they can be substantial. This becomes clear when looking at figure 5.4, which shows the yield changes in the selected local banana production areas of Colombia, Costa Rica, the Dominican Republic, and Ecuador in 2050 and 2070 for the two RCP scenarios compared to the average yields of 1990 to 2018.

**Figure 5.4:** Climate change impacts on yields for specific banana production areas in the selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador under various scenarios compared to 1990–2018

2050 RCP 2.6	2070 RCP 2.6	2050 RCP 8.5	2070 – RCP 8.5
Area in Antioquia			
-3.5 %	-3.6 %	-6.8 %	-12.9 %
Area in Azua			
-0.9 %	-2.5 %	-9.0 %	-21.6 %
Area in El Oro			
0.6 %	2.6 %	2.7 %	4.0 %
Area in Heredia			
-4.1 %	-2.9 %	-4.2 %	-9.8 %
Area in La Guajira			
-1.0 %	-3.9 %	-5.8 %	-9.4 %
Area in Magdalena			
1.1 %	1.2 %	1.7 %	-0.9 %
Area in Valverde			
-2.8 %	-3.1 %	-8.0 %	-17.4 %

Source: Own figure.

By zooming from the regional level to the local level, we can substantiate the findings derived from our analysis so far. More particularly, the following should be considered a remarkable accentuation:

- In the case of Antioquia, zooming into the specific banana production area of Urabá reveals that this area is facing a temperature above 25°C already in the reference scenario, and that it will therefore most probably be confronted with future yield decreases – instead of increases – in any of the chosen scenarios.

- In the specific banana production area of Azua, all the scenarios show remarkable differences compared to the use of regional average data. The rise of temperatures above the optimal level combined with precipitation levels that are still too low act to decrease yield in any scenario. The yield impact is substantial in the case of RCP 8.5 in 2070.
- Our prior conclusion that banana production in the broader region of El Oro might benefit from climate change can no longer be supported when looking at the specific local level. The local temperature near/east of Machala is already close to 25°C in the reference scenario, and the future temperature increase will therefore partially lead to temperatures higher than optimal. In combination with precipitation levels that are still very low, this results in an almost negligible yield effect to be expected from climate change.
- Temperatures higher than optimal are also expected in the local banana production area in Heredia. In combination with increasing precipitation levels that are already too high for optimal banana growth, climate change will lead to slightly decreasing yields when switching from the regional to the local perspective. This is again different from the slight yield increases projected on average for the region as a whole.
- In contrast, the findings do not differ too much when comparing the local and regional level in the case of La Guajira. For the local production area, the current temperature level remains almost unchanged, while a slightly higher precipitation level can be noted in comparison with the regional average. Future changes in temperature and precipitation will still result in predicted yield decreases of now between 1 and almost 10 percent and, thus, be partially lower than for the region on average.
- In Magdalena, the selected banana production area receives more precipitation than the regional average. While local precipitation and temperature levels are now slightly closer to the defined optimum, this will not considerably alter the local yield situation.
- Finally, in the banana production area in Valverde the situation basically does not change when compared to the regional average, since the local current climate and its future changes remain very similar to the situation and predictions for the regional level.

From the above, it becomes evident that the analysis at the local level is able to reveal more (and sometimes different) information than the discussion of the regional perspective alone, and that it can therefore substantiate our analysis. This also becomes clear by looking at figure 5.5.

Using the only available source and wording which applied a similar approach as we did, i.e. Varma and Bebbler (2019a), allows to evaluate the "affectedness" of a region's and/or area's banana production facing climate change at different geographic levels<sup>52</sup>. While Varma and Bebbler (2019a)

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<sup>52</sup> Concerning own calculations, a region or an area is considered to be "at risk", if the climate change related yield impact is -5.0 percent or lower. A region or an area is considered to be "adaptable" if the

assess Colombia as "at risk", our analysis of the regional and local level allows for a finer differentiation: In both cases – i.e. when looking at the regional and local levels – one of the three Colombian regions/local areas is not considered to be at risk. In the case of the chosen Costa Rican region and area, we come to the same conclusion as Varma and Bebber (2019a) did for the country as a whole. A similar conclusion cannot be drawn for Azua and Valverde. For both specific banana production areas we arrive at a conclusion worse than "adaptable" as proposed by Varma and Bebber (2019a). In addition, we must conclude that El Oro, or more precisely: the banana production area near/east of Machala, is not facing an "advantage" as the results from Varma and Bebber (2019a) would suggest for Ecuador, but should only be considered as "adaptable".

**Figure 5.5:** Risk assessment for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador using the RCP 8.5 scenario in 2050

Assessment of Varma and Bebber (2019a)		Own assessment for the regional level		Own assessment for the local level in ...	
Colombia	At risk	Antioquia	Advantage	... Antioquia	At risk
		La Guajira	At risk	... La Guajira	At risk
		Magdalena	At risk	... Magdalena	Adaptable
Costa Rica	Adaptable	Heredia	Adaptable	... Heredia	Adaptable
The Dominican Republic	Adaptable	Azua	Adaptable	... Azua	At risk
		Valverde	At risk	... Valverde	At risk
Ecuador	Advantage	El Oro	Advantage	... El Oro	Adaptable

Source: Own figure.

From the above it can be concluded that our analysis is robust and leads to differentiated outcomes if local and uncertainty aspects are added. In fact, the more local the focus of the analysis is, the more the aspect of uncertainty must be considered since global climate models, such as those used here and in many other studies (see, for instance, Armenta Porrás et al., 2016) tend to become blurred while zooming into very particular loci. With respect to uncertainty, the following additional question arises: What about the predicted regional susceptibility to more frequent and/or severe weather events?

To find an answer, the state of the art in research analyzing the future temporal and spatial variability of climate change-induced extremes in the LAC region must be discussed following the excursus on climate model uncertainties below<sup>53</sup>:

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impact is between -5.0 and +5.0 percent, and a region or an area is assessed to face an "advantage" if a yield impact of +5.0 percent is predicted.

<sup>53</sup> Note: Marmai et al. (2016) argue that looking at such aspects is still a very "young" science object.

*Excursus: Considering climate model uncertainties while analyzing banana yield impacts*

The case of El Oro shall be taken as an example to discuss the outcomes of different climate models and our subsequent analysis aiming at calculating the yield impacts of climate change. Numerous peer-reviewed and widely used climate models exist today, and each of these models has its advantages and disadvantages. Consequently, selecting an appropriate climate model for a specific scientific analysis is not an easy task. In this regard, one can select one of the following two categories:

- a climate model which best reproduces past weather data or
- a model which best integrates and covers atmospheric and climatological processes.

The first approach neglects that a good reproduction of past weather data does not necessarily mean that future changes will be captured just as well, because certain relevant processes, which may play an important role in the future, might not be considered in this climate model. The second approach requires an extensive evaluation of various climate phenomena relevant for the region(s) of interest. Our selection of the CORDEX CORE ensemble (see annex E) leans towards the second approach, as higher spatial resolution of climate models means that more small-scale processes are integrated and resolved in the models. More particularly, in our assessment we use the latest generation of RCM simulations from the CORDEX CORE initiative, which have been developed to contribute to the most recent IPCC 6<sup>th</sup> Assessment Report for regional analyses, as high-resolution RCM simulations cover regional heterogeneity better than for instance GCM simulations (Solman, 2013; Solman and Blazquez, 2019).

Particularly in regions with a diverse topography these RCMs cover extremes as well as climate patterns influenced by the topography better than GCMs. In fact, RCMs dynamically downscale GCMs, in our case to a spatial resolution of 22 km. In comparison with statistical downscaling methods, RCMs can, thus, resolve climatologically relevant factors and processes on a higher spatial resolution, which could only be considered by GCMs to a limited amount. This is also the case if the data points (weather stations), which are used for the statistical downscaling, are not equally distributed in a region as this is often the case in Latin and South America (Ambrizzi et al, 2018; Armenta Porrás et al., 2016; Hidalgo et al., 2017; Imbach et al., 2018).

However, it is important to mention that both, GCMs and RCMs, have a high degree of uncertainty as both types of models often do not agree in their results, neither in the trend nor in the projected changes. Thus, an ensemble of climate models (both from RCMs and GCMs) is useful to show the full picture of uncertainty related to the proper selection of climate models for further analyses. Accordingly, we will hereafter provide a dual comparison for the banana production area in El Oro and related yield impacts exemplified for RCP 8.5 and 2050.

- First, we will compare our RCM approach with the GCM concept applied in Armenta Porrás et al. (2016) and, in addition, with the most recent data officially used by the Ecuadorian Ministry of Agriculture, provided by Metzler (2020).

- Second, we will analyze the uncertainty range implied in our climate model approach by also looking at minimum and maximum changes of modelled temperature and precipitation.

A comparison of our approach with the approaches used by Armenta Porras (2016) and Metzler (2020), respectively reveals the following differences applicable to the banana production area within the region of El Oro:

- We use average observations of 23.72°C and 780 mm to describe the reference scenario for 1990–2018. Armenta Porras et al. (2016) refer to 24.1–26.0°C (or 25.0°C as a mean) and 600–900 mm (or 750 mm as a mean) but use the years from 1981 to 2005 as the reference time horizon. Metzler (2020) refers to 25–26°C (or 25.5°C as a mean) and 1,024 mm for 1985–2009.
- For the chosen scenario and time horizon (RCP 8.5 and 2050) we arrive at the conclusion that temperature will increase by 1.5°C and precipitation by 2.9 percent, while Armenta Porras et al. (2016) referring to a median year of 2055 conclude that temperature will increase by 1.85°C and precipitation by 10.9 percent. In addition, Metzler (2020) argues that temperature will increase until 2040 by 0.5–1.0°C (or 0.75°C as a mean) and precipitation by 0–5 percent (or 2.5 percent as a mean).

As can be seen, both observations and predictions are different for the three approaches. Hence, it makes sense to also calculate and compare the potential yield impacts for the different sources. The result is shown in figure E.1.

**Figure E.1:** Future climate change impacts on yields for the specific banana production area in El Oro, Ecuador, comparing different climate model approaches

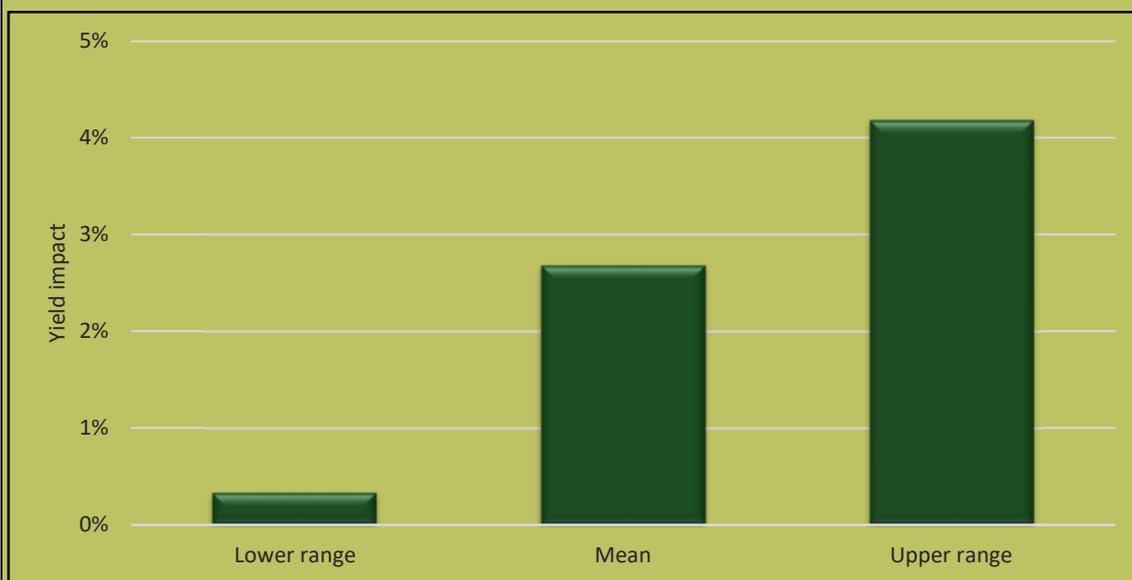


Source: Own figure and calculations.

*In this figure, we additionally included the yield impact obtained when using data from The World Bank (2018) that combines all major climate models. Accordingly, figure E.1 shows that our calculated yield impact for 2050 in comparison with 1990–2018 is 2.7 percent (see also figure 5.4). This is higher than the yield impact calculable with data from Armenta Porras et al. (2016), which is 0.3 percent and refers to 2055 in comparison with 1981–2005. Our yield impact is also higher than the yield impact calculated with the information provided by Metzler (2020), which results in a yield impact of –0.6 percent. However, our yield impact is lower than the calculated yield effect of 5.6 percent that can be obtained when using the model ensemble from The World Bank (2018) comparing 2050 with 1991–2016. Consequently, our calculation is well within the range of other models' mean runs.*

*In fact, at this point our calculation of the yield impact in 2050 compared to 1990–2018 is still only based on a single mean value for predicted temperature and on a mean value for projected precipitation changes. However, uncertainty is also included in our models. Taking this uncertainty into account, the temperature in the specific banana production area of El Oro may increase between 1.21 and 1.89°C in the chosen RCP 8.5 scenario by 2050, and precipitation might change between –2.54 and 7.04 percent. Applying these lower and upper range values therefore leads to a further differentiation of our results, as shown in figure E.2. This allows us to state that this effect might range between 0.3 and 4.2 percent, while a mean climate change yield impact of 2.7 percent is calculated for 2050 and the RCP 8.5 scenario. In any case, our assessment of the specific banana production area within El Oro being "adaptable" remains unchanged.*

**Figure E.2:** *Climate change impacts on yields for the specific banana production area in El Oro, Ecuador, for mean as well as lower and upper range model data*



Source: Own figure.

- In this respect and more generally, Calberto et al. (2018) stress that for the entire region a continued increase of extreme events, such as droughts, rainfalls, cold snaps and/or heat waves<sup>54</sup> and stormy winds<sup>55</sup> should be predicted for the future.
- An increasing frequency and magnitude of adverse weather events in the entire region should, in fact, be a considerable cause for concern (FAO, 2020c).
- This is also the outcome of an analysis provided by Shannon and Motha (2015). The authors stress that the frequency and intensity of extreme events, in particular droughts, floods, heat waves, and storms, will increase with climate change in the LAC region.
- Using a statistical approach, Marmai et al. (2016) also demonstrate that it is very likely that production regions such as Colombia and Ecuador already have severe losses due to extreme weather events and that this likelihood may further increase.
- According to Campozano et al. (2020), El Oro as part of the Coast Region of Ecuador will face droughts as extraordinary events, which may be moderate, severe, or extreme. In comparison with other Ecuadorian regions, the Coast Region shows a higher probability for especially moderate droughts<sup>56</sup>. In the future, this situation might not change significantly. However, the probability of extreme droughts in the El Oro region is expected to increase by a few percentage points, especially when considering a future development along the RCP 8.5.
- Following Birkel (2005), Heredia belongs to the Atlantic Vertient, where drought behavior tends towards having a lower impact. More particularly, however, Heredia is part of the Northern Zone of the Atlantic Vertient, and apparently, the drought severity for that region has already increased. Hence, a more clear and distinct statement on the changing level of frequency and severity of drought events in this Costa Rican region cannot be made.

Although the particular information background is unfortunately still weak, it already becomes evident that also for the future short-term considerations (extreme events and subsequent potentially devastating yield impacts) must be distinguished from mid to long-term considerations (i.e. fluctuating yield impacts around the trend) when it comes to assessing the predictable impact of climate change on banana yields in the study region. However, the poor data availability unfortunately does not allow to meaningfully calculate the additional "likely" impact, and our quantifying analysis of banana yield impacts stops with what has been visualized in figures 5.2 and 5.4. It should be considered a best-case scenario since extreme events always tend to lower yields.

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<sup>54</sup> High temperatures are considered more problematic than low temperatures (Calberto et al. 2018).

<sup>55</sup> In accordance with Calberto et al. (2018), very strong winds for short periods should be considered as being more problematic than strong persistent winds.

<sup>56</sup> In opposite to that, Oñate-Valdivieso et al. (2020) do not detect a remarkable increase.

## 6 Analyses of other climate change impacts

Analyzing effects of climate change in terms of yield constitutes an important, but only one aspect of a comprehensive and holistic assessment. Other variables may also be affected and require further analysis. In sub-chapter 4.1, various other natural, managerial, and technological factors have been mentioned. Not all of them can properly be reflected hereafter due to the defined scope and workload of the study. Nevertheless, a few but important variables also subject to (climate) change shall be discussed in the following:

- Banana production is the product of banana yield and the area planted with banana. Hence, the suitability of areas for banana production is another important issue which needs to be discussed. This rather direct impact of climate change will be analyzed in the following sub-chapter 6.1.
- Climate variables influence yield not only directly but also indirectly. An important indirect yield impact in this respect is that climate change alters the frequency and severity of pests and diseases. For the cases of Black Sigatoka and TR4, this will be discussed in more detail in sub-chapter 6.2.
- Both, the suitability of production areas as well as the frequency and severity of pests and diseases, together with the above discussed direct climate change related yield impacts will alter future banana production in the selected regions. The aggregated "net" effect will be assessed in sub-chapter 6.3.
- Productivity and/or production changes will alter economic variables such as the market price and farm income or profitability. Based on available case studies, these effects will be analyzed in sub-chapter 6.4.
- Not only primary production and secondary economic impacts are important when it comes to analyze climate change impacts from a broader societal perspective. Moreover, environmental indicators are worth being discussed. Hence, sub-chapter 6.5 will deal with impacts on biodiversity. In addition, it will look at GHG mitigation options that can be related to banana production.

### 6.1 Direct production impacts due to a change in area suitability

Climate change can affect banana production in various different ways. Apart from direct impacts on yields, shifts in the suitability of production areas are also essential to be taken into consideration (Machovina and Feeley, 2013). In fact, one adaptation option to climate change is to move crop production systems away from areas that have become unsuitable for a particular production system towards areas in which climatic conditions are becoming more suitable (see, e.g., Iglesias et al.,

2011). Only a few studies conducted so far have tried to assess these movements of banana production, and these studies will be described in the following:

- Calberto et al. (2015) used a scenario technique to determine the suitability of areas for banana production in various countries around the globe. All regions in the focus of this study were located in the tropics (which can be further divided into specific zones), and the authors find that this broader region will face an increase of suitable area for banana production in 2050 (2070) of 15 percent (21 percent), as increasing temperatures are considered highly favorable for banana production. However, the authors also map additional regional changes, and this leads to interesting differences within the LAC region. Zones like Ecuador might face a rather favorable future in terms of area suitability for banana production. For 2050 (2070) an increase of almost 50 percent (more than 60 percent) is predicted by Calberto et al. (2015). In opposite to that, zones like Colombia and the Dominican Republic will face a decrease in suitable area. The amount of suitable area for banana production in Colombia is assessed to shrink by about 63 percent (70 percent) in 2050 (2070), and the corresponding decreases in the Dominican Republic are seen at 70 and 80 percent, respectively. The evaluation for zones like Costa Rica, for which Calberto et al. (2015) predict a comparably small increase in the suitability of area for banana production of 12 percent in 2050 and 18 percent in 2070, is in between these assessments.
- Using various climate models and comparing the historic situation in 1950–2000 to the projected outcome in 2060, Machovina and Feeley (2013) come to a rather similar result. The authors conclude that an increased average temperature and a mean decrease in precipitation will lead to a potential decrease in the suitability of area for banana production by almost 19 percent on average in altogether eleven Central and South American countries. More particularly, the authors argue that Colombian banana production will suffer the most as the suitability of area might decrease by almost two thirds. In opposite to that, suitability of area in Ecuador may slightly increase by 17 percent. Banana production in Costa Rica will also suffer, although not as much as in Colombia: Here, the decrease of suitability is expected to be of around 50 percent<sup>57</sup>.
- Finally, Prager et al. (2020) have most recently arrived at the conclusion that the suitability of area for banana production will shrink in all of the four countries, namely by approximately 55 percent in Colombia, 85 percent in Costa Rica, 57 percent in the Dominican Republic, and 37 percent in Ecuador. Here, the changes refer to 2050 in comparison to 2020.

While the results of the various authors partly point into the same direction, they are also partly contradictory<sup>58</sup>. Nevertheless, figure 6.1 summarizes the studies' findings described above, and the average of these three analytical findings shall be considered the best available "condensed expert

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<sup>57</sup> The Dominican Republic was not covered in the study.

<sup>58</sup> Lane and Jarvis (2007) showed that the direction and magnitude of geographical crop suitability considerably depends on the specific climate and crop models used.

wisdom". Accordingly, the following simple conclusion can be made with respect to the suitability of area for banana production around the year 2050:

- It decreases by 61 percent in Colombia,
- It decreases by 41 percent in Costa Rica,
- It decreases by 64 percent in the Dominican Republic, and
- It increases by 10 percent in Ecuador.

**Figure 6.1:** Climate change impacts on the suitability of area for Colombia, Costa Rica, the Dominican Republic, and Ecuador around the year 2050

Country	Calberto et al. (2015)	Machovina and Feeley (2013)	Prager et al. (2020)
Colombia	-63 %	-65 %	-55 %
Costa Rica	12 %	-50 %	-85 %
Dominican Republic	-70 %	n. a.	-57 %
Ecuador	50 %	17 %	-37 %

Source: Own figure and calculations based on Calberto et al. (2015), Machovina and Feeley (2013), as well as Prager et al. (2020).

Although remarkable shifts may be the outcome, the available information does not allow to assess the potential developments more precisely as regards the specific suitability of area for Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde. In fact, such a specification turns out to be quite a challenging endeavor. Apart from the fact that – to our best knowledge – regionalized information is currently not available, two additional aspects must be mentioned in this regard:

- First, the argument that the suitability of a specific area for banana production changes in a negative way does not allow to distinguish between changes that would make this area completely unsuitable ("not suitable") or only "less suitable". In fact, for other crops than bananas, Prager et al. (2020) do assess these differences by marking areas either as "becomes unsuitable" or as "less but still suitable".
- Second, the result that the banana production area potentially becomes less suitable or unsuitable does not necessarily mean that the area cultivated with the crop must or will shrink. Indeed, Machovina and Feeley (2013) point out that only 1.4 percent of the entire suitable area was planted with bananas in Colombia, while in Costa Rica and Ecuador it was 2.7 percent and 5.7 percent, respectively. Therefore, although this might be considered highly problematic from an environmental and climatic perspective, this would also mean that land

in suitable areas that is not yet used for banana production could be newly cultivated, or that land could be "borrowed" from other crops that are currently planted in these areas.

Nevertheless, the approach chosen by Machovina and Feeley (2013) can be combined with our own approach at least to a certain degree, as it allows to calculate a gradient of suitability. If we use the change rates of annual temperature and precipitation provided by Machovina and Feeley (2013), a drop of the climate–yield coefficient of 17.3 percent can be calculated for the LAC region and set into relation with the average decrease of area suitability for banana production of 18.6 percent predicted by Machovina and Feeley (2013) in that region. In other words:

- Each percentage point that the calculated climate–yield coefficient is lower (or higher) compared to the reference scenario
- might at the same time cost (or add) 1.07 percent of suitability of area for banana production.

Applying this concept to our yield calculations would mean that – in terms of tendency – the banana production impacts due to lower/higher yields are "enhanced" by the criterion of suitability of area<sup>59</sup> and must therefore be greater than the yield impact alone (see also chapter 6.3).

## 6.2 Indirect production impacts due to changing pests and diseases

Several insects and plant diseases are known to affect banana plants. Insects, for instance weevils, nematodes, flies, bugs, beetles, and ants may attack the banana rhizome, pseudostem, leaf, and fruit. Occasionally, this may cause cosmetic damage directly to the fruit and, hence, may reduce the marketability of the harvest. However, more often pests do not attack the bunch, but cause indirect damage: Attacks on the rhizome and pseudostem cause yield reductions through plant loss, delayed maturation, and bunch weight reduction. In addition, pests are also a vector of serious plant diseases (Tinzaara and Gold, 2008).

Historical climate change has already altered the disease risk of banana production (Yeeles, 2019), and it is expected that future climate change will continue to do so. In fact, biological processes are strongly influenced especially by water availability and temperature changes, which alter the migration pattern and phenology of most organisms, including pests and parasites (Parmesan and Yohe, 2003). In this respect, it is obvious that largely in line with expectations of climate change crop pests and pathogens are also spreading rapidly around the world (see, e.g., Bebber et al., 2014; Burrows et al., 2011; Thornton and Cramer, 2012).

It is therefore of major concern – and of utmost importance for our study – that precisely pests and diseases of banana plants have been among the most rapidly spreading crop pests and diseases in recent decades (Bebber, 2015; 2019), and that climate change will certainly alter the pressure of

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<sup>59</sup> Intuitively, this makes sense. If climate change in a specific area tends to be favorable in terms of yield it should also act to be favorable in terms of overall production suitability.

certain pests and diseases in the regions/areas of this study. According to Ravi and Mustaffa (2013), disease pressure is strongly influenced by changing temperature, rainfall patterns, humidity, and – in some cases – also atmospheric CO<sub>2</sub> concentration. Hence, the authors state that the incidence of diseases will be most severe towards the equatorial regions, as this is where higher climate change impacts are also expected. In addition, climate change is expected to lead to a spread of pests and diseases to regions and altitudes where they had not occurred before (Erima et al., 2017).

In this respect, banana production is particularly threatened by various fungal diseases (Tripathi, 2019)<sup>60</sup>. One of these emerging diseases is Fusarium Wilt, commonly called the Panama disease, which is caused by a suite of Fusarium (Maryani, 2019; Ploetz, 2007). Its most recent strain named *Fusarium oxysporum f. sp. cubense tropical race 4* (TR4) has already triggered tremendous losses<sup>61</sup>, and this does have severe impacts on banana production and subsequently also on the livelihoods of banana producing small holder farmers and other stakeholders along the banana value chain. Therefore, avoiding contamination by infected planting materials, spores, water, or soil particles from infested areas is crucial. TR4 infects plants of all ages, and while first signs of the disease are yellowing leaves, it will later cause wilting, and will ultimately lead to the plants' death.

Gasparotto and Pereira (2008) suggest that the pressure of the Panama disease or TR4 will increase under climate change due to increased temperatures and drought periods, which cause plant stress. Also, FAO (2020a) projects that the disease may spread further around the globe and cause increasing damages<sup>62</sup>.

However, Fusarium Wilt is currently not the most important disease in banana production (Bebber, 2019). The disease that is most virulent against a wide range of banana genotypes (Churchill, 2011) and is currently re-emerging (Bebber, 2019) is Black Sigatoka, a destructive foliar disease that primarily affects banana and plantain plants. Black Sigatoka is caused by the fungus *Mycosphaerella fijiensis* and represents a principal phyto-pathological problem for banana and plantain crops (Guzmán Quesada and García, 2020). In fact, Black Sigatoka is the most important banana disease worldwide as it is present in all banana producing countries and is considered to cause a significant economic impact by reducing yields and overall plantation productivity, while leading to higher

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<sup>60</sup> As bananas are reproduced vegetatively, most export bananas not only represent just one variety, but they are also genetically identical, and this heavily reduces the variety's resistance against diseases. Apart from the Cavendish variety, which is the most popular variety today, also other varieties cultivated by small holder farmers are susceptible to various fungi (see also García-Bastidas et al., 2020).

<sup>61</sup> In past years Southeast Asia was heavily affected, and large areas of banana production were abandoned because the soil-borne disease cannot be abated once it is established, and because the disease remains viable for decades. In South America, the first report on the continent occurred in 2019 in La Guajira, Colombia (García-Bastidas et al., 2019).

<sup>62</sup> So far, it is not possible to assess the specific impact of the disease in a precise way. But history can give an indication of what could potentially happen in the LAC region. In the past century, a different race of the fungus (race 1) spread across the region and nearly devastated global banana production, which at that time mainly relied on the banana variety Gros Michel (FAO, 2016a; Ploetz 2005, 2015). Banana production and export could only be continued by switching to the Cavendish variety, i.e. by a major change in production.

production costs for disease control. The pathogen rapidly destroys leaf tissue, and as a result, photosynthesis is reduced, affecting plant growth and production (Guzmán Quesada and García, 2020). All stages of the disease can be found on plantations, from imperceptible marks to advanced stages with necrosis or burning of the leaf area. Depending on the effectiveness of measures to prevent and treat the disease, yield losses can range from small to large:

- In the absence of control measures, the disease can reduce bunch weight by up to 50 percent and may even cause a 100 percent loss of production due to deterioration in the quality of the fruit as length and thickness may suffer (Guzmán Quesada and García, 2020).
- Even if optimally controlled via proper fungicide management, yield losses of at least around 5 percent per annum should be anticipated (Cook et al., 2013).

If plants are affected by Black Sigatoka, banana yield losses will often be in between these two extremes. Guzmán Quesada and García (2020) for instance report a loss of about 13 percent in Ecuador, and Yonow et al. (2019) refer to losses of up to 38 percent in Central America in recent years<sup>63</sup>. Furthermore, large costs are incurred by combatting the disease (Jesus Júnior et al., 2008). FAO (2013) argues that application of fungicide treatments is prohibitively expensive and at least 25 percent should be added to the production costs.

Predictions by Jesus Júnior et al. (2008) suggest that the global area suitable for the disease will decrease in the future due to climate change. However, regional projections are very heterogeneous as many variables such as temperature and humidity play a role in disease development. Drier conditions e.g. will reduce the inoculum production and, hence, reduce the disease pressure while longer periods of high humidity will promote the spread of the disease. In this respect, it is worth highlighting that in general certain temperature and humidity ranges are more/less favorable for Black Sigatoka development than others (Jesus Júnior et al., 2008):

- A temperature between 25 and 28°C in combination with a relative humidity of more than 90 percent is considered highly favorable.
- A temperature between 25 and 28°C in combination with a relative humidity of more than 80 and less than 90 percent is considered favorable.
- A temperature between 20 and 25°C or between 28 and 35°C in combination with a relative humidity of more than 80 percent is considered relatively favorable.

Using these criteria and looking at future temperature and precipitation levels in the specific banana production areas of Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde (see figure 5.3) the following may initially be concluded:

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<sup>63</sup> On a global scale, approximately 3 percent of all banana production (including the unaffected areas) is apparently lost due to the Black Sigatoka disease (Strobl and Mohan, 2020).

- In Antioquia, temperature will remain within the 25–28°C interval, except for RCP 8.5 in 2070. Given the rather high amounts of precipitation, relative humidity should also be quite high. Accordingly, we assume the area will remain favorable or even highly favorable for Black Sigatoka development.
- Azua will remain suitable for the disease since – except for the RCP 8.5 scenario in 2070 – temperature will increase within the optimal interval for Black Sigatoka development. Then, much will depend on the temporary relative humidity, especially if precipitation slightly decreases in a climate change scenario.
- Suitability of Black Sigatoka development should also increase in the banana production area of El Oro since temperature will be above 25°C and below 28°C while precipitation is slightly increasing, thus offering more opportunities for periods with rather high relative humidity.
- Heredia and its banana production area will most probably face highly favorable conditions for Black Sigatoka development since temperature in any scenario will be within the optimal interval in combination with high precipitation and subsequently also very often high relative humidity.
- An almost similar conclusion can be drawn for the banana production area in La Guajira. However, here the RCP 8.5 scenario in 2070 as well as temporarily lower humidity due to lower precipitation might also include favorable instead of only highly favorable situations as regards Black Sigatoka.
- On average, Magdalena should also become more suitable for the disease in the future. Temperature will increase and move towards the 25°C frontier and above. In combination with rather high precipitation and, hence, relative humidity this could encourage the spread of the fungus.
- The prediction for the banana production area in Valverde is less clear as at least in the RCP 8.5 scenario for 2070 the temperature is projected to exceed the 28°C mark and as precipitation is projected to decrease. This might slow down the development of Black Sigatoka.

By and large, it can be stated that for most of the regions analyzed in this study the predictions by Jesus Júnior et al. (2008) for the global scale – namely that climate change will lead to a decrease in the area suitable for the Black Sigatoka disease – do not apply. This is also in line with Bebbler (2019), who argues that the infectious risk will increase in the LAC region because of wetness and temperature conditions more suitable for the pathogen<sup>64</sup>. More particularly, on the basis of historic

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<sup>64</sup> Also, Thornton and Cramer (2012) as well as Yonow et al. (2019) suggest that the disease will spread due to increased temperatures. In particular, Yonow et al. (2019) state that all the regions covered within this study are projected to remain climatically suitable for the persistence of the fungi causing Black Sigatoka.

observations Bebber (2019) calculates an increase of the Black Sigatoka disease pressure for banana-growing areas of:

- 0.8 percent per annum in Colombia,
- 1.1 percent per annum in Costa Rica,
- 0.5 percent per annum in the Dominican Republic, and
- 1.2 percent per annum in Ecuador.

These findings are congruent with our own assessment above and might, thus, be used as a best proxy to describe the potential future as regards Black Sigatoka development in the various regions.

### 6.3 Potential aggregated production impacts of climate change

The findings of chapter 5 as well as those of sub-chapters 6.1 and 6.2 will now be merged to provide a condensed overview of the aggregated climate change impacts on banana production. As analyzing the broader regions would hide too much complexity in this case, the focus will now be on the specific banana production areas located within the seven selected banana producing regions of Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde.

First of all, potential banana production is a function of yield and area. Accordingly, changes in banana production can be considered a function of changes in banana yield and in banana cultivation area due to climate change. A summary of our previous findings is given here before assessing the overall impact on banana production in the different areas:

- Basically, climate change manifests itself through changes in temperature and precipitation levels which will then alter the yields of a crop. Focusing on banana production areas within Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde, these climatic changes often act to decrease banana yields (see again figure 5.4). Moreover, future banana yields in most of these areas are expected to decline in any climate change scenario, i.e. even if the Paris Agreement is met. Only in the cases of the analyzed banana production areas in El Oro and Magdalena, positive yield developments might be the potential outcome of climate change. However, the calculated increases are rather small and do not exceed 4.0 percent.
- The potential yield changes detailed above should be considered a best-case scenario since climate change-driven developments other than those related to the average annual changes in temperature and precipitation are not accounted for. In fact, climate change is also a function of (short-term) weather variability, and the frequency and intensity of extreme events are both considered to increase with increasing global temperatures. Although their impacts might sometimes differ, extreme events such as droughts and floods, short-term heat- or cold-waves or strong winds, have got one thing in common: They negatively affect

agricultural production. The potential yield changes discussed above will, thus, certainly be more pronounced when such events occur. In consequence, in banana production areas with slightly positive yield projections these may become negative after incorporating the impacts of extreme events, and in regions where negative yield changes had already been predicted these will get even more pronounced.

- The same that applies to weather variability can also be said for pests and diseases. It can generally be stated that pests and diseases will more rigorously spread with ongoing climate change and that they are therefore considered to become more challenging for banana production in the future. This can particularly be shown for Black Sigatoka, currently the major disease for bananas also within the regions considered in this study, while other diseases such as TR4 may additionally intensify the associated negative yield impacts. The effects of pests and diseases will therefore substantiate the argument mentioned above, namely that projected positive yield changes may become negative, while predicted negative yield changes will become even more negative.
- Finally, the suitability of area for banana production will also be affected by climate change. In this respect, a similar tendency to the one already postulated for yields can be expected. This is because banana production areas in which projected climate conditions will tend to have a negative influence on yields can at the same time be considered as areas that become less suitable for banana cultivation – or vice versa.

How can these findings be summarized now? Figure 6.2 presents a summary of the hypotheses explained above referring to the RCP 8.5 scenario in 2050 and to the specific banana production areas<sup>65</sup>. Two symbols are used in the figure:

- A "+" is used to describe a potential positive yield impact (in accordance with figure 5.4) as well as a positive change in the suitability of area.
- In opposite to that, a "-" is used to describe a potential negative yield impact (in accordance with figure 5.4) as well as a negative change in the suitability of area.

In addition, the symbols are used to refer to an increase in yield depressing impacts that are induced by a higher variability of weather events (extreme events) and also by emerging pests and diseases.

It becomes clear from figure 6.2, then, that most of these climate change induced drivers will have potential negative impacts on the selected areas as 24 of the 28 symbols displayed are negative, while only four are positive. This means that – in general – compared to yield enhancing impacts, more yield decreasing impacts from climate change should be expected<sup>66</sup>.

<sup>65</sup> Similar figures for the other three climate change scenarios can be obtained from annex K.

<sup>66</sup> The broader picture would not change if the other three scenarios were used here (see annex K).

**Figure 6.2:** Assessment of the direction of the yield impact of various climate change-induced drivers (RCP 8.5 scenario in 2050)

Banana production area in ...	Impact of ...			
	... temperature & precipitation	... weather variability	... pests and diseases	... suitability of area
... Antioquia	-	-	-	-
... Azua	-	-	-	-
... El Oro	+	-	-	+
... Heredia	-	-	-	-
... La Guajira	-	-	-	-
... Magdalena	+	-	-	+
... Valverde	-	-	-	-

Source: Own figure. "+" indicates a potential positive impact and "-" refers to a potential negative impact.

This qualitative assessment will now be nuanced by presenting some quantitative results. For this purpose, we use a scenario technique that allows us to quantify the production impacts of climate change. As a first step in this analysis, hence, we need to define specific assumptions that in turn need to be based on sound meta-analyses – as those provided in this report. It is important to mention, however, that the potential scenarios that can principally be drawn from these assumptions are numerous, and that calculating the production impact for all possible scenarios is (far) beyond the scope of this study. Nevertheless, we aim at providing at least a tendency of the magnitude of the accumulated production impact of the various climate change-induced drivers. The following scenario to be analyzed is defined in this respect:

- Accumulated production impacts in the specific banana production areas of Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde are calculated for the RCP 8.5 scenario in 2050.
- Yield impacts due to changing annual temperature and yearly precipitation are taken from figure 5.4.
- Yield impacts of pests and diseases are exemplarily discussed for Black Sigatoka. Following Bebbler (2019), an increase of the specific disease pressure of 0.8 percent per annum (over a period of 45 years<sup>67</sup>) is assumed for the three banana-growing areas in Colombia. Referring to the status quo of production (i.e. where the current effects of Black Sigatoka are already

<sup>67</sup> The scenario year is 2050 and the reference period is 1990-2019, i.e. the year 2005 as the mean.

included), this would lead to an increase of production (i.e. land and/or yield) being affected by Black Sigatoka by 0.8 percent per year. Similarly, an increase of 1.1 percent per annum is used for the corresponding area in Costa Rica, 0.5 percent for the two areas in the Dominican Republic and 1.2 percent for the area in Ecuador.

- Following Guzmán Quesada and García (2020), as well as Yonow et al. (2019), regional yield losses of at least 13 percent should be envisaged for production that is newly affected by the disease<sup>68</sup>.
- The suitability of area is assumed to change along a uniform gradient which in accordance with Machovina and Feeley (2013) means that each percentage point of a yield impact is accompanied by a change of 1.07 percent in the suitability and subsequently in the use of the area for banana production.

This is certainly a subjective selection of assumptions and numerous other scenarios would also be conceivable, especially if other factors such as technological developments and management options were additionally considered. However, as stated before, we only intend to approximate the partial effect of climate change-induced drivers on regional banana production. In a context of agricultural economics, we also refer to a *ceteris paribus* approach<sup>69</sup>. In this respect, figure 6.3 summarizes the assumptions made, and figure 6.4 shows the overall impact on banana production in the specific areas of the seven selected regions resulting from the outlined scenario analysis<sup>70</sup>:

- It becomes clear that all the specific banana production areas in this study will suffer production losses given the specific scenario analysis conducted.
- This is also the case for the areas located in El Oro and Magdalena, where changes in annual temperature and yearly precipitation may still act in favor of banana yield and the suitability of area for banana production.

Thereby, it must be taken into account that the impact of more frequent and more intense extreme events due to climate change is not considered in this scenario analysis. This means that under the set assumptions and definitions the picture drawn in figure 6.4 only displays a best-case scenario. Most probably, then, weather variability will act to further reduce local banana yields and, hence, overall banana production in the specific areas. As such, the outcome presented in figure 6.4 shall only be considered a rough "best guess" assessment of the potential minimum production impact of climate change not merely in terms of qualitative arguments but also in quantitative terms.

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<sup>68</sup> Note: This should be considered a best-case scenario as additional production costs for at least proper plant protection must actually be taken into consideration too.

<sup>69</sup> A softening of the *ceteris paribus* clause of course allows other perspectives, which must be neglected here due to the scope of the study.

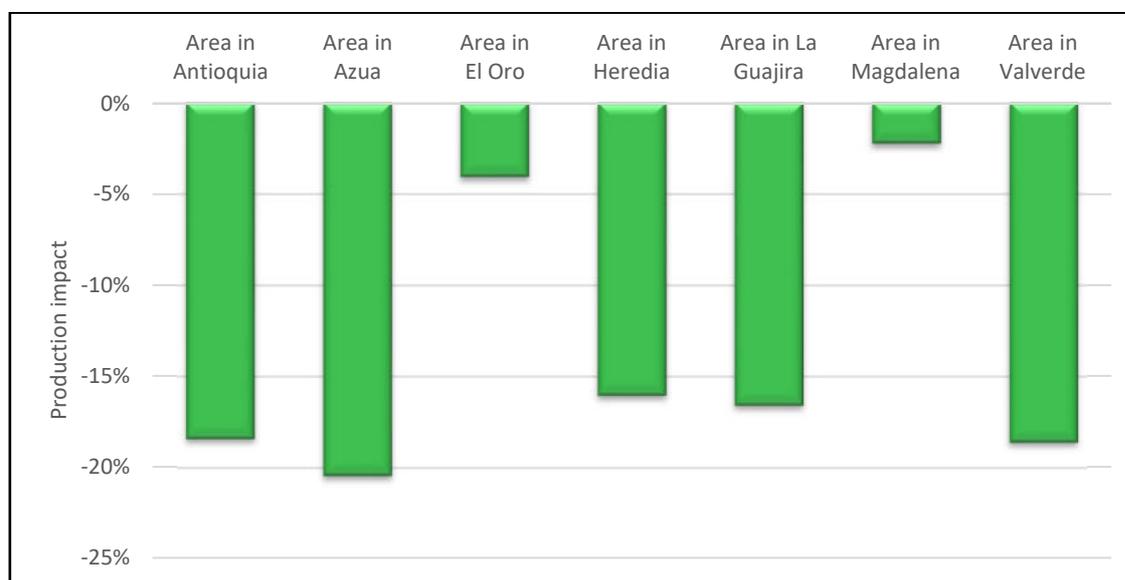
<sup>70</sup> The overall impact is simply the product of the three individual impacts.

**Figure 6.3:** Assumptions for a scenario analysis to calculate the production impact of various drivers of climate change for the RCP 8.5 scenario in 2050

Banana production area in ...	Impact of ...		
	... temperature & precipitation	... pests and diseases (i.e. Black Sigatoka)	... suitability of area
... Antioquia	-6.8 %	-5.6 %	-7.3 %
... Azua	-9.0 %	-3.3 %	-9.6 %
... El Oro	2.7 %	-9.2 %	2.9 %
... Heredia	-4.2 %	-8.3 %	-4.5 %
... La Guajira	-5.8 %	-5.6 %	-6.2 %
... Magdalena	1.7 %	-5.6 %	1.8 %
... Valverde	-8.0 %	-3.3 %	-8.6 %

Source: Own figure and calculations.

**Figure 6.4:** Accumulated production impact of various drivers of climate change for specific banana production areas and the RCP 8.5 scenario in 2050



Source: Own figure and calculations.

## 6.4 Further economic impacts

As the result of relative changes in yield and suitable areas for banana production, percentage changes in the harvested tonnages will have an impact on marketable volumes. And these changing volumes will affect other economic parameters such as trade volumes, market prices, and farm income or profitability. Hence, the following discussion on the implications of these effects for domestic and international markets will again be mainly of qualitative nature but will also include some quantitative examples.

It has been stated above that climate change, *ceteris paribus*, acts to limit and even to decrease banana production throughout the various regions and specific areas analyzed in this study. In economic terms, this is equal to a shortening of supply. Less produce is available to meet the existing demand, be it domestic demand or foreign trade demand. In fact, various stakeholders have already expressed concern over the fact that supply chains, including those for bananas, will become more vulnerable to climate change in the future (see, e.g., Blake et al., 2018; Smith et al., 2016).

However, answering the question of how much market and trade volume may be affected by climate change is a challenge, since our regional analysis – and even more our analysis of the specific areas – cannot be extrapolated to the national (domestic) and also to the international (foreign trade) market level. This would require taking into consideration all banana producing regions and not only those of Antioquia, La Guajira and Magdalena in Colombia, of El Oro in Ecuador, etc. For a comprehensive analysis, respective changes in, for instance, Valle del Cauca and Santander in Colombia and Los Ríos and Guayas in Ecuador would also need to be observed and analyzed<sup>71</sup>. This is clearly outside the scope of this study. However, a best guess about the affected production as well as about the affected market and trade volumes can be provided by using the potential production impacts in relative terms (as outlined in figure 6.4) and relating these impacts to the country-wide production and export volumes. For this purpose, FAO (2020b) data and FAO (2020e) information are additionally used. Accordingly, figure 6.5 shows the average banana production and export volumes of Colombia, Costa Rica, the Dominican Republic, and Ecuador of the past three years<sup>72</sup>.

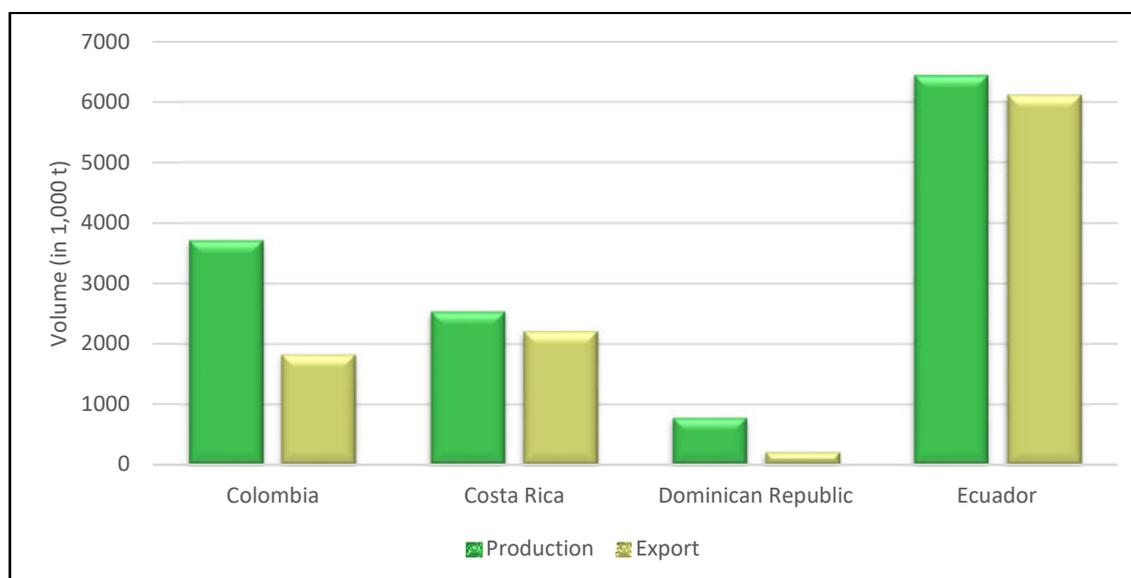
From figure 6.5 it becomes evident that Costa Rica and Ecuador mainly produce bananas for export markets, while in Colombia and especially in the Dominican Republic parts of the banana production are also particularly targeted towards domestic demand. Taking the ratios of domestically consumed vs. internationally traded produce embedded in figure 6.5 and integrating the production losses due to climate change depicted in figure 6.4 (i.e. losses ranging from approximately 5 to 20 percent), could therefore result in the domestic market and trade volume effects as displayed in figure 6.6. The results will, thus, depend on the "severity" of the assumed climate change impact and on the country under consideration.

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<sup>71</sup> The same applies to all other banana production regions in the countries of this study and beyond.

<sup>72</sup> While conducting economic analyses, it is standard to use several-year averages to avoid distortions.

**Figure 6.5:** Banana production and export volume of Colombia, Costa Rica, the Dominican Republic, and Ecuador, average for 2016–2018



Source: Own figure based on FAO (2020b; e).

**Figure 6.6:** Potential market volume impacts of a 5 and 20 percent production reduction due to climate change

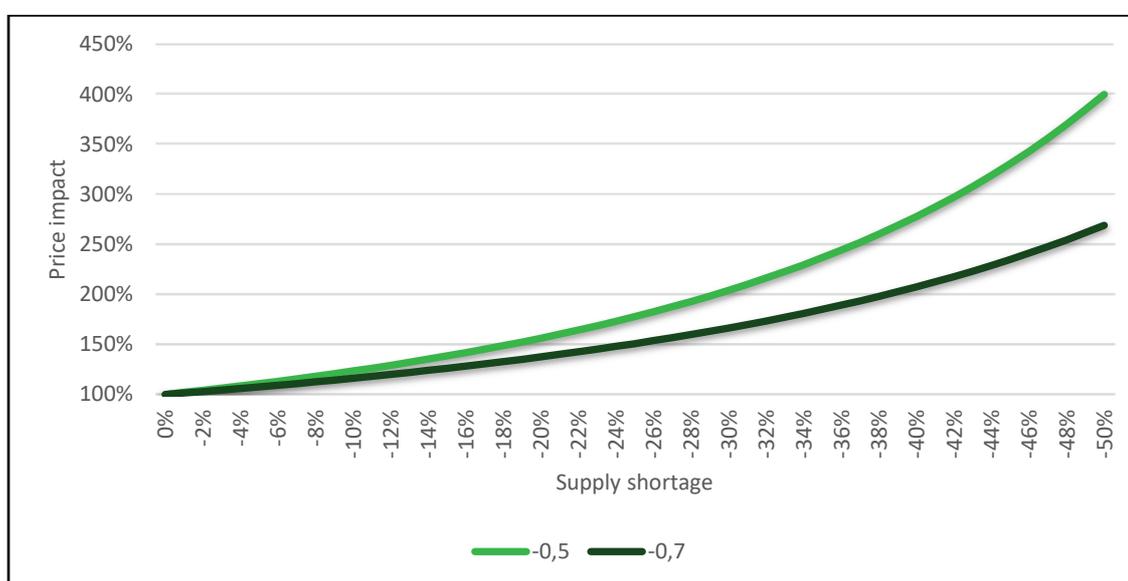
Country	5 percent reduction		20 percent reduction	
	Domestic market	Export market	Domestic market	Export market
Colombia	94 kt	91 kt	377 kt	365 kt
Costa Rica	16 kt	111 kt	63 kt	443 kt
Dominican Republic	28 kt	10 kt	113 kt	42 kt
Ecuador	16 kt	306 kt	66 kt	1,222 kt

Source: Own figure and calculations.

According to figure 6.6, in the "20 percent-scenario" more than 2 million tons of the four countries' total export volume would be missing for international banana trade. This is equal to over a third of all EU banana imports in recent years (see FAO, 2020e) and should therefore not be considered a trivial effect, but rather a remarkable market distortion.

To assess the resulting price impacts, it is necessary to distinguish between domestic and international markets. The following market effects are considered if banana is consumed domestically: In the face of a constant food demand, a shortage in supply will potentially lead to considerable price increases, especially when the cuts in supply happen at rather short notice, as is the case with supply shortages caused by the occurrence of most extreme events<sup>73</sup>. Accordingly, figure 6.7 visualizes the potential domestic market price impacts (ex-farm level, prior wholesale level)<sup>74</sup> of a short-term banana supply shortage in cases where the following conditions are met: The short-term supply shrinks by 1 to 50 percent, the price elasticity of demand is within the range of -0.50 and -0.70<sup>75</sup> and bananas cannot easily be substituted from other "sources" instantly after the event<sup>76</sup>.

**Figure 6.7:** Potential domestic market price impacts of a short-term banana supply shortage due to climate change, for different elasticities, ex-farm gate and without substitution



Source: Own figure and calculations.

<sup>73</sup> In this respect, it must be noted that banana market dynamics are still extremely underreported in the academic literature (Blake et al., 2019). Hence, gathering more data on price elasticities and basing a sound analysis upon it are major challenges.

<sup>74</sup> Therefore, a standard single market model is applied. For more information on the theory and applicability of single market models see, for instance, Jechlitschka et al. (2007) and Cook et al. (2013).

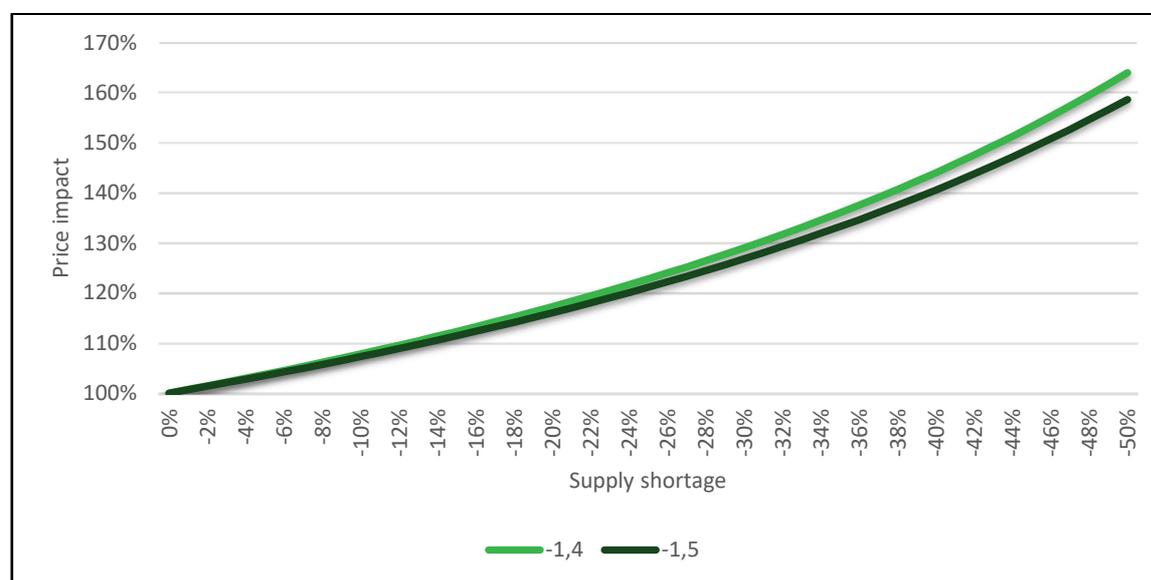
<sup>75</sup> Newest research of Femina (2019) suggests that price elasticities of demand for banana in LAC could be in the range of -0.50 and -0.71. This does not differ too much from earlier estimations concluding that short-term price elasticities of demand for banana are between -0.52 and -0.66 (Chadwick and Nieuwoudt, 1985).

<sup>76</sup> It is assumed that other options to immediately compensate regional supply shortages such as the transport and marketing of bananas from other regions with sufficient/excess banana supply cannot temporarily be accomplished, or can only be accomplished with a considerable time delay.

Considerable temporary (short-term) price increases may therefore occur if climate change induced production losses are fully transferred to a rather non-reactive domestic market. Demand in such a case is rather inelastic meaning that people (here banana consumers) will buy about the same amount of the product no matter whether the prices fall or rise. This market behavior is common for staple foods such as bananas and plantains in remote or very poor areas. However, the price changes displayed in figure 6.7 will most certainly be softer, since most final banana consumers will normally buy their bananas at the retail market level. As retail markets usually also have other food options available, consumers would be able to substitute bananas for a different staple food in the case of stronger price increases.

To account for this fact, figure 6.8 shows the price impact of a more elastic demand<sup>77</sup>, where the price increases are now much lower but still remarkable. Accordingly, production losses of 20 (50) percent should temporarily be associated with price increases of approximately 15 (60) percent on markets satisfying domestic food demand. In the long run, this price impact might further decrease since the adaptability of consumers (i.e. looking for other food substitutes) needs to be factored into the analysis. In such a case, price increases would be around 13 (50) percent if a supply shortage of 20 (50) percent was assumed<sup>78</sup>.

**Figure 6.8:** Potential domestic market price impacts of a short-term banana supply shortage due to climate change, for different elasticities, retail market level and with substitution



Source: Own figure and calculations.

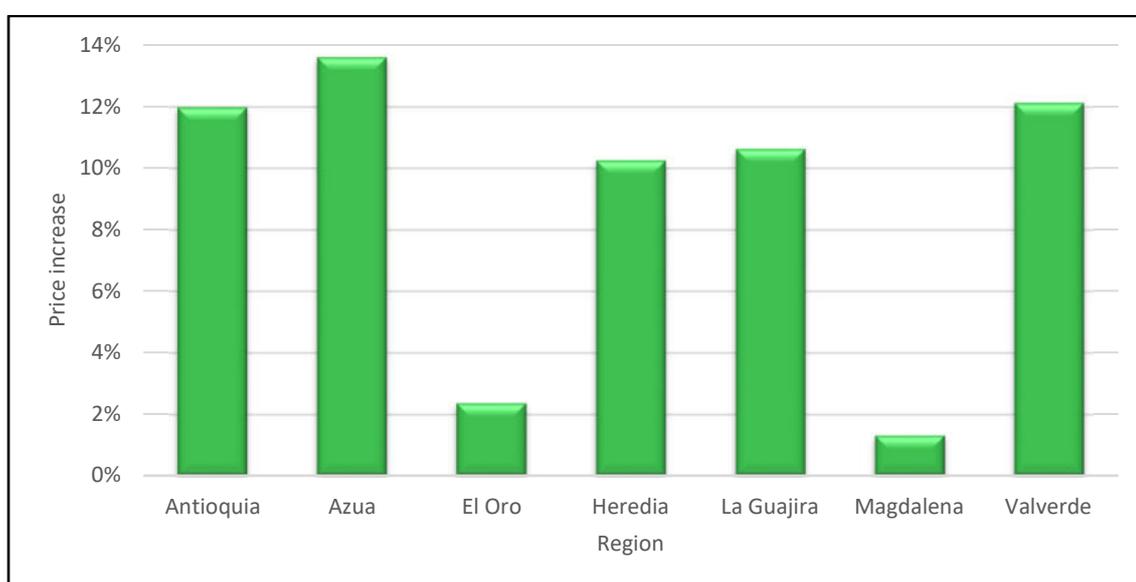
<sup>77</sup> Corresponding price elasticities of demand are taken from Chadwick and Nieuwoudt (1985).

<sup>78</sup> Again, corresponding price elasticities of demand are taken from Chadwick and Nieuwoudt (1985).

However, even these smaller price increases might have severe consequences, especially if banana is consumed as a major staple food by rather poor households. In such a case, temporary price increases may significantly threaten household food security at least in the short run (see also FAO, 2019).

The long-term concept depicted in figure 6.8 can also be used to roughly assess the price impacts caused by the various climate change-drivers in the different specific banana production areas<sup>79</sup>. The results of this assessment are shown in figure 6.9.

**Figure 6.9:** Domestic market price increases of calculated production losses due to climate change for specific banana production areas and the RCP 8.5 scenario in 2050



Source: Own figure and calculations.

Accordingly, it can be stated that if the calculated production losses were applied to the entire regions of Antioquia, Azua, El Oro, Heredia, La Guajira, Magdalena, and Valverde, domestic market price increases of 2 to 14 percent could be expected. Using data on the average price of banana by country provided by Statista (2020), this would be equal to a price increase between 1 and 15 Cent of a U.S. Dollar (USD).

These values should, however, not be overinterpreted since regional banana markets are interlinked and since in the long run – i.e. by the year 2050 – price incentives will lead to changing market flows as well. In our specific setting, this would mean that certain banana production volumes will be re-allocated from regions with relatively high price decreases towards regions with comparatively lower price decreases, which will act to “average” the price movements somewhere in between the

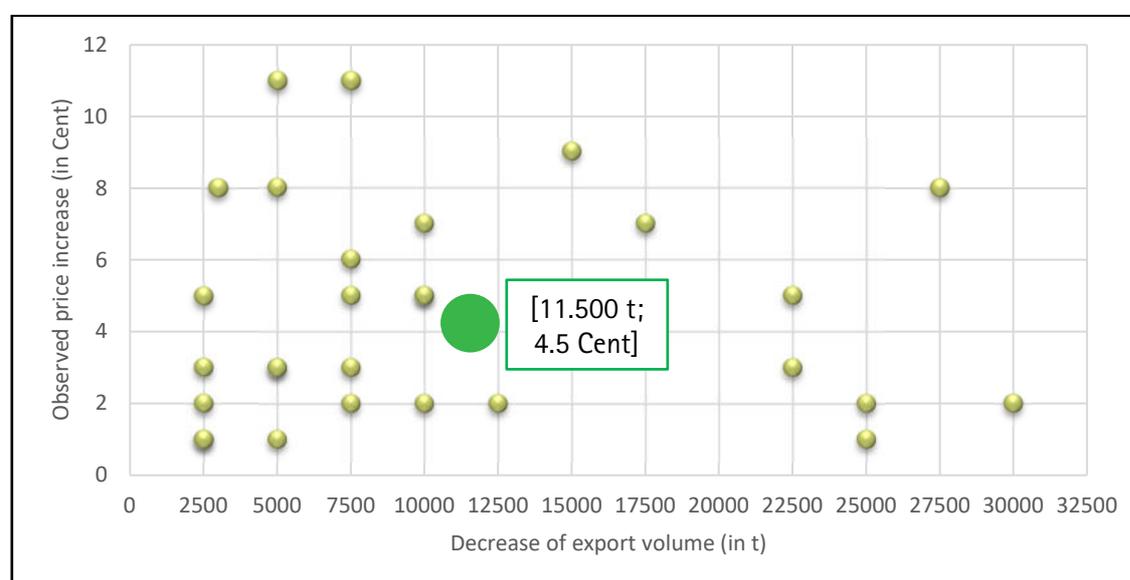
<sup>79</sup> The calculated production impacts of these drivers have previously been displayed in figure 6.4.

displayed range. In accordance to figure 6.9 this might lead to an inter-regional price increase by around a middle single-digit percent value.

But what about international (trade) market prices? Answering this question is a challenge since so far researchers have not attempted to model such impacts in a more sophisticated way. The standard approach would be to use a market model, or more precisely a partial or general equilibrium model<sup>80</sup>. However, the own- and cross price elasticities as well as other parameters that are needed for soundly modelling the banana market and its interlinkages with other markets are currently not available. Too many assumptions would be necessary to conduct such a complex analysis and therefore another approach must be chosen.

Blake et al. (2019) already looked at the price impact of climate change on world banana markets. Using the information provided by the authors, we can plot the following figure 6.10, where short-term (weekly) production losses induced by climate change-related extreme events are related with import price changes observed loco port in France. Altogether the impact of 33 of such events in Colombia, Costa Rica and Ecuador identified by Blake et al. (2019) between 2006 and 2015 are included, and the mean of all observations is indicated by the embedded coordinates of the large green dot. Consequently, figure 6.10 shows that on average a short-term (weekly) export cut of 11.500 tons induced by an extreme weather event caused a mean price increase loco port in France of 0.045 Euro or of approximately 7 percent.

**Figure 6.10:** Observed export decreases due to climate change-induced extreme events and international trade market price increases loco port in France, 2006–2015



Source: Own figure based on Blake et al. (2019).

<sup>80</sup> For more information on partial equilibrium modelling, see, e.g., Lüttringhaus and Carlsburg (2018).

Causes of the included export decreases are temporary national and/or regional production losses of 10 to 50 percent or on average 25 percent. This means that the induced world market price changes are lower than the domestic market price changes analyzed above<sup>81</sup>, and points to the fact that international markets are able to partially absorb regional production limitations. In fact, Blake et al. (2019) make clear that various actor strategies and especially competition along with logistics can – among other factors – compensate for regional production losses caused by climate change-induced extreme events. Together with consumer reactions, these factors will therefore act to lower price volatility, at least in the short run.

From the perspective of agricultural economics this should not only apply in the short run, but also in the long run. Through integration and innovation market actors will implement and adapt strategies to cope with climate change-induced long-term trends in regional production volumes. Hence, international market price changes due to regional shortages can probably be expected to be (well) below the domestic price impacts visualized in figure 6.9. As mentioned before, a quantification of the effect is, however, not possible within the scope of this study due to the weak data and information background for proper modelling and scenario analysis.

Another economic parameter to look at is farm profitability, which can be measured in various ways. Usually, a cost-revenue approach is applied which uses farm revenues as a base and subtracts interest, taxes, and amortization, as well as other production costs<sup>82</sup> to calculate, for instance, the net farm income, an operating profit margin ratio, and/or a rate of return (Langemeier, 2017). Scientifically sound cost-revenue approaches (see, e.g., McBride, 2016) require the input of a high amount of farm-specific data, and the applicability of a desirable full-cost-full-revenue approach to arrive at meaningful conclusions for farm-based and political decision-making is limited when information backgrounds are weak. Unfortunately, such a weak information background is the case regarding the objectives of our study. Reliable production cost statistics for banana production in LAC countries are not available. Nevertheless, some exemplary calculations can be provided in the following by separately looking at farm revenues and farm-based costs.

Farm revenues of a banana producer can be related to the harvest of a farm measured in a certain unit and the price per unit of harvest. Changes in market revenue – here due to climate change – are then the result of changes in production and changes in prices. For an average banana producing farm located in the banana production areas in one of the focus regions of this study, this concept can now be applied to the data already discussed with figure 6.4 (accumulated production impact of various drivers of climate change) and figure 6.9 (information on domestic market price changes). Accordingly, the following can be stated for an average farmer if the regional impact of climate change on local markets is considered (*ceteris paribus*):

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<sup>81</sup> See, for instance, figure 6.8 which shows a price increase of around 20 percent if a production cut of 25 percent is assumed.

<sup>82</sup> In the case of crop production, these are, for instance, costs related to plant material or seeds, fertilizers, plant protection products, fuel and lubricants, and labor.

- In Antioquia, a production reduction of 18.4 percent is accompanied by a price increase of 12.0 percent.
- In Azua, a price increase of 13.6 percent can be associated with a decrease in production of 20.5 percent.
- An average farm in El Oro faces a production impact of minus 4.1 percent and a price effect of plus 2.4 percent.
- In Heredia, the average farm faces a price increase of 10.2 percent which can be linked to a production decrease of 16.1 percent.
- In La Guajira, the production impact is minus 16.6 percent, and the price effect is plus 10.6 percent.
- In Magdalena, average farm production shrinks by 2.3 percent while the price increases by 1.3 percent.
- Finally, an average farmer in Valverde must cope with a production reduction of 18.6 percent but would get a 12.1 percent higher price.

The numbers above show that a negative production impact is always larger than the positive domestic market price impact. This central message is important as – on aggregate<sup>83</sup> – it tends to lower farm revenues. This is visualized in figure 6.11. Accordingly, by 2050 farm revenues could shrink by up to 10 percent<sup>84</sup> when considering only regional production and domestic market access as well as the respective price changes. However, climate change does not only occur in the regions assessed in this study. Instead, it is a global phenomenon, and hence in the long run the market price will also be a function of interregional and international market volume reallocation. In this case, individual farmers may benefit in terms of market revenue in regions where the relative long-term production losses due to climate change are lower than the relative long-term interregional price increase which must be within the range displayed in figure 6.9. Given our exemplary calculation, this might apply to some banana farmers in El Oro and Magdalena. In opposite to that, many farmers in regions where the production loss is higher than the average price increase may suffer even more than is displayed in figure 6.11 above.

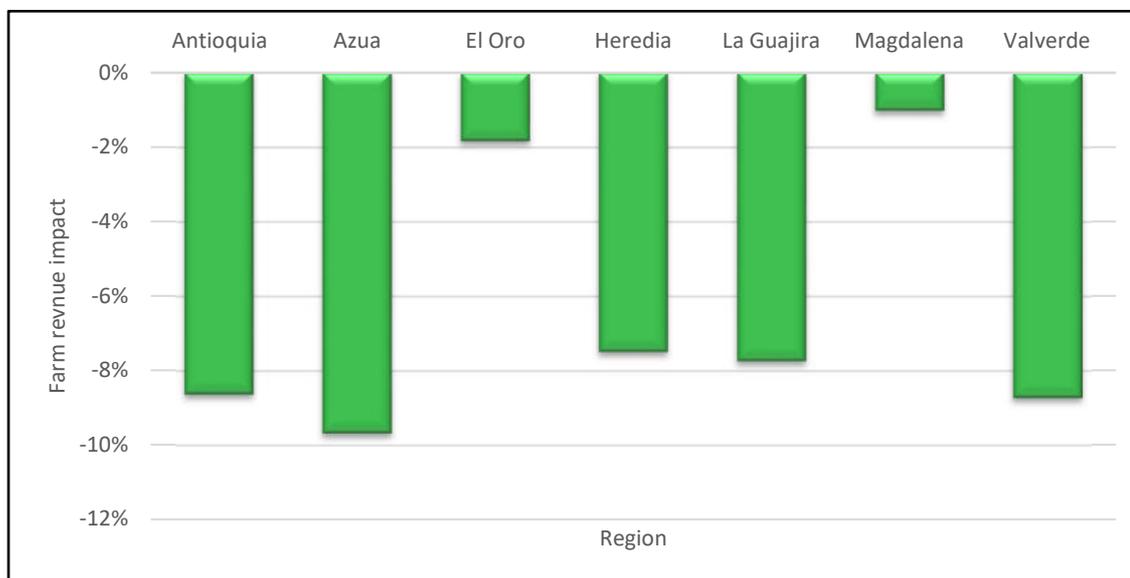
The results displayed in figure 6.11 relate to the long-term impact of climate change on farm revenue. However, what about the short-term effect on farm revenue if market integration cannot instantly absorb production losses in a region through interregional, domestic, or international trade?

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<sup>83</sup> To calculate the aggregate, the two change rates per region must be added to 1.0, and the two sums have to be multiplied, then.

<sup>84</sup> Note that the RCP 8.5 scenario is used to describe the climate change impact. Other scenarios such as RCP 2.6 might lead to “reduced” impacts.

**Figure 6.11:** Partial regional farm revenue impacts due to production and price changes induced by climate change for specific banana production areas in selected regions and the RCP 8.5 scenario in 2050



Source: Own figure and calculations.

To assess this temporary impact on farm revenue, let us look once again at figure 6.8 which plots supply shortages (or production losses) and the associated price increases. Following the plotted lines, we may conclude that short-term losses of up to a third of production can be related to relative price increases that are lower than the relative production shock. More precisely, this means: If short-term regional production losses are lower than approximately 33 percent, farm revenues will temporarily decrease. Whereas if short-term regional production losses are higher than 33 percent, this may temporarily act to slightly increase farm revenues due to higher prices.

Of course, this finding is based on the applied economic model and particularly on the embedded constant price elasticities<sup>85</sup>. Nevertheless, as a rule of thumb it can be stated that climate change, i.e. the associated temperature and precipitation trends in the long-term and the weather variability in the short-term, will often act to lower farm revenues. Only in the cases of very high production losses in the short-term due to extreme events combined with long-term price increases that are larger than these production decreases in relative terms, some (local) farmers may also experience a small revenue increase<sup>86</sup>.

<sup>85</sup> A log-linear function is applied. The price elasticity serves as an exponent.

<sup>86</sup> The potential benefit from very high short-term production losses should be considered not long-lasting. In fact, it will surely be more than "compensated" over time assuming functioning markets, thus, leaving also these temporarily benefiting farmers worse off in the medium and long-run.

In addition to farm revenues, production costs may also be affected by climate change. When assessing production cost developments, the following arguments should be taken into consideration:

- Climate change is already a challenge for banana farmers today and will continue to be so in the future. Therefore, farmers will have to cope with proper climate change adaptation (see chapter 7.1).
- This adaptation, however, is partly accompanied by huge investments and management adjustments. Some investment examples for climate change adaptation are the use of climate-smart planting material, the construction of irrigation facilities, the installation of wind breakers, etc. These investments are also cost-relevant in the long run via depreciations and re-installments. In addition, e.g. more innovative (i.e. also typically more costly) plant protection products, a better information access, the design and implementation of humus-building measures, etc. must be financed on an annual basis along with a better trained and skilled labor force.
- All these long-term investments, annual operating assets and better skilled labor force have one in common: They tend to increase production costs.

In general, this also means that in combination with decreasing farm revenues, higher production costs may contribute to problematic situations for farmers. Even in the rare cases where climate change does lead to slightly increasing farm revenues, this small added value could be overcompensated by financial burdens necessary to maintain production.

The magnitude of this aggregated effect of changing farm revenue and production costs can only be analyzed by looking at specific banana farms in the form of case studies. As stated previously, however, the data base accessible for this purpose is very weak. Nevertheless, in the following we will provide at least an idea of what climate change could mean for banana farmers in quantitative terms by using information on selected and well-defined banana farms that has been obtained from scientific literature and expert knowledge. Three examples are provided hereafter, and the results are shown in figure 6.12<sup>87</sup>.

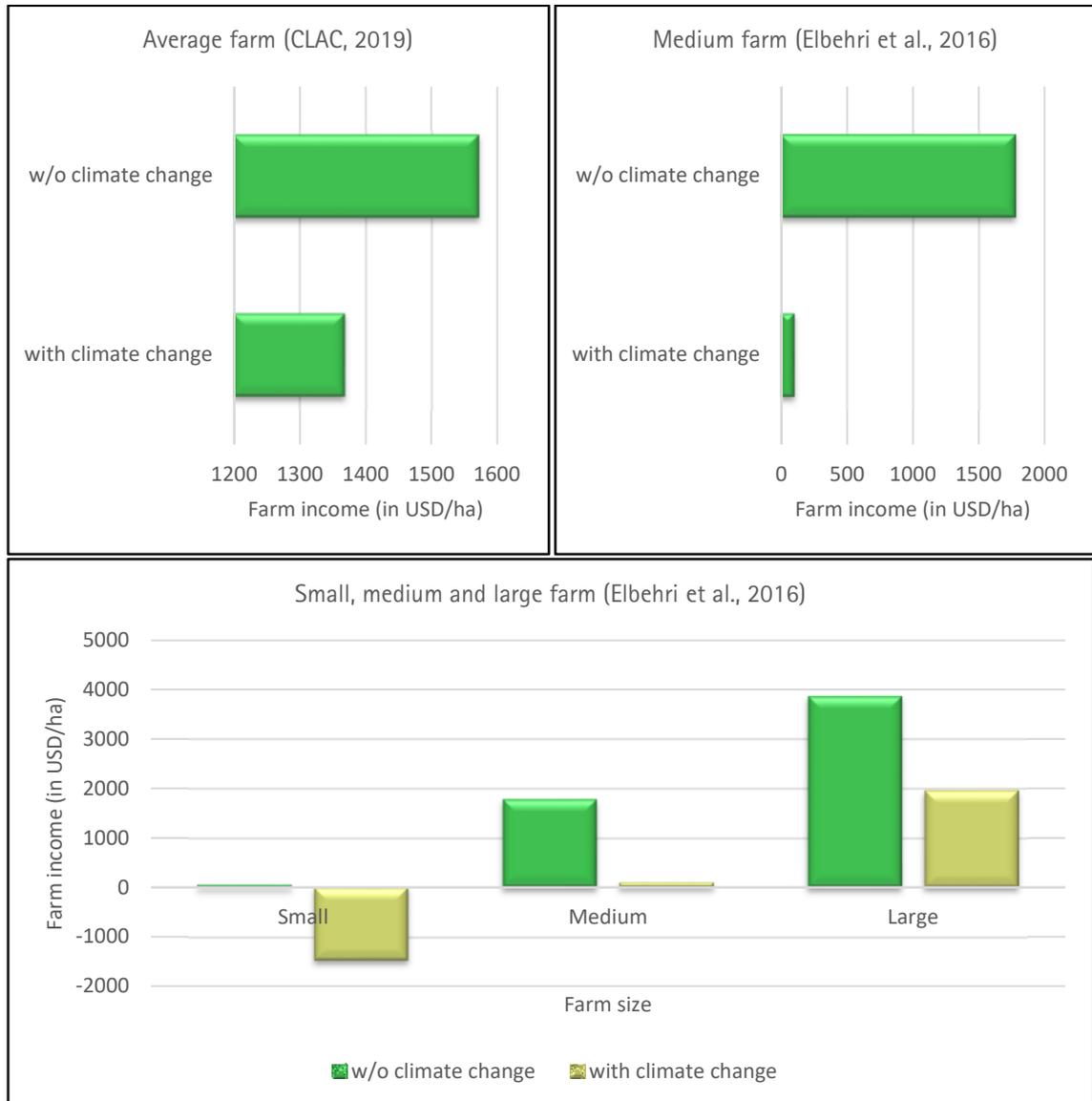
The first example – displayed in the upper left corner of figure 6.12 – refers to a banana farm described in CLAC (2019). This case study is assembled using data from four (unfortunately undefined) origins bridging Colombia, Ecuador, and the Dominican Republic<sup>88</sup>. This average "model farm" generates a market revenue of 10,172 USD per hectare and year while having fixed production costs of 8,600 USD. Consequently, the annual farm income is 1,572 USD per hectare.

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<sup>87</sup> Indeed, the following should be considered a potpourri of potential outcomes. It does not necessarily mean that these outcomes are representative. They are rather typical for the specific underlying scenario and, thus, only valid under the defined assumptions, which of course might be set differently.

<sup>88</sup> Costa Rica was not part of the CLAC (2019) analysis, instead Peruvian data is apparently included as well.

**Figure 6.12:** Exemplary annual farm income effects of climate change for specific banana farm case studies and the RCP 8.5 scenario in 2050



Source: Own figure and calculations.

To account for the climate change-induced yield impacts (see figure 6.3) and for the changes in domestic market prices (see figure 6.9), we calculate an average that includes all regions of Colombia, the Dominican Republic and Ecuador that are part of this case study compilation<sup>89</sup>.

<sup>89</sup> Note again that Costa Rica is not included in the CLAC data. Therefore, Heredia data are excluded here.

Consequently, the following yield and price impacts due to climate change are assumed and will be used in our case study to project a farm income change by 2050 (holding all other parameters constant<sup>90</sup>):

- Banana yields will shrink by 9.5 percent.
- Banana prices will increase by 8.6 percent.

Incorporating these two impacts into the cost–revenue approach leads to a decrease of farm income by 11 percent as displayed in figure 6.12. This is equal to a decrease by 143 USD per hectare and year and is remarkable since in our concrete example production costs only cover fixed costs and would therefore be higher if variable costs were also included. In addition, potential increases in fixed costs due to climate change are also not included.

As a second example, we use information on a medium-sized farm located in Ecuador that is discussed in Elbehri et al. (2016). Information on this farm is depicted in the upper right corner of figure 6.12. Accordingly, this banana farm harvests 1,585 boxes of bananas per hectare and year and generates a selling price of 6.01 USD per box. Hence, market revenue per hectare is 9,526 USD. Total costs of production, i.e. variable and fixed costs, accumulate to 7,743 USD per hectare. Consequently, an annual farm income of 1,783 USD per hectare and year is generated.

Let us now assume that this Ecuadorian farm is hit by future climate change until 2050 in the following way:

- The yield impact is plus 2.7 percent as described in figure 6.3 for banana production in El Oro.
- However, the farm must cope with the Black Sigatoka disease. In accordance with FAO (2013), fully combating the disease increases production costs by (at least) 25 percent (see again chapter 6.3).

The consequences of this scenario are devastating, as the exemplary farm would lose most of its profits. In fact, the annual farm income would be reduced by 94 percent meaning that instead of close to 1,800 USD per hectare and year, only around 100 USD could be generated. This would also mean that the exemplary farmer most probably would not be able to fully cover his production costs including his own remuneration.

The data provided by Elbehri et al. (2016) also allows for an exemplary comparison in terms of farm size. The authors provide information not only for a medium-sized farm, but for a small and large farm as well. The small (large) farm has a lower (higher) land productivity and also lower (higher) production costs. In comparison to the medium-sized farm, and given a fixed price per box of bananas, this means on aggregate that:

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<sup>90</sup> This also applies to the suitability of area since this farm is assumed to still produce bananas on the hectares used for the analysis.

- In the reference situation, the small farm generates a profit of only 51 USD per hectare and year.
- The large farm, however, can make an annual profit of 3,861 USD per hectare.

After applying the same impacts defined for the medium-sized farm above, we arrive at the following conclusions:

- The exemplary small farm would probably have to give up its business quickly as its production costs are well above the market revenue, and as the farm would not be able to compensate this in the long run.
- The exemplary large farm, however, would probably survive as its profits would "only" be halved. And this is the case because for the larger farm the relative reduction in farm income is much smaller than for the medium and small farms.

By and large, these results point at a comparative advantage of larger farms, while smaller farms seem to be at a comparative disadvantage under long-term climate change impacts.

A final very particular question is whether conventional or organic farms are better able to cope with climate change in terms of market revenue and production costs. A general answer cannot be given here, as this will most certainly depend on the specific conditions of the farm. However, some data comparing organic and conventional farms in Ecuador can also be obtained from Elbehri et al. (2016), and accordingly, the yield in organic farms is 17 percent lower than in conventional farms<sup>91</sup>. If this yield gap is not – or only partially – compensated by higher prices, the market revenue per hectare of the organic farm will be lower. However, the data also shows that if prices for organic bananas were at least 21 percent higher than those for conventionally produced bananas, the farm revenue might be higher in the exemplified organic system<sup>92</sup>.

In organic banana cultivation, production costs count as well. According to Elbehri et al. (2016), organic farms neither use synthetic fertilizers nor synthetic plant protection products. Instead they use natural plant extracts, apply higher amounts of manure, or use other products that are approved for organic production. This also means that they do not necessarily use less inputs, but that certain inputs are substituted for others. As the way in which this substitution of inputs influences production costs cannot be assessed in this study, the question whether the profitability of conventional or organic banana farmers is generally more affected by climate change will have to remain unanswered at this point.

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<sup>91</sup> Bellu et al. (2015) also show that a yield gap of 17 percent might apply to organic banana production.  
<sup>92</sup> In this respect, Evans and Gordon (2011) report more than 30 percent higher banana prices for organic bananas. In addition, Bellu et al. (2015) argue that organic banana producers usually profit from higher prices.

## 6.5 Selected environmental effects

Our analysis has concentrated so far on primary production and secondary economic impacts of climate change. In this section, some environmental effects shall be analyzed. More particularly, the issues of mitigating GHG emissions and protecting biodiversity while producing bananas under conditions of climate change shall be discussed.

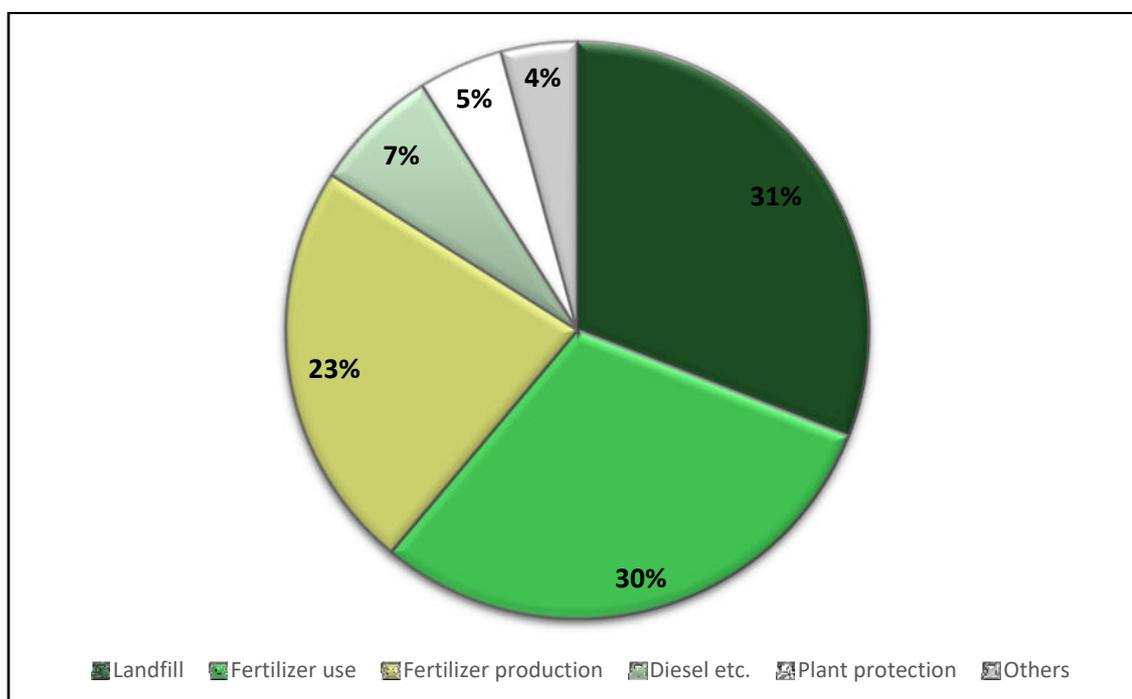
Banana production is and will continue to be affected by climate change. However, banana production – as any agricultural activity emitting GHGs – is also a contributor to climate change. Therefore, it is essential to look at mitigation potentials in banana production to combat climate change, thus, contributing to a future situation which will be closer to the RCP 2.6 scenario than the high emission RCP 8.5 or BAU scenario. This is especially important because banana demand is predicted to increase globally. Compared with 2010, a recent study predicts that food demand in Africa, Asia and LAC will increase substantially – growth rates of 60 to more than 200 percent are projected for these regions – while the demand in Europe and North America will remain more or less constant (Petsakos et al., 2019). The basic determinants behind this development are population and income growth. To meet this increasing demand, banana producers have two options: They can devote more land towards banana production and/or they may react by accomplishing more yield per unit of land due to intensification.

To better understand what can be done to limit GHG emissions under such circumstances, it is necessary to look at GHG releases from banana production and the entire banana value chain. Svanes and Aronsson (2013) and more recently FAO (2017a) provide respective background information. Accordingly, primary banana production accounts for “only” a sixth to a fifth of all GHG emissions that can be related to the entire banana value chain. Transport and storage of the fruits emit more as both activities account for two thirds of all banana GHG emissions. Therefore it is crucial to also look at the mitigation potential ex-farm. However, this analysis focusses on banana production at farm level and hence, identifying the major on-farm sources of GHG emissions from banana cultivation is necessary. In this respect FAO (2017a) lists the following major sources:

- Use of chemical fertilizers and plant protection products,
- Use of plastics,
- Machinery including fuels and lubricants, and
- Packaging.

According to FAO (2017a), inorganic fertilizers have the highest carbon footprint in banana production. However, Svanes and Aronsson (2013) add further important sources: organic manure and plant waste landfills. They use a slightly different list of major sources than FAO (2017a) and consider landfills to be most important as regards GHG emissions in primary banana production (see figure 6.13).

**Figure 6.13:** Shares of farm inputs and farm-based activities regarding greenhouse gas emissions of primary banana production



Source: Own figure based on Svanes and Aronsson (2013).

Consequently, options for reducing GHG emissions from banana production should target various sources (Svanes and Aronsson, 2013; FAO, 2017a):

- Plant waste landfill can substantially be decreased by biological treatment. More specifically, the generation of ethanol derived from banana agricultural waste has the potential to reduce GHG emissions (Guerreroa and Muñoz, 2018).
- Also better nutrient management in combination with precision agriculture, can substantially reduce GHG emissions through improved nitrogen application. Innovative nitrogen-inhibitors may further contribute to a controlled, i.e. more efficient, release of especially mineral fertilizer.
- Other options are intercropping (i.e. the planting of seasonal crops between banana rows to increase the soil fertility), cover cropping (i.e. the introduction of specific plants with different root systems, shade demands, etc.), crop rotation to improve soil fertility, proper weed management (e.g. mulching, mechanical weed management, biological control), water conservation to preserve moisture in the plantation (e.g. by building terraces), soil conservation through the application of, for instance, compost and organic manures, as well as planting of nitrogen-fixing plants.

Although FAO (2017a) as well as Svanes and Aronsson (2013) consider the GHG reduction potential of the listed measures as large<sup>93</sup>, their lists do not include two other major determinants: postharvest losses and land use changes. In fact, postharvest banana losses are considered remarkable (Mattsson et al., 2018) despite obvious challenges in the quantification of the actual loss (see, for instance, Porter et al., 2018). Each wasted banana would not have been needed to be produced and, hence, each unit of waste represents an opportunity to cut on-farm GHGs. This holds especially true if the demand is partially met by bananas that were produced on areas that had formerly been dedicated to other ecosystems.

Indeed, land-use changes induced by agricultural activities substantially contribute to global GHG emissions. Simply speaking: Converting a hectare of land from natural or nature-like habitats emits considerably more GHG emissions than the production of a crop on an already converted hectare. For banana production this can be set into perspective:

- Depending on the methodology and the crop growing system, FAO (2017a) estimates that primary banana production emits approximately 50 to 200 kg equivalents of carbon dioxide per kg of bananas. Assuming 40 tons per hectare (see, e.g., figure 4.1), this means to calculate with a net emission of 2 to 8 tons per hectare and year.
- However, in accordance with Searchinger et al. (2008), Marelli et al. (2011) and Tyner et al. (2010), carbon dioxide emission factors of converting land towards agricultural production in LAC are between 151 and 337 tons per hectare.

In other words: Using newly cultivated land for banana production has also the potential to release much more carbon dioxide equivalents than the production of the crop on an already used hectare. Averaging the numbers above would lead to a factor of almost 50. That means the land use conversion of one hectare has the potential to emit as much GHGs as 50 years of constant banana production per hectare in the LAC region.

Why is this so important to know? Petsakos et al. (2019) provide an answer. Accordingly, most of the future banana demand increase is projected to be met by bringing more area under cultivation. This subsequently increases the pressure on still natural or nature-like habitats. Converting such habitats, however, must be linked to extraordinarily large GHG emissions. To avoid this, all options must be used to sustainably intensify banana production where possible. Otherwise, the contribution of banana production in the LAC region to future GHG emissions will be even higher and the RCP 2.6 (RCP 8.5) scenario would become less (more) likely. This threat must be met.

Same applies to threats related to natural (and agricultural) biodiversity in LAC that can be linked to banana production and climate change. These risks are numerous. Among others, sedimentations of streams, extraction of firewood, hydrological changes, agrochemical runoff, logging, fire/burning, soil erosion, squatting and invasion of lands, as well as hunting are noteworthy (see, for instance,

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<sup>93</sup> The authors provide a qualitative assessment and do not provide precise numbers.

Harvey et al., 2004). The impact, however, is always site-specific and depends on particular ecological and biophysical conditions supported or hindered by social and economic behavior. A comprehensive assessment of the climate change-driven impact of altering banana production on biodiversity would, thus, also require regional and even local knowledge about yet given biodiversity and its determinants. Gathering this information is beyond the scope of this analysis. Nevertheless, some meaningful aspects can be added to our analysis.

Already now, some production systems have disproportionately affected biodiversity in the broader LAC region, and among these is banana production. In fact, banana production impacts biodiversity through improper intensification<sup>94</sup>, medium erosion rates, no fallow presence once a year, high contamination of water, low presence of tree cover or natural habitat within these, and a rather homogenous land use (Harvey et al. 2004). Consequently, negative biodiversity impacts can be reduced, for instance by establishing polycultures and retaining a higher degree of natural tree cover and natural habitats as well as applying integrated pest management and organic management practices (Harvey et al., 2004).

Moreover, banana production needs large areas of land and triggers the expansion of these (see, again, Harvey et al., 2004). As has been discussed with respect to GHG emissions: Even more land will most likely be used in the future for banana production to satisfy global demand. For LAC countries this could mean to increase banana area by 50 percent (Petsakos et al., 2019). This "external" pressure in combination with yield depressions and a decreasing suitability of the analyzed areas caused by climate change constitutes a major challenge. The following partial impacts must be highlighted and distinguished in this respect:

- If yield growth is limited due to climate change, the land requirement will further increase to cope with increasing banana demand.
- If suitability of area potentially shrinks in some regions, this will trigger movements or expansions to other areas, the suitability of which for banana production increases.
- If regional suitability of area remains unchanged, the ratio of land used for banana production vs. other land use in that region will also tend to increase due to improving comparative advantages.

The effect of the three determinants is the same: Land that is currently not used for banana production will probably be used to grow the crop in future. The subsequent environmental effects depend on the type of land use prior to the change (e.g. conversion to banana production). If the land was used for other agricultural activities, biodiversity might not be threatened or only to a

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<sup>94</sup> In particular, the intensive production of export banana is considered to have a rather high impact due to the frequently inappropriate application of plant protection and fertilizer.

limited extent. However, if the future banana land is for instance generated via deforestation or grassland conversion, regional/local biodiversity will most probably be negatively affected<sup>95</sup>.

Looking now at the results displayed in figure 6.3, we may conclude that the shift in land use will be more likely in regions where suitability of area does not shrink or even is increasing. Hence, El Oro, Magdalena and may be also Heredia might face an even greater challenge to preserve biodiversity than for instance Antioquia, Azua, La Guajira, and Valverde. But this conclusion shall not be overinterpreted since – from an economic point of view – banana producers in any region would try to benefit from future incentives that are created by an increased global banana demand<sup>96</sup>, and banana production may intra-regionally shift as well<sup>97</sup>.

To summarize: The consequences of climate change driven banana production developments tend to negatively affect biodiversity in all the selected regions and their banana producing areas. However, the impact shall be considered "only" an accentuation of the more substantial impact arising from global banana markets. The question, now, is: What can be done on-farm and along the banana value chain when the pressure on land increases?

In principle, the answer is comparable to what has been stated with respect to GHG emissions. To avoid a substantial biodiversity loss, all options must be used to sustainably intensify banana production where possible. This essentially helps to avoid land use changes and, hence, preserve as many natural and nature-like habitats as possible. And any banana that does not get lost on its way from the primary producer to the final consumer supports this process. In addition, the following options contributing to a partial avoidance of biodiversity losses shall at least be mentioned (see, e.g., FAO, 2003; Vargas, 2006):

- Biodiversity within banana cultivations can positively be influenced by proper crop management (e.g., an appropriate usage of plant protection products). In fact, an often humid tropical climate plus monoculture make banana plants susceptible to various pests and diseases, and applying the right plant protection product at the right amount and right time will lower run-offs that negatively affect the environment.

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<sup>95</sup> In this respect, Myers et al. (2000) argue that banana plantations that entail deforestation and intensive resource use threaten biodiversity hotspots which are important for wildlife conservation. It might also be interesting to note that banana monoculture of the Cavendish varieties that covers large areas that is sometimes termed "green desert" (Vargas, 2006).

<sup>96</sup> At this stage of the analysis, it would be worth to also look at other banana producing regions in the LAC region which may benefit from especially future temperature increases. Most probably, these will be areas located in regions which currently face temperatures just a few °C below the temperature optimum for banana production (25 °C) with plenty of water supply. To identify such regions, a closer look into figures 3.1 and 3.2 is recommended.

<sup>97</sup> Looking at figures 3.1 and 3.2, it might be that under future climate change conditions the conditions for banana production comparatively improve for instance eastbound of Urabà, in the northern part of Azua or the southern part of Heredia.

- Not only therefore, good agricultural practices which involve integrated pest management as well as conservation and reforestation practices must be implemented.
- One alternative land use option that is conducive to farmers' livelihoods, wildlife conservation and natural forest preservation is for instance agroforestry where banana and cocoa are intercropped with other fruits, tubers etc. Harvey et al. (2006) found that mammal and beetle species were richer in such a combined system than in banana monocultures.

Finally, the influence of biodiversity that surrounds banana plantations on banana production shall briefly be discussed. In this respect three aspects are worth mentioning:

- Castelan et al. (2018) argue that bananas growing close to natural forests perform better. In particular, plant health and fruit ripening as well as postharvest behavior are positively influenced among bananas growing near natural ecosystems. Neighboring natural biodiversity contributes to a higher green life and a more homogeneous profile during ripening.
- Sensorial and nutritional quality of bananas harvested near natural forests is also considered to be higher than those of bananas distantly harvested (Nascimento et al., 2019).
- More generally speaking, it can be stated that such natural ecosystems nearby agricultural landscapes such as banana plantations and fields are able to provide richer environments for growing crops by – among others – enhancing natural control of pests (Gardner et al., 2009) and diseases (Kageyama et al., 2002; Tomas et al., 2009; Claflin et al., 2017), nutrient cycling, erosion control, and carbon sequestration (Jarvis et al., 2007).

This can be an indicative evidence base for the necessity to conserve biodiversity near crop plantations to improve plant health and fruit quality. This would also help to limit the climate change-induced yield decreases discussed above.

It becomes obvious that many interactions must still be elaborated and scientifically penetrated to fully assess partly recursive biodiversity changes – and other environmental aspects which cannot be discussed in this study – that might or will occur because banana production is affected by climate change. In any case, future research should include one or more of these aspects as will be pointed out in the following and final chapter of this study.

## 7 Recommendations for private and public decision-making as well as policy advice

As has become evident throughout our analysis, climate change will strongly affect banana production in all LAC regions we have looked at. All regions will face further temperature increases and will especially encounter challenges due to an increasing climate variability in the future. Banana producers, however, will have no choice but to adapt to this new normal. Therefore, decision making by farmers or private entrepreneurs as well as by policy makers must prioritize adaptation to climate change, while also working towards the mitigation of GHG emissions from the sector. Based on our analysis above, we will now proceed to derive specific conclusions and recommendations for private decision-making (see sub-chapter 7.2) as well as policy decision-making (see sub-chapter 7.3). First, however, some of the limitations of our approach must be mentioned in order to put these conclusions and recommendations into perspective. This is important as certain issues and factors have been left out in our analysis and as pending future knowledge generation might alter the suggestions based on these research findings at least to some degree. These limitations (see sub-chapter 7.1) will, thus, also directly point at further research requirements and shall, hence, be considered an essential part of the overall recommendations.

### 7.1 Further research needs based on the scope and limitations of this study

To better understand and frame the study and its results, we would like to reiterate some important aspects regarding the study's scope and limitations and provide additional points for consideration. All of them lead to concrete research needs to improve the holistic assessment of climate change impacts on banana production. The following topics are most important from our perspective:

- There are different approaches to select climate models: The main concepts are either to select the climate model which best reproduces past weather data or to select the model which best integrates and covers atmospheric and climatological processes. We chose the latter approach and hence our selection of the CORDEX CORE ensemble is based on the processes resolved in the models. More particularly, we use RCM simulations as the embedded high-resolution covers regional heterogeneity better than GCMs. However, it is important to mention that both GCMs and RCMs do have their advantages and disadvantages and, first of all, include a high degree of uncertainty as they often do not agree neither in the trend nor in the projected change. Thus, using multiple models or even the entire ensemble of climate models (both from RCMs and GCMs) is useful to show the full picture of potential climate futures. The bigger picture may, thus, act to reduce climate change uncertainty. Therefore, future studies should ideally use different model ensembles for their analyses to enable a comparison and discussion of the different resulting climate futures and their results for banana production.

- The approach to calculate a climate–yield coefficient is just one amongst various methods to analyze the climate impacts on banana yields. Yet given the regional data availability and knowledge as regards climate change impacts on banana production, this method provides a robust and efficient approach to analyze climate change–induced yield effects in the context of this study. Once more data and better information become available other methods such as the various crop models described e.g. in Müller et al. (2019) should additionally be used.
- We calculated the climate–yield coefficient with average annual temperature and yearly precipitation as endogenous variables for our model. To compare these observed or projected variables with the optimal climate for banana production, we used a specific optimum, minimum and maximum value to define a range of annual temperature and yearly precipitation conducive for banana growth. Hence, the results of our analysis can be considered bi–factorial and are within a well–defined range. As the optimal growing conditions for bananas may differ between specific banana producing regions and management regimes, further regional analyses looking into specific ecological niches for banana production might provide additional insights. The same applies to the integration of other climate variables, the impacts of which on banana production must be quantified. This also includes putting more emphasis on the seasonality of climate, sea level rise and ENSO phenomena than was possible in this study. For instance, Li et al. (2013) show that ENSO activities presently tend to show more anomalies than in the past. If this trend continues, it may substantiate our findings especially with respect to the frequency and severity of climate change induced–extreme events.
- Yield is multi–factorial and, hence, also depends on many factors other than climate variables. This mainly concerns other natural conditions (e.g. soil) as well as “human–made” factors such as crop management, technology development and politics. Given the scope of this study we cannot fully disentangle these other yield–influencing factors and their interrelations. An integration of such factors and their interlinkages, however, would add value to the analysis and should therefore be envisaged by further research, especially since other factors are also affected and driven by climate change (e.g. management options and politics)<sup>98</sup>.
- Probability considerations with respect to tipping points were not included in our analysis. If such tipping points were reached due to climate change, they would cause an irreversible change in terrestrial systems which would then lead to a new state of equilibrium. Such an event would certainly have tremendous consequences. Enlarging uncertainty analyses to take account of potential tipping points is a specific but important requirement for further research on the topic.

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<sup>98</sup> New or emerging plant diseases and pests, for instance, can develop more resistances to plant protection products or start to affect (formerly) resistant crop varieties. Once such resistances are established, the forms of plant protection currently used will not be effective anymore. This could further decrease yields but may also lead to new innovative approaches of disease management.

- The results of our study should be interpreted within the particular context of the LAC region. Rather similar temperature increases are projected for the entire region, but precipitation projections are highly heterogeneous. In other words: Water availability considerations must be elaborated. In our study, water availability was discussed in the context of precipitation and PET. Given the great impact of water availability on banana yields and the delay factor of noticeable impacts, it is crucial for further investigations to look at irrigation and water availability in a broader interregional context. For instance, expanding irrigation schemes might stabilize yields despite lower precipitation, but might deplete the water supply in the long run. In this respect, it is also worth considering regional hydrological conditions. A banana producing region might benefit (suffer) from a positively (negatively) affected groundwater situation, which is also influenced by precipitation in other regions than the one investigated. Rivers, or more generally speaking watersheds, can transport water over long distances. It is therefore of utmost importance to also look beyond political or administrative boundaries of a banana producing region as the topographic maps provided in annex L suggest. In fact, water supply in a particular banana production region is also influenced by greater aquifers and the overall (multi-regional or even multi-national) water shed management. Hence, it is not only controlled by local banana producers, and other means of sustainable integrated water management must be considered.
- Our study focuses on the climate change impacts in banana production and on the rather narrow banana sector. We did not include impacts on other sectors, such as the labor and human health sector. Also, several environmental aspects are not included in our analysis as this is (far) beyond the study's scope. However, considering the repercussion of other sectors and of various natural conditions on banana production is expected to have a large impact and an analysis of these impacts on the banana sector should therefore also be envisaged by further research.
- Finally, adaptation efforts within the banana sector are not included in our study. Including these is likely to alleviate the adverse climate change effects on banana production. As adaptation could be a real game-changer, this should also be considered in further science-based assessments.

However, climate change impacts on banana production are robustly covered in this study and (having in mind the described scope and limitations) the results allow to draw conclusions for appropriate decision-making for private businesses and policy makers.

## 7.2 Conclusions for private businesses

Banana farmers' livelihoods are impacted by climate change. On-farm adaptation measures must cope with changes in temperatures, water availability, winds, and a higher frequency and severity of extreme weather events. Before providing reasons and detailed measures for climate-smart

banana production in this respect, it is important to state that gaining site-specific knowledge on the changes and options for action it is a prerequisite for changing or adopting management processes. Therefore, farmers and other stakeholders along the banana value chain should be able to improve their knowledge regarding climate change and other challenges ahead. This process must be sustained by policy makers (see next section). In the following we provide some more detailed conclusions for private businesses.

A first important issue is integrated water resource management. According to Magrin et al. (2014), it is the key for a sustainable and climate-smart banana production, as bananas need constant water supply to produce high yields and good qualities. In this context, several aspects must be considered a necessity for adaptation:

- **Climate-smart professional practices:** Practices to address the delay of a start in the rainy season include many of the common management routines in rainfed banana production<sup>99</sup>. One such practice is irrigation, which can be used to directly address the water deficit until the rainy season starts. Practices to reduce water deficits should also include application of organic matter and diversification of banana varieties. Specific foliar sprays that act as anti-transpirants might also help to reduce evapotranspiration and, thus, water loss from the plant. At the same time, other management practices should be (temporarily) suspended during prolonged dry seasons, for instance de-leafing, de-suckering and weeding.
- **Climate-smart irrigation:** To avoid an overuse of water resources, what would ultimately deteriorate banana production for all producers, the use of well-timed and water-efficient irrigation methods is crucial. Rainwater harvesting or drip irrigation are such methods, which can be implemented to prevent plant injury due to water shortages or droughts<sup>100</sup>. Besides, different more advanced irrigation systems such as micro-sprinkling and micro-aspersion could be implemented (see Adaptation Partnership, 2012) when finance options are available.
- **Recovery after water stress events:** In the aftermath of water stress or droughts, some practices might help to accelerate recovery when the rains return. These include the stimulation of growth through fertilization, de-suckering and weeding, which are often suspended during prolonged dry seasons. In addition, replanting in case the effects have been severe can sometimes be unavoidable.
- **Soil moisture management:** Mulching should also be considered a valuable management option to be practiced to reduce evaporation of water from the soil as well as to control weeds, reduce the displacement of topsoil by running water, reduce the compaction of soil particles, and nourish the soil with green manure. Common mulch options include the use of dried

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<sup>99</sup> Among others, Magrin et al. (2014) and Rodriguez Valencia et al. (2019) argue that traditional indigenous knowledge systems and practices about specific banana cultivars, their agro-ecological niches and pathogens should be used and strengthened as well.

<sup>100</sup> When used in combination with weather forecast information and advice on crop water demand, the water supply can be much better matched to the actual needs of the plant (Reay, 2019).

weeds, grass, and other crop or banana plant residues such as banana peelings, pseudo-stems and pruned dry or fresh leaves<sup>101</sup>. As banana plants have shallow roots, mulching their soils with clippings or planting low-growing cover crops can also provide a shaded understory that helps to maintain soil moisture even when temperatures soar<sup>102, 103</sup>. The maintenance of an optimum number of leaves at flowering can also help to cope with limited water supply, as water loss through transpiration can be reduced and cut leaves can be used for mulching to cover the soil surface (see also Ravi and Vaganan, 2016).

- Improved water and nutrient efficiency: In addition, practices to build root health can be beneficial to improve the efficient use of available nutrients and water (FAO, 2016).

In this "water" context it is also important to reiterate that extreme events related to an excess or deficit of rains will probably happen more frequently than other events such as winds and critical temperatures (see, e.g., sub-chapter 4.2). Along with irrigation, other options to cope with these events are building dikes to block flood waters, improving the soil organic matter<sup>104</sup>, and improving the drainage of the soils<sup>105</sup>. However, practices to directly cope with the excess or lack of rains require proper planning and investment in drainage canals, within-field levelling or an irrigation infrastructure, while indirect practices to mitigate the effects are shorter term and are often already integrated into current management routines. One example are ropes that stabilize the plant and reduce the risk of plant damage. Noteworthy is also, that the plants' recovery after extreme events can and should be helped by cleaning up fallen plants, selecting replacement suckers and replanting. Also moving from monocropping to a more diverse cropping system or agroforestry system can reduce the impacts of extreme events as different crops and varieties are differently affected. For example, traditional cropping systems often combine bananas and coffee plants.

Canals built around the banana plants (so called drainage channels) also might help to combat flooding and avoid standing water<sup>106</sup>. This infrastructure could also help in times of water stress. To cope with droughts during the main rainy season, banana growers generally should resort to supplementary irrigation<sup>107</sup> if possible. Supplementary irrigation is particularly vital during floral primordial initiation and development, flowering, and a month post flowering to ensure successful

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<sup>101</sup> These specific options are also named by Nansamba et al. (2020) as a suitable cultural practice to be employed by banana growers for the management of drought stress.

<sup>102</sup> Such mulching and use of cover crops have the added benefits of suppressing weeds, reducing soil erosion, and cutting run-off of pesticides and herbicides during times of very heavy rainfall (Reay, 2019).

<sup>103</sup> Cover crops, such as chickpeas, can be used as "living mulch". Such crops have the capacity to bind atmospheric nitrogen in the soil and protect the soil as ground cover (Nansamba et al., 2020).

<sup>104</sup> Healthier root systems and a soil mulch layer reduce the impact of rainfall variability without increasing the entry of water into the field (Calberto et al., 2018).

<sup>105</sup> This technique particularly evacuates water more quickly rather than blocking the entry of water into the field (Calberto et al., 2018).

<sup>106</sup> They are promoted as an adaptation technique also by the Adaptation Partnership (2012), for instance.

<sup>107</sup> In case of such an event, they should also reduce the application of plant protection products (FAO, 2016).

bunch emergence and fruit filling (see also Ravi and Vaganan, 2016). Apart from that, in many environments supplementary irrigation can also be made more effective if the water is systematically applied before planting<sup>108</sup>.

For banana production, high temperature events are more problematic than low temperature events. Consequently, a preventive measure is the use of banana varieties that can cope with higher temperatures (see also FAO, 2016)<sup>109</sup>. However, such regionally adaptable varieties must be identified or developed first. Another option that might be more quickly to implement and more effective given the heterogenous growing conditions, is to adapt certain key production processes and technologies to the changing weather conditions. This includes the points mentioned above as well as different pre-harvest and post-harvest processes such as using different types of bags for protecting the banana bunch. These processes can also be adapted to changing temperatures, changing ultra-violet radiations, etc.<sup>110</sup>.

Wind-related extreme events are also a big issue for banana production (see sub-chapter 4.2). Practices to prevent the effects of high winds require good planning and sound investments in, for instance, windbreaks. In addition, more indirect practices to reduce the effects of strong winds can be implemented, if they are not already integrated into the "normal" management routine<sup>111</sup>. To cope with high gusts of wind, banana trees can be tied through string reinforcements to prevent the plants from toppling over<sup>112</sup>. In this respect it is also noteworthy that banana plants grow from a large rhizome, so even if a storm damages their leaves and stems, they can often regenerate if given the chance. Where wind damage destroys large numbers of plants, as can happen with hurricanes, having robust systems for recovery in place – like rapid infrastructure repair, disease-free rhizomes, and equipment re-supply – can help limit the overall economic impacts<sup>113</sup>.

In the region, climatic variability caused by ENSO must be considered. Mainly – but not only – in Ecuador, losses to the banana sector from an extreme ENSO event are most likely to be the result of severe rainfalls. This argues for putting increased attention on providing flood, drainage and emergency systems for a wider range of adverse rainfall outcomes (FAO, 2016). An effective adaptation measure to increased flood risks would also be to shift banana production to higher altitudes in case of necessity and whenever possible. Adaptation measures to cope with heavy rains during the rainy season also include an increased application of plant protection products for the control

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<sup>108</sup> Pre-planting irrigation allows the crop to have a sufficient water supply early in the season, thereby ensuring its proper establishment and growth despite unexpected rainfall variations (Nansamba et al., 2020).

<sup>109</sup> Vanhove et al. (2012) explicitly suggest adopting drought-tolerant banana varieties.

<sup>110</sup> In Ecuador, for instance, some banana growers already use different types of bags with fewer perforations during periods with cooler weather and depending on the season (FAO, 2016).

<sup>111</sup> In accordance with Calberto et al. (2018), recovery after wind events can particularly be addressed by cleaning up fallen plants, selecting replacement suckers and proper replanting.

<sup>112</sup> This is already being done in various banana plantations (Adaptation Partnership, 2012).

<sup>113</sup> Reay (2019) argues that this should be envisaged as a very important option to get production up and running quickly.

of pests and diseases like Black Sigatoka, and particularly the appropriate use of systemic fungicides and herbicides<sup>114</sup>, as well as a reduced fertilization<sup>115</sup>.

### 7.3 Request for targeted policy making

It is the task of agricultural, economic, climate, and research policy to set the proper framework conditions so that farmers' livelihoods are sustained under climate change and in the face of other changes in the future. Sound policy making can enable and foster a transition towards, or a continuation of climate-smart banana production. Before focusing on important specific policy aspects with respect to banana production it is therefore crucial for policy makers to continue their active participation in international negotiations and fora to combat climate change and also to implement the corresponding policies in their home countries. The importance of these actions cannot be highlighted enough. Halting or significantly slowing down climate change would ultimately reduce the need for adaptation. In this respect, the following specific policy aspects are most important from our point of view and should therefore be considered:

- On a national and regional level, farmers and other stakeholders along the value chain should have easy and low-cost access to education, training, and information regarding sustainable and climate-smart banana production. Therefore, educational programs and extension services should be supported and made available at low costs. These programs should also provide and discuss specific options for action, e.g. measures to be implemented in case of the occurrence of extreme weather events (Shannon and Motha, 2015).
- Targeted education and training programs should also promote the diversification of incomes (e.g. through off-farm work) and reduce the existing regional dependencies on banana production. For example, the programs could promote the use of intercropping and agroforestry systems or support the cultivation of other crops than bananas in areas where the suitability for banana production is decreasing due to climate change. Of course, this will again need to be supported by corresponding awareness-raising efforts and by the provision of information and training. Political decision-making should therefore more frequently consider and promote agricultural diversification in areas where banana production is especially threatened by climate change, as this will be vital for the farmers' livelihoods and development in the future.
- Infrastructure should also be enhanced and developed in such a manner that it improves access to markets, inputs and technologies while reducing post-harvest losses. In this respect,

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<sup>114</sup> Fungicides and herbicides applications on bananas plants and the surrounding soil will eliminate pests while not harming the beneficial underbrush that can prevent erosion, can, in fact, be a good adaptation strategy to climate change if done appropriately (Adaptation Partnership, 2012).

<sup>115</sup> To cope with heavy rains during the late dry season, improving the maintenance of drainage canals is considered a must as well (FAO, 2016).

access to finance (e.g. via micro credits, cooperative financing, subsidies) is vital to ensure that farmers still have the opportunity to adapt, even when financial investments are needed. The provision of insurances to cover harvest losses caused by extreme weather events could also become more important in this regard.

- Regional and global collaboration are very important to exchange best-practices and learnings between the different banana growing regions. The existing fora and platforms should therefore be strengthened and if needed their scope should periodically be adjusted to include new topics and adequately address the various challenges lying ahead. In the context of our study the sharing of information and knowledge across the LAC region is especially important and should be significantly facilitated<sup>116, 117</sup>. Some topical ideas for closer collaboration could be the comparison of yield and quality differences in banana production and the investigation of reasons for these differences, or the improvement and/or establishment of short-term and seasonal weather forecasts as well as early warning systems for extreme events<sup>118</sup>. The dissemination of climate information to banana growers could be an additional important outcome of such a collaboration and would also be relevant to other crops and sectors.
- The installment or improvement of reliable weather stations and early warning systems for extreme weather events, shifts in dry and rainy seasons as well as disease detection (Magrin et al., 2014) should be a politically supported investment as well. Warning systems for the control of important banana diseases (e.g. Black Sigatoka and the Panama disease) should aim at optimizing the control of these diseases, which in many regions are expected to occur more often because of climate change<sup>119</sup>.

Research is a policy topic of its own when it comes to managing climate change. With respect to banana production, the following research policy topics are suggested (see also sub-chapter 7.1):

- Research is vital to develop and test the necessary management practices for farmers to cope with climate change impacts. Such research should therefore be of high priority in banana-

<sup>116</sup> Promoting the sharing and exchange of experiences and lessons learned on cross-sector topics like water management and the use of climate and weather information is also considered to be essential by Adaptation Partnership (2012).

<sup>117</sup> Reay (2019) argues that improved knowledge and in addition to that more access to training, sharing of good practices, and increased research are central to climate change adaptation in the banana industry.

<sup>118</sup> For the powerful storms and hurricanes, for instance, that threaten the Caribbean, i.e. the Dominican Republic, each year early warning systems and recovery plans may help save bananas as well as many lives (Reay, 2019).

<sup>119</sup> The aim of these systems should also be to minimize fungicide applications resulting in a lower cost of control, lower risk of fungicide resistance and lower negative environmental impact. An exemplary disease control system requires the early detection of a disease, fast aerial spraying, strong curative effects through the use of systemic fungicides, fungicide resistance management, and, in addition, the centralization of control over the whole banana producing areas, as well as a shortening of decision-making and implementing of fungicide applications to be a successful strategy (Guillermet et al., 2014).

related scientific and development activities taking place in banana producing regions<sup>120</sup>. More particularly, research should for instance include approaches to build the social capital necessary to identify and safeguard viable adaptation practices at the regional scale. It should also focus on the development and improvement of integrated water and resource management, on building and improving the buffering capacities in watershed management, and on the development and improvement of resilient cropping systems. The development of scenarios for an efficient and low-cost recovery of banana production after extreme events is also an important point here.

- A specific focus of research (policy) should be on plant breeding, so that banana varieties that are (more) resistant and tolerant to biotic and abiotic stress factors can be detected and/or (further) developed (Lane and Jarvis, 2007). As mentioned before, bananas are very sensitive to water stress, which may cause severe yield reductions. Therefore, banana varieties able to produce reasonable yields in a more water-efficient way offer a very promising adaptation method to reduced water availability in the future<sup>121, 122</sup>. Thereby, it must be highlighted that drought tolerance in plants is a complex trait, the expression of which is controlled by many genes, and which environmentally varies over location and time. This complicates the development of a standard gene pool for drought resistance. The banana gene pool is very diverse and, hence, presents a great opportunity for the enhancement of complex quantitative traits<sup>123</sup>. Besides, tolerance to higher temperatures and to temperature extremes is a crucial trait for new banana varieties. Despite the large gene pool, most banana plantations destined for export only plant clones of the Cavendish type and, hence, have no genetic diversity. This is different in home-gardens and other farming sites managed by smallholder farmers, which could be a good starting point to explore local landrace diversity and wild relatives for breeding programs. Recent technological developments such as high-throughput precision phenotyping and marker-assisted selection should also be exploited to speed up the improvement of banana varieties as they permit a thorough and precise selection of suitable candidates<sup>124, 125, 126</sup>. Apart from breeding for higher tolerance towards abiotic stresses, the

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<sup>120</sup> Putting the respective programs of adaptation to climate change high on the agenda is also requested by Calberto et al. (2018).

<sup>121</sup> Breeders and growers of banana are therefore asked to more often apply clonal selection to identify plant types suited to the particular conditions of the area in which they are producing (FAO, 2016).

<sup>122</sup> In fact, with disease resistance being an urgent focus of most banana-breeding programs around the world, research on more drought-tolerant plants has so far been limited. Some varieties do show more drought-tolerant traits though and for those farmers facing the biggest drought risks or having the least ability to adapt through irrigation, development and supply of such new varieties could be vital (Reay, 2019).

<sup>123</sup> This includes drought tolerance (Nansamba et al., 2020).

<sup>124</sup> Moreover, genome editing using the CRISPR/Cas9 technology, a type of genetic engineering, can be used to insert drought tolerance genes in the banana genome and silence or knock out genes associated with drought susceptibility (Nansamba et al., 2020).

<sup>125</sup> However, these need to be coupled with tolerance to abiotic stresses (Tripathi et al., 2019).

<sup>126</sup> For the banana sector to benefit from climate change and/or overcome negative impacts due to climate change, cultivars should also be bred with resistance to diseases and tolerance to temperature

development of varieties that are resistant to pests and diseases is essential. The high susceptibility of the Gros Michel variety to the Panama disease in the 1950s is a striking example of what can happen to global banana production if a variety's resistance is suddenly bypassed by pathogens.

- Generally, the data availability for banana research needs to be considerably improved. For example, it is currently challenging to specify the real and potential frequencies and intensities of different weather events affecting banana production in the LAC region. A first step to improve the data basis is the installation of weather stations and a better monitoring of daily and hourly data in the evaluation of plant responses to these weather events<sup>127</sup>. Among others, this requires the combination of and collaboration between plant and climate science and would most probably lead to results with site-specific practical applicability (Calberto et al., 2018).
- Further research efforts must also be made to explore the effect of abiotic stresses<sup>128</sup> and of possible adaptation options on banana production. For example, water-efficient irrigation can be further explored to develop irrigation methods that are effective and cost-efficient. In this regard, disciplines such as agricultural economics can carry out cost-benefit analyses of adoption measures and of practices that have proved to be climate-smart according to applied research. In doing so, it is important to not only include the aspect of water quantity into the analysis, but to also consider water quality and to explore the option of using wastewater for irrigation. Also, the effect of irrigation or fertigation on banana production should be further explored.
- Research can also help to improve and adapt land use policies so that these can better facilitate climate change adaptation (Adaptation Partnership, 2012).
- International and regional water shed management is crucial to not overuse certain water sheds and to quickly react when there is a risk of overuse. Globally and in the LAC region, there are unfortunately negative examples of resource degradation due to overuse of water.
- The policy makers of banana importing countries should also be mentioned here as they could e.g. establish policies to promote consumer acceptance of other banana varieties (apart from the Cavendish banana), reduce food loss, etc. These policies would also impact banana

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fluctuations and extremes and drought and have greater productivity under conditions of more variable water supply (Ramirez et al., 2011).

<sup>127</sup> In this respect, the proliferation of lower cost devices to measure weather and the abiotic status of crops and their environment is considered a useful step to better identify the key variables in banana crop performance facing climate change (Calberto et al., 2018).

<sup>128</sup> Among the abiotic stresses, drought, salinity, and heat are the most important issues to be analyzed (Ravi and Vaganan, 2016).

production in the LAC region (and globally) so that producers could for example switch towards planting other, more water-use-efficient and disease resistant varieties.

- Finally, a regional or global framework in research should be fostered with the aim to facilitate mutual exchange as well as a common data collection and analysis thereof. This would again help to develop and improve banana management practices, e.g. in response to specific extreme events, and could in fact provide a useful and practical return to research investments.

The present study can be seen a first and limited attempt towards the establishment of such a regional and global research framework on climate change and banana production. As should have become clear from our conclusions, climate change and banana production are both very complex topics and areas of research, where many factors are involved and interlinked. Improving the knowledge base to better understand these factors and interlinkages should increase the ability of banana farmers to better cope with the future climatic conditions be it on the farm and market level, on the regional and national level, on the administrative and political level, or on the level of research and development assistance. The challenges ahead are numerous and will require cooperation and collaboration between all stakeholders involved and at all levels to ensure banana production can continue to thrive also in the future.

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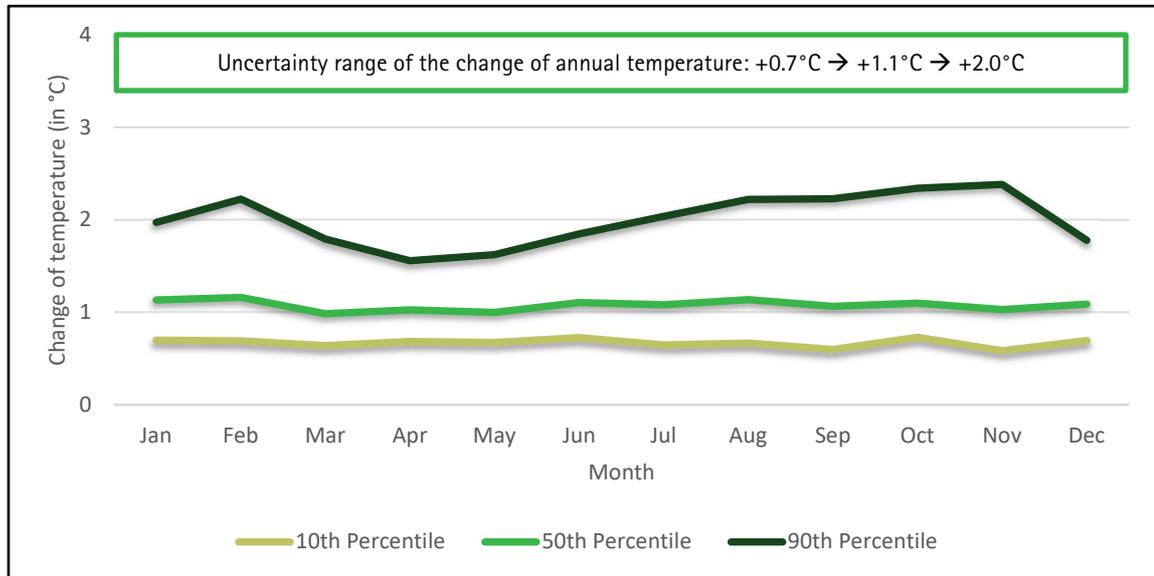
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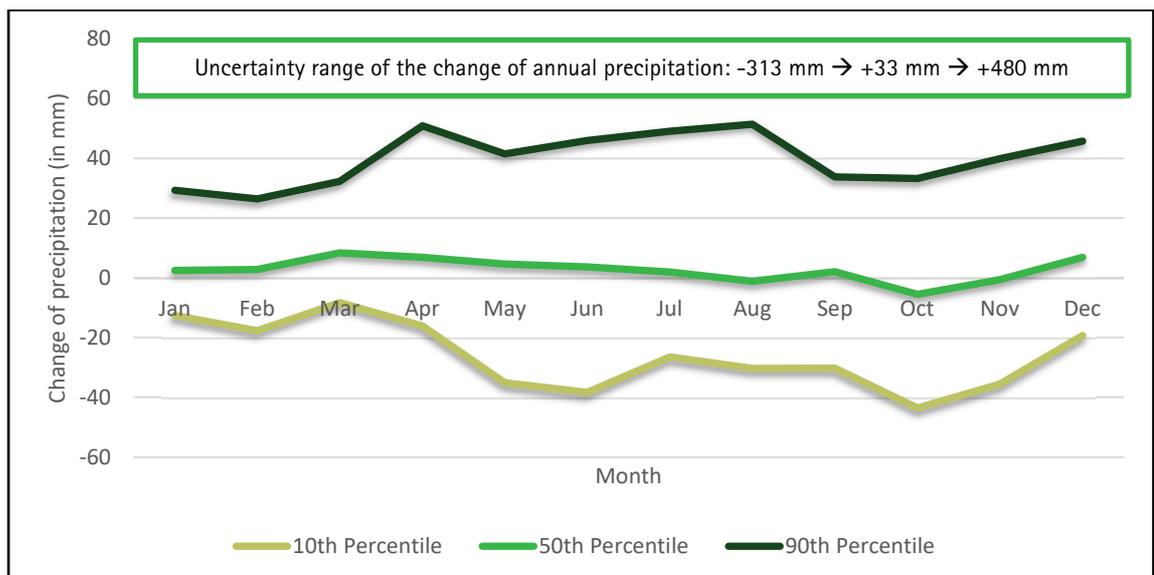
## Annex A: Uncertainty of climate change: Colombia

**Figure A.1:** Change of average temperature of Colombia for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



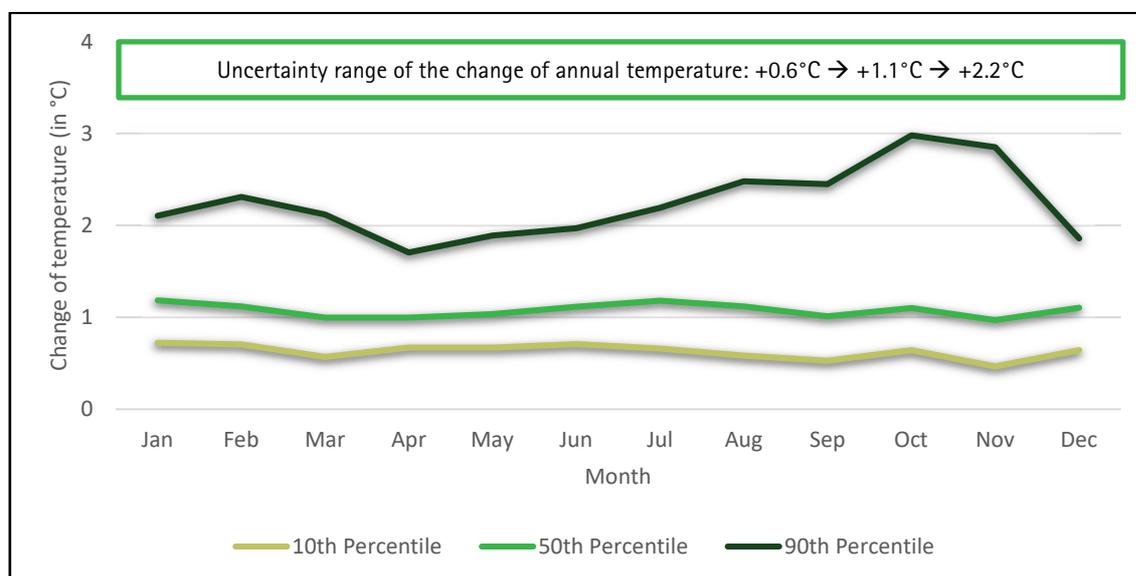
Source: Own figure based on The World Bank Group (2020b).

**Figure A.2:** Change of average precipitation of Colombia for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



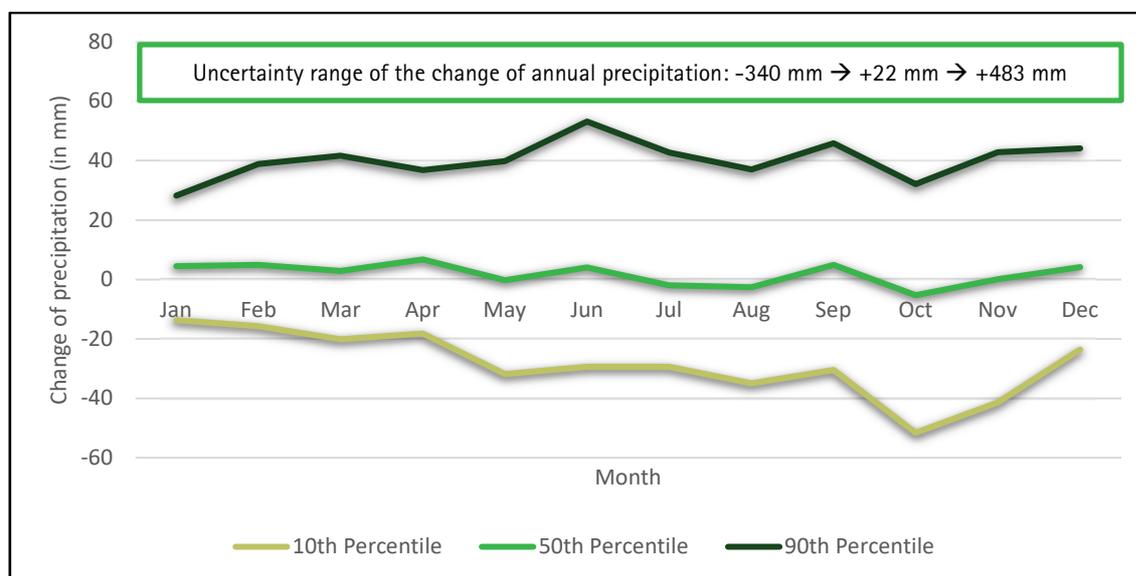
Source: Own figure based on The World Bank Group (2020b).

**Figure A.3:** Change of average temperature of Colombia for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



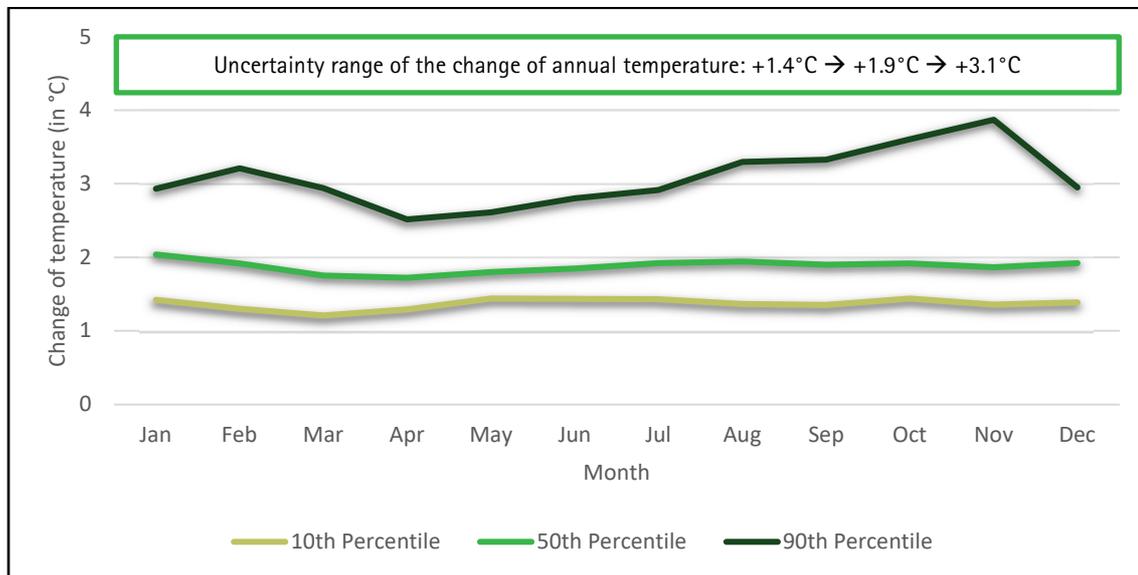
Source: Own figure based on The World Bank Group (2020b).

**Figure A.4:** Change of average precipitation of Colombia for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



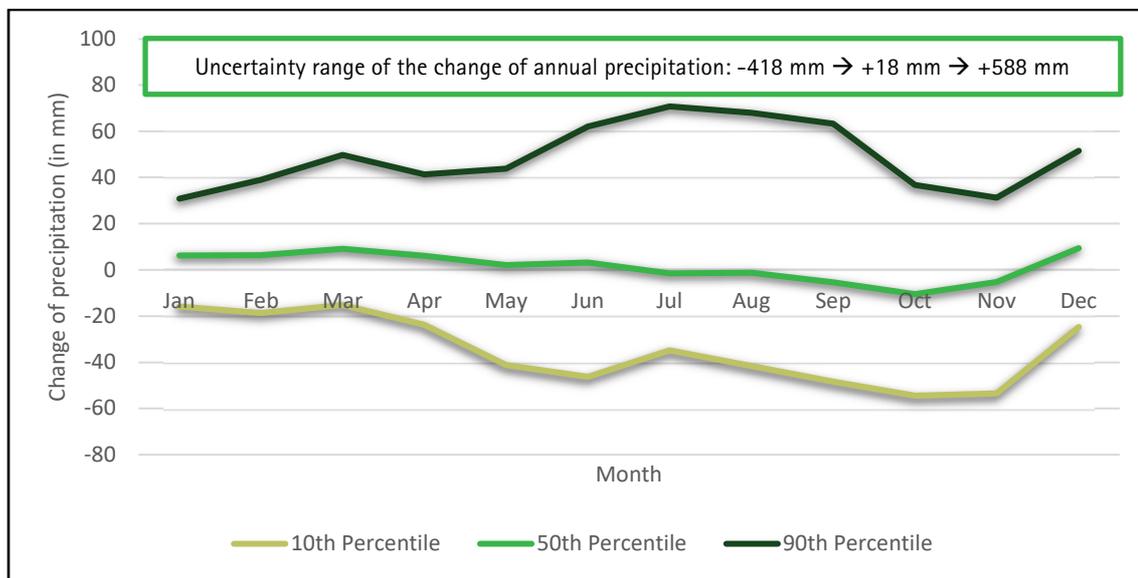
Source: Own figure based on The World Bank Group (2020b).

**Figure A.5:** Change of average temperature of Colombia for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



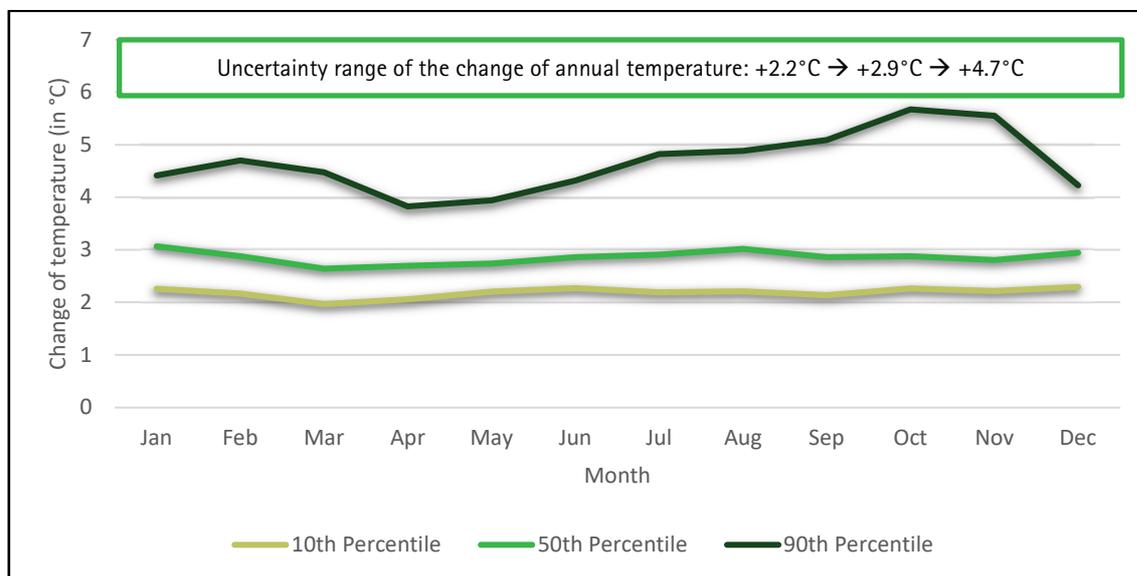
Source: Own figure based on The World Bank Group (2020b).

**Figure A.6:** Change of average precipitation of Colombia for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



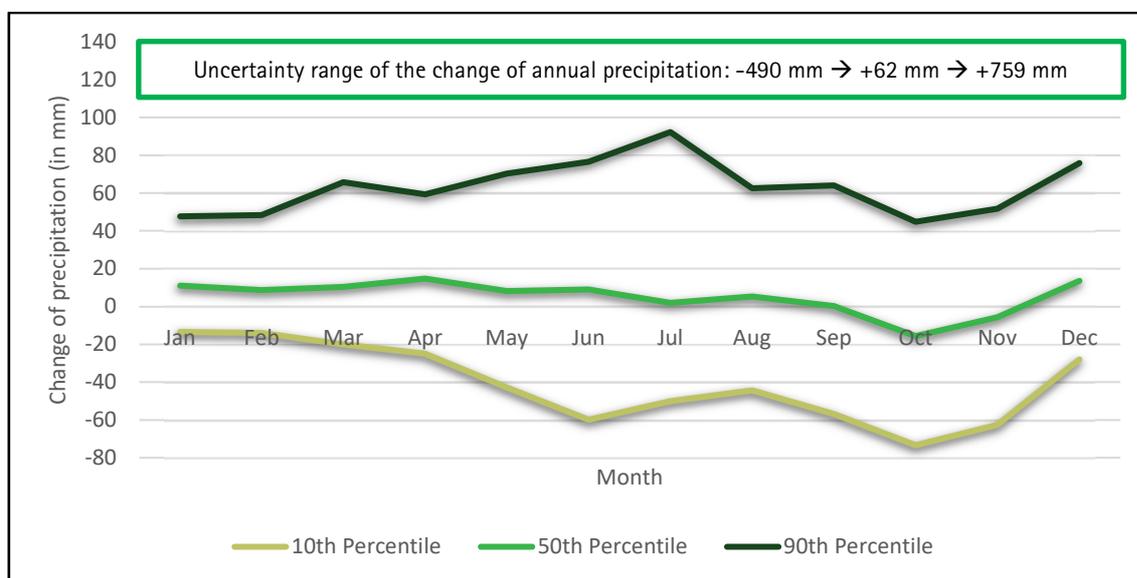
Source: Own figure based on The World Bank Group (2020b).

**Figure A.7:** Change of average temperature of Colombia for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

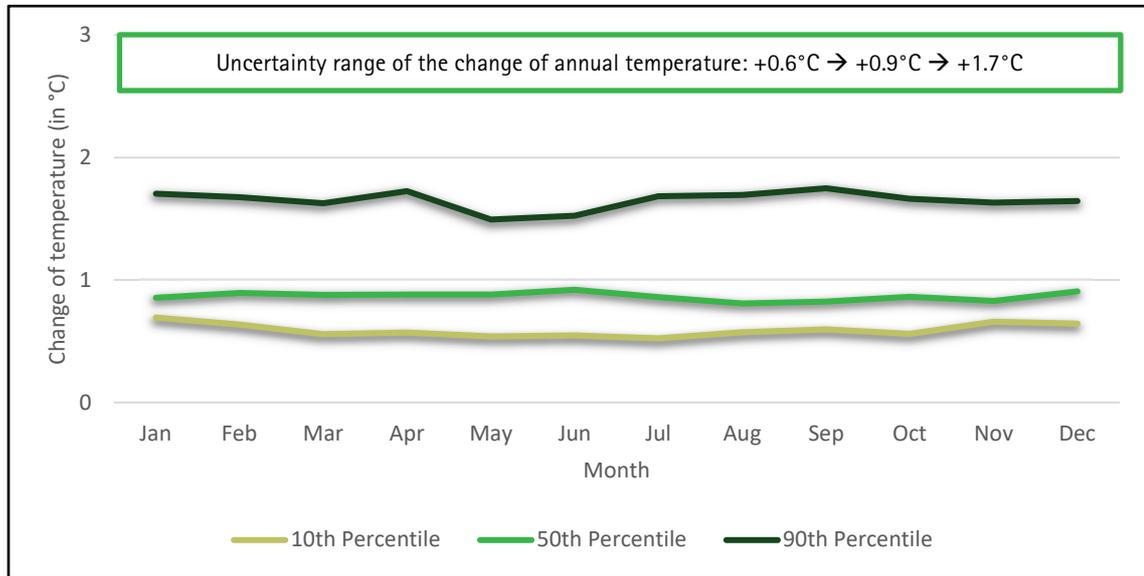
**Figure A.8:** Change of average precipitation of Colombia for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

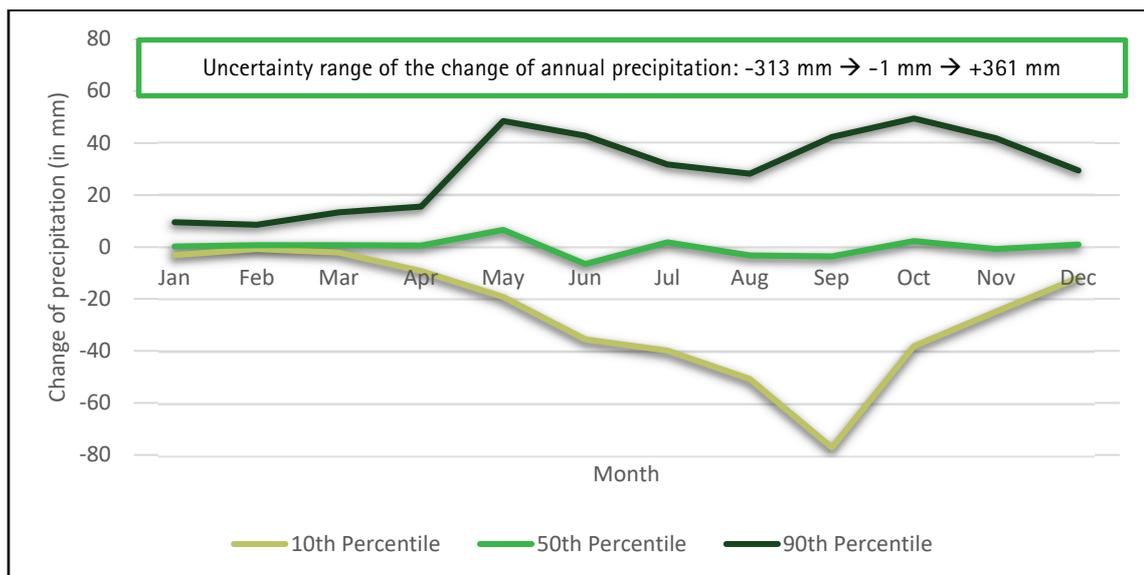
## Annex B: Uncertainty of climate change: Costa Rica

**Figure B.1:** Change of average temperature of Costa Rica for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



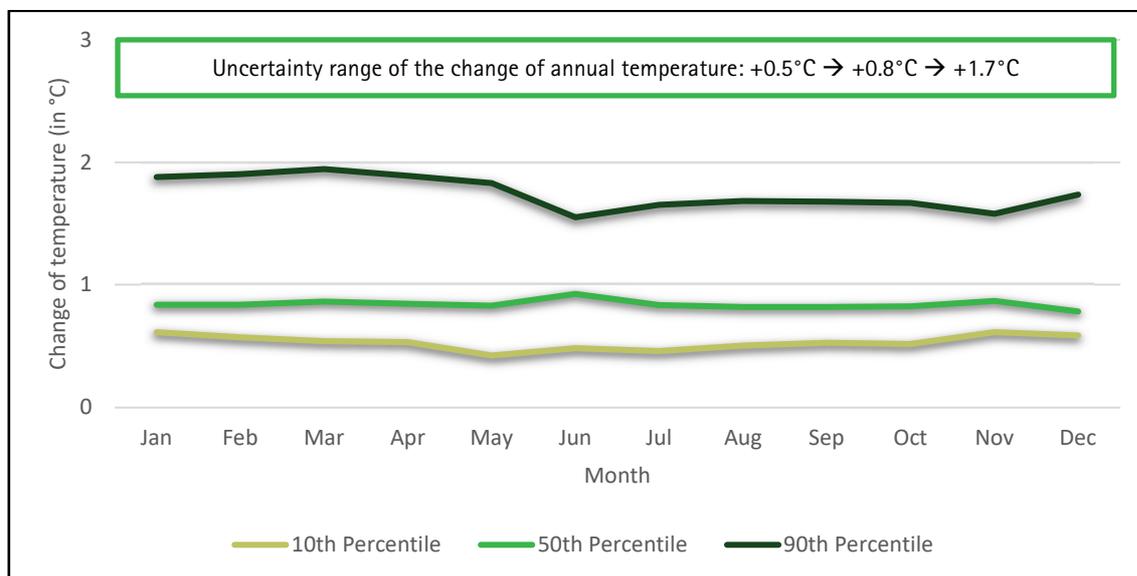
Source: Own figure based on The World Bank Group (2020b).

**Figure B.2:** Change of average precipitation of Costa Rica for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



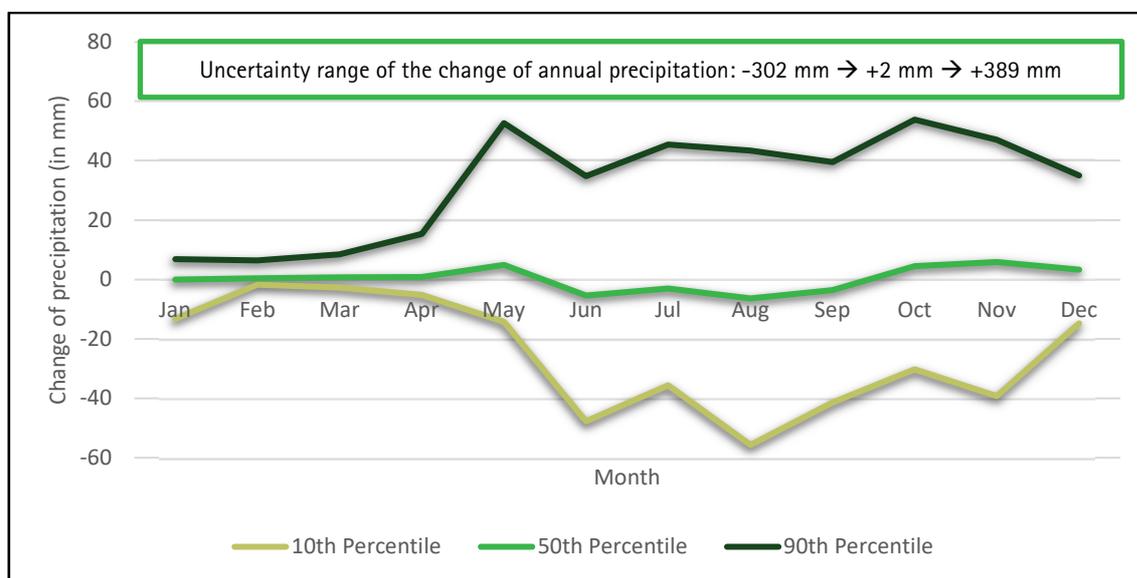
Source: Own figure based on The World Bank Group (2020b).

**Figure B.3:** Change of average temperature of Costa Rica for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



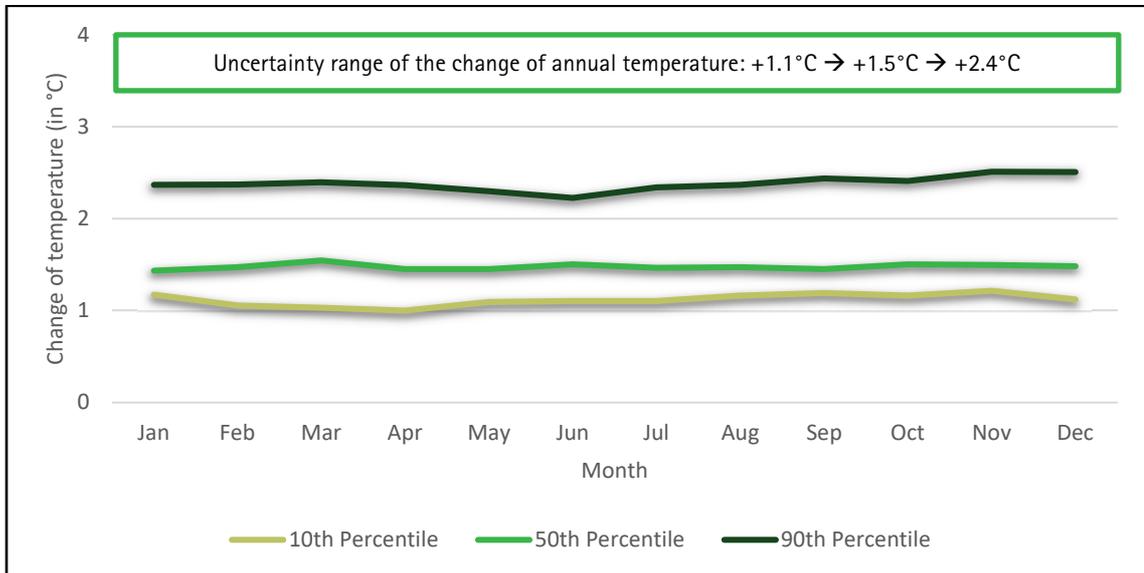
Source: Own figure based on The World Bank Group (2020b).

**Figure B.4:** Change of average precipitation of Costa Rica for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



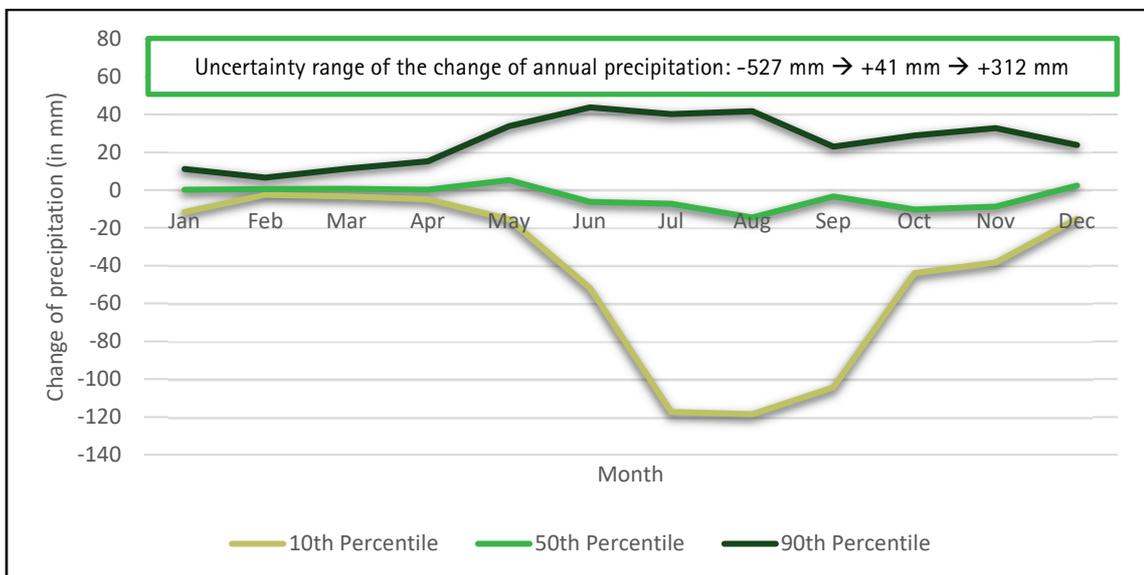
Source: Own figure based on The World Bank Group (2020b).

**Figure B.5:** Change of average temperature of Costa Rica for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



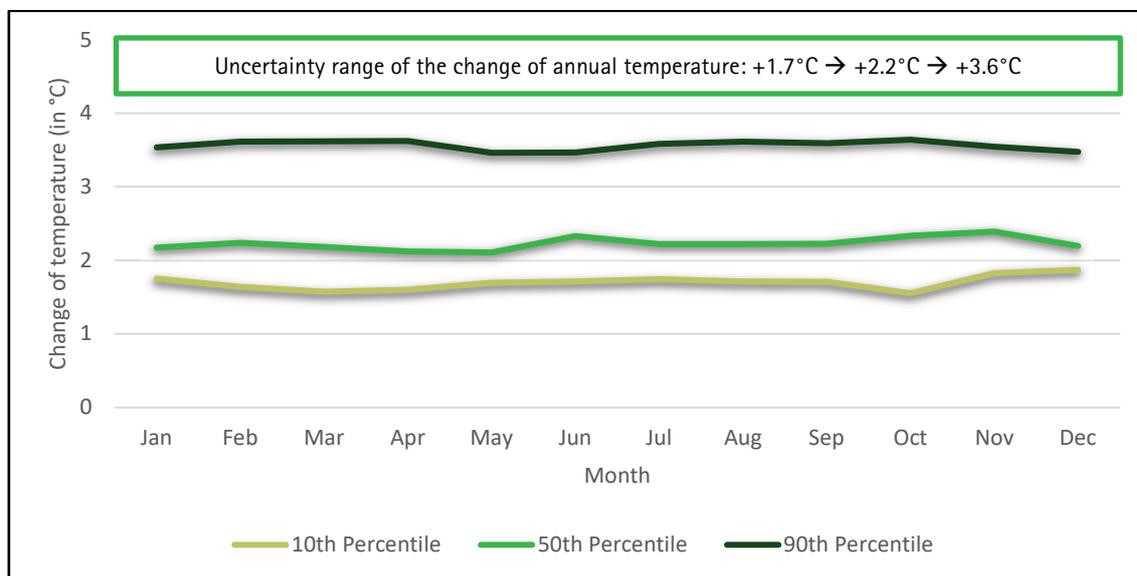
Source: Own figure based on The World Bank Group (2020b).

**Figure B.6:** Change of average precipitation of Costa Rica for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



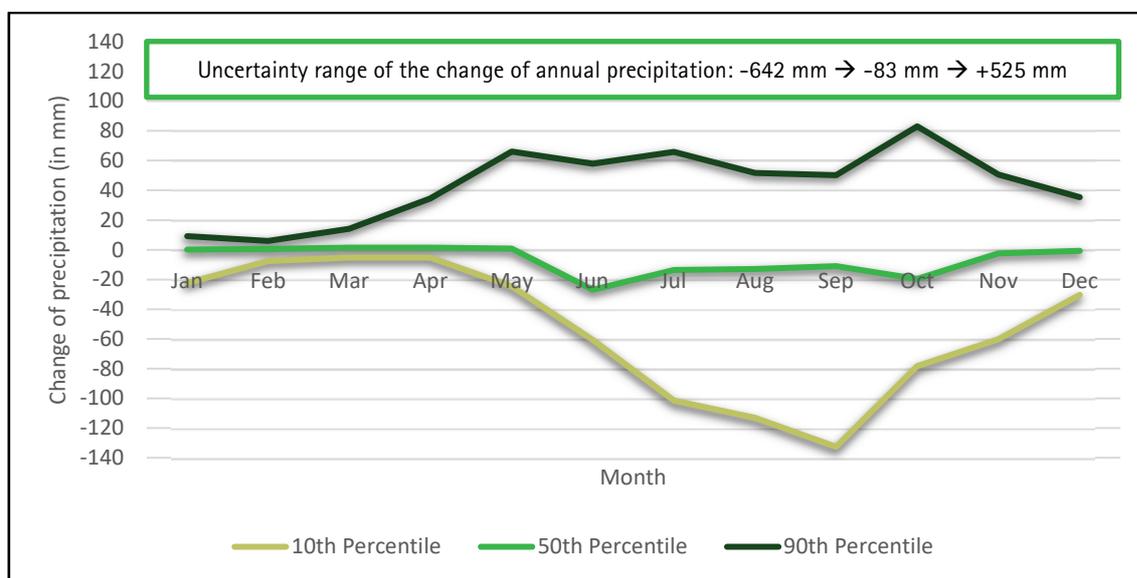
Source: Own figure based on The World Bank Group (2020b).

**Figure B.7:** Change of average temperature of Costa Rica for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

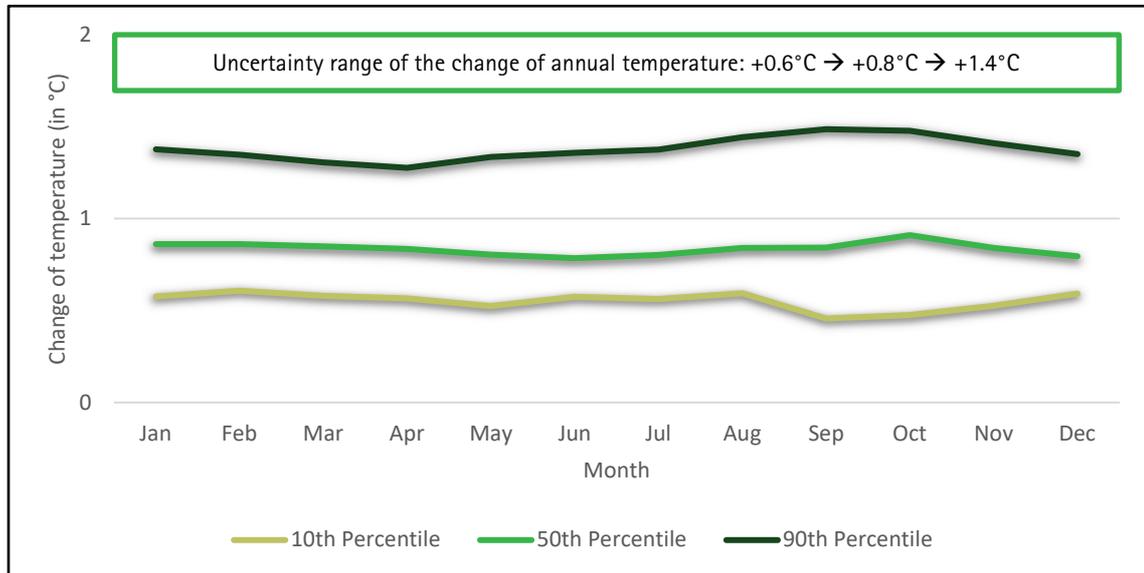
**Figure B.8:** Change of average precipitation of Costa Rica for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

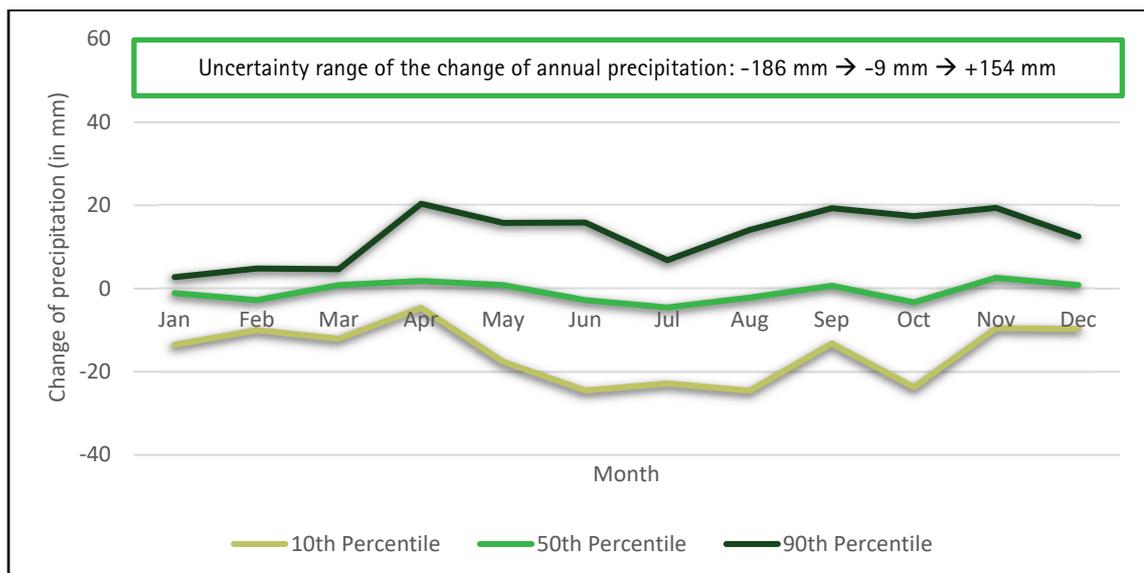
## Annex C: Uncertainty of climate change: Dominican Republic

**Figure C.1:** Change of average temperature of the Dominican Republic for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



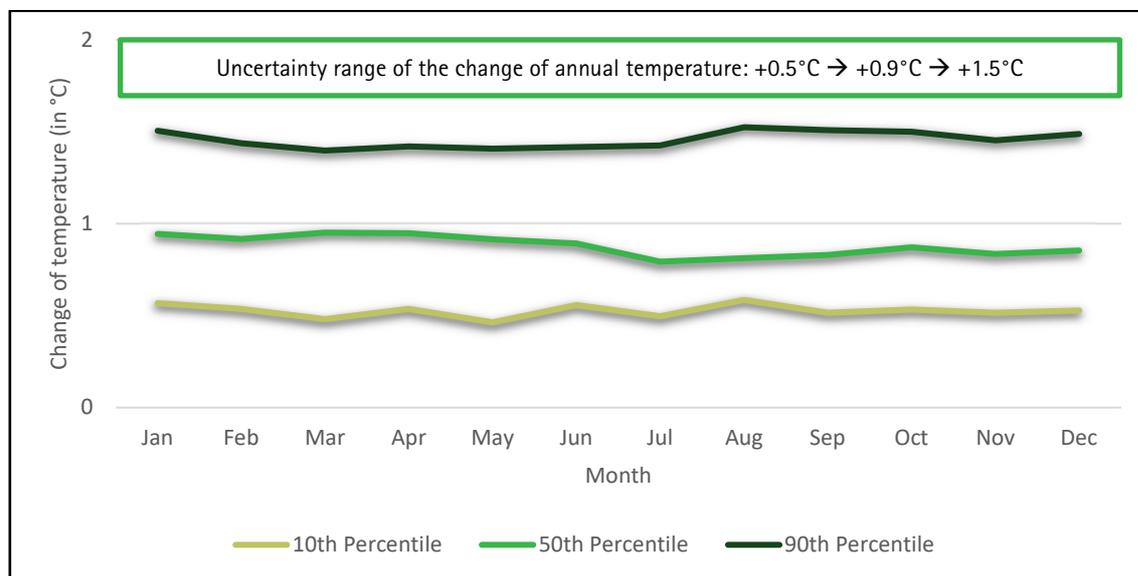
Source: Own figure based on The World Bank Group (2020b).

**Figure C.2:** Change of average precipitation of the Dominican Republic for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



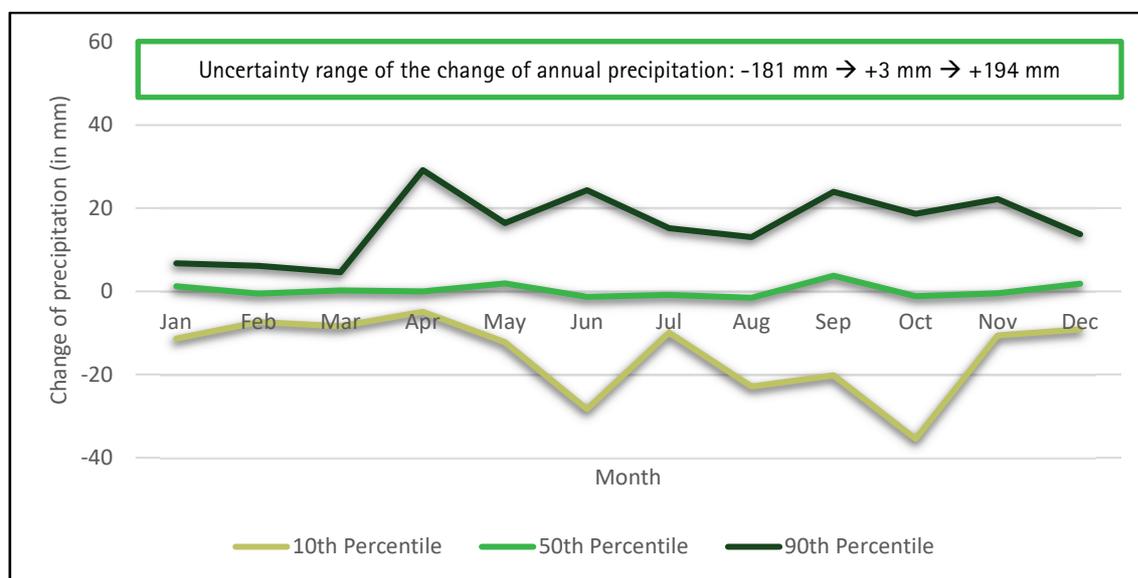
Source: Own figure based on The World Bank Group (2020b).

**Figure C.3:** Change of average temperature of the Dominican Republic for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



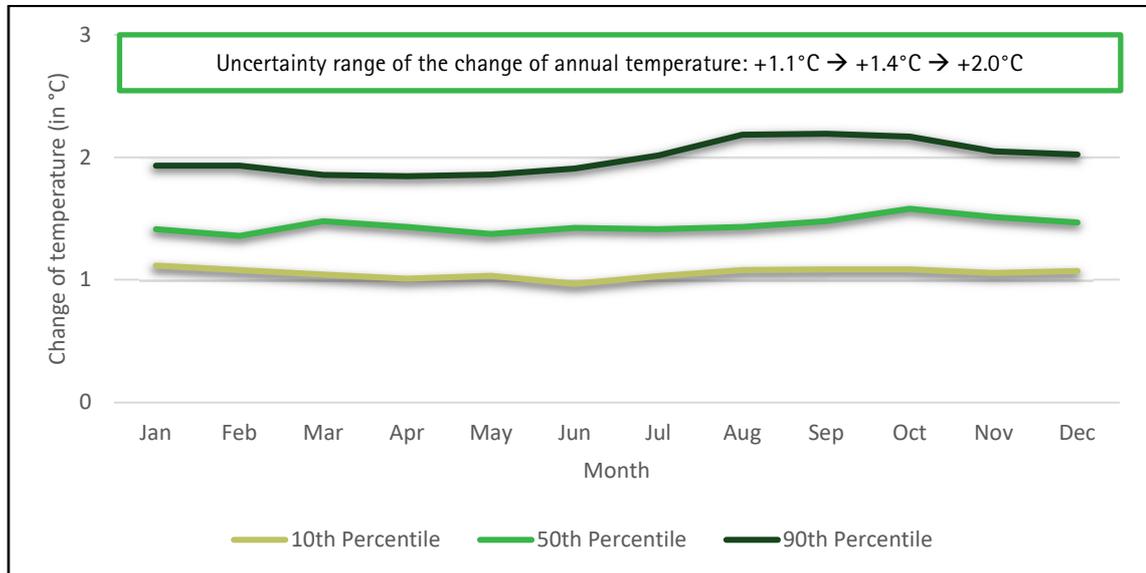
Source: Own figure based on The World Bank Group (2020b).

**Figure C.4:** Change of average precipitation of the Dominican Republic for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



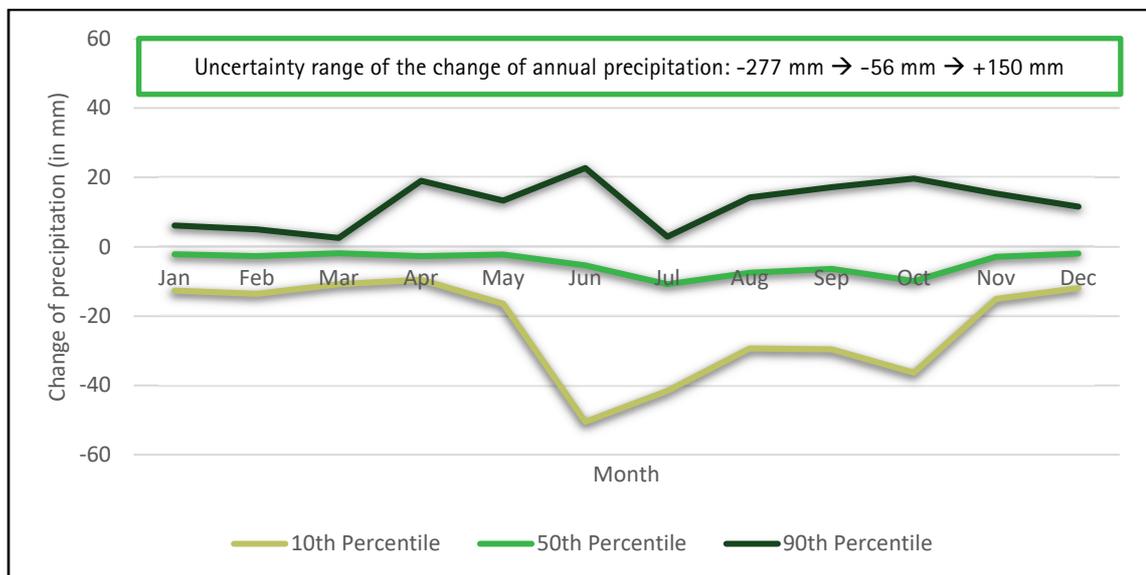
Source: Own figure based on The World Bank Group (2020b).

**Figure C.5:** Change of average temperature of the Dominican Republic for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



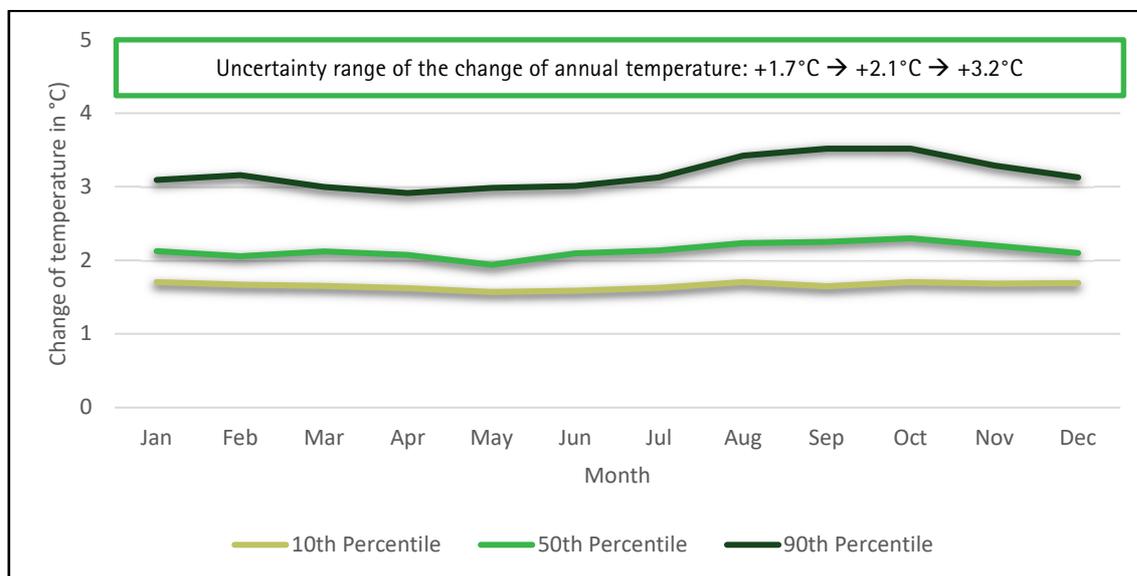
Source: Own figure based on The World Bank Group (2020b).

**Figure C.6:** Change of average precipitation of the Dominican Republic for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



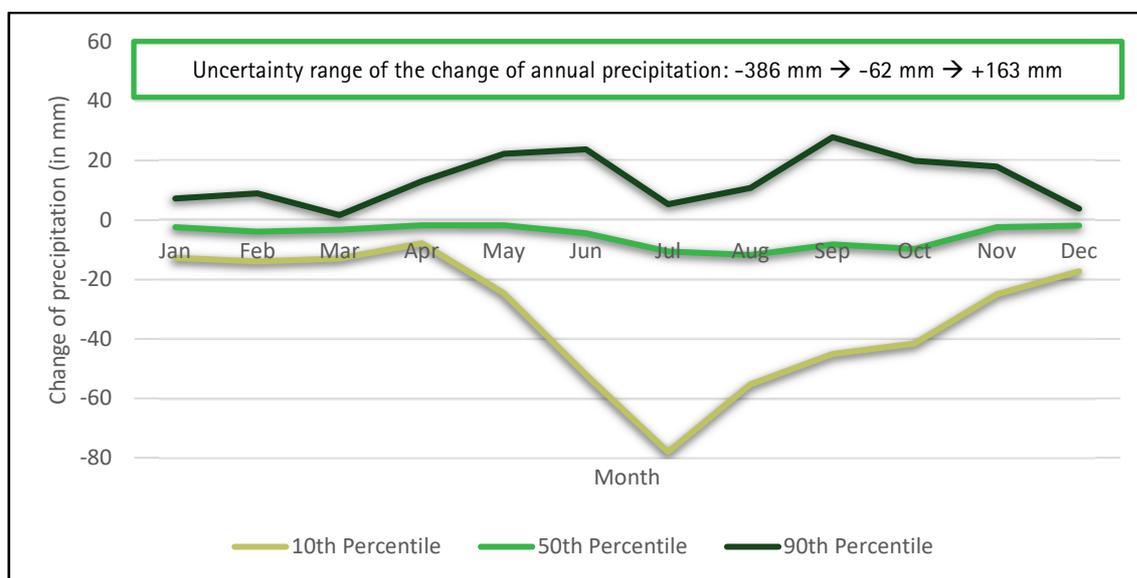
Source: Own figure based on The World Bank Group (2020b).

**Figure C.7:** Change of average temperature of the Dominican Republic for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

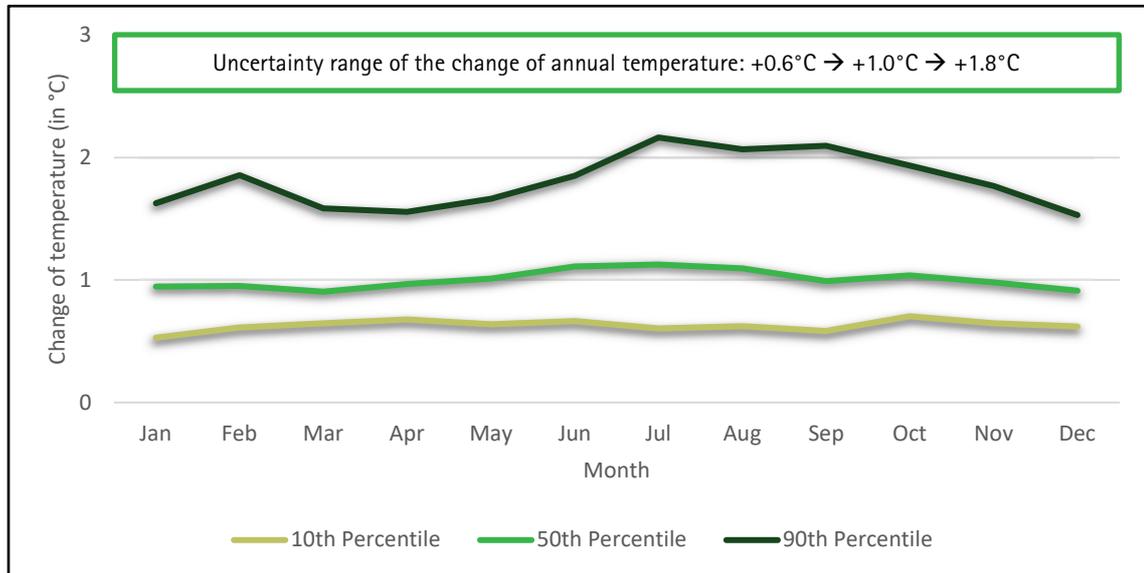
**Figure C.8:** Change of average precipitation of the Dominican Republic for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

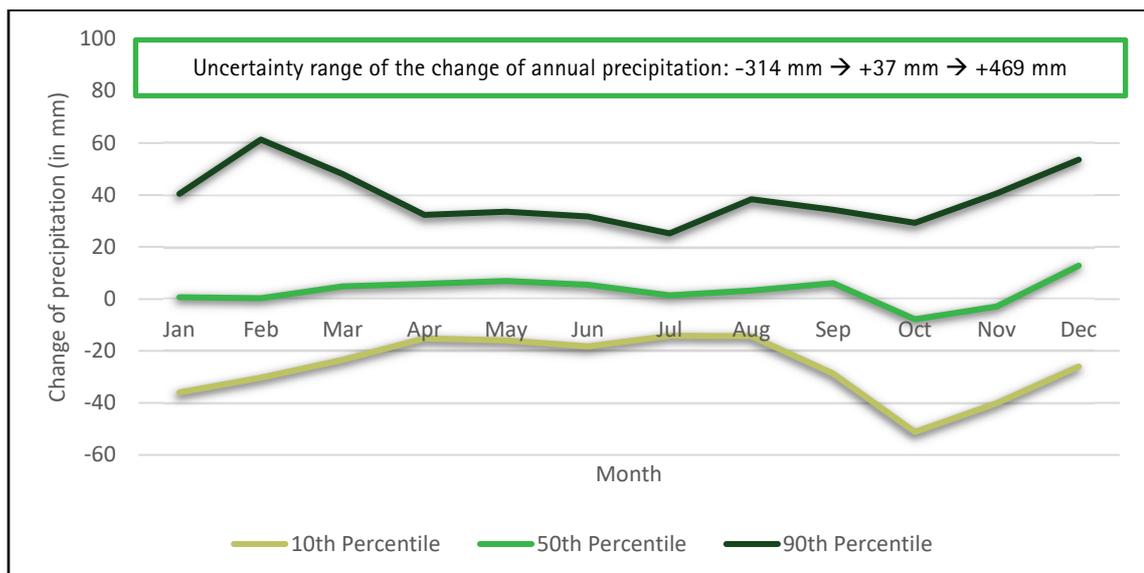
## Annex D: Uncertainty of climate change: Ecuador

**Figure D.1:** Change of average temperature of Ecuador for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



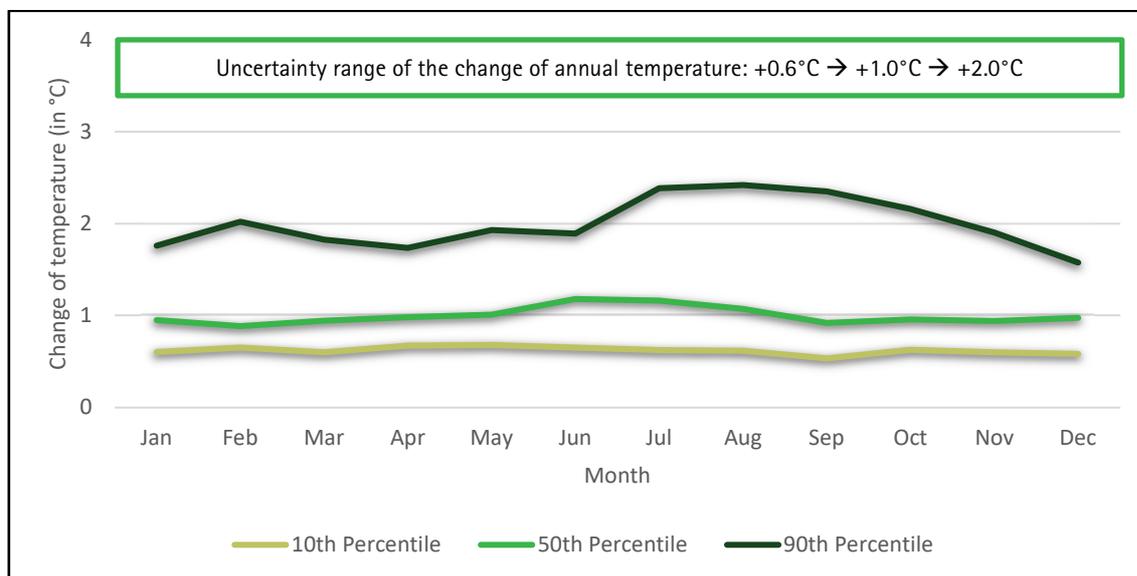
Source: Own figure based on The World Bank Group (2020b).

**Figure D.2:** Change of average precipitation of Ecuador for the year 2050 and the climate change scenario RCP 2.6 compared to 1986–2005



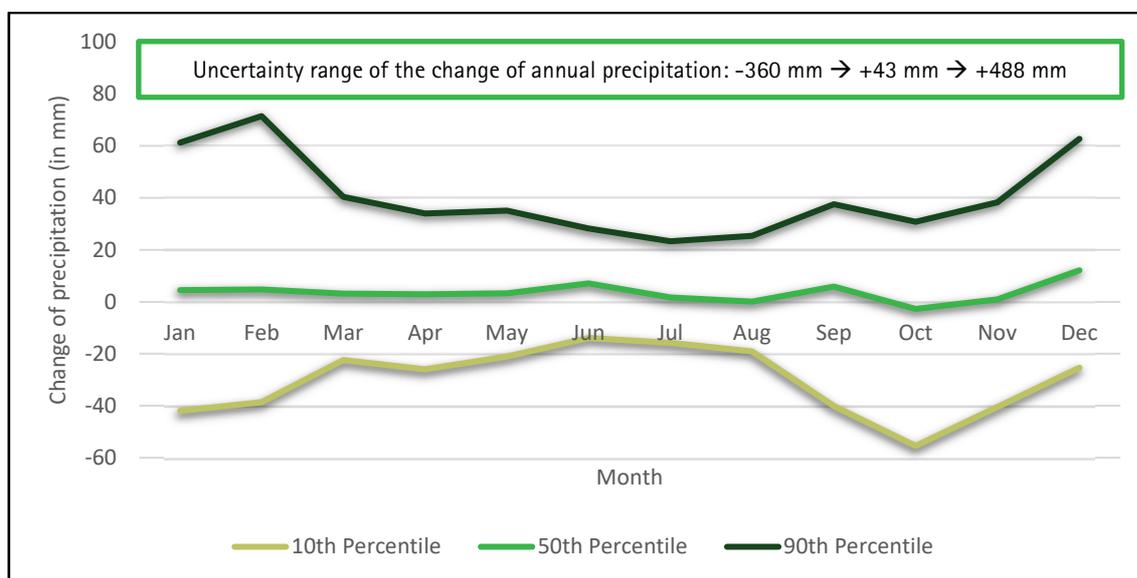
Source: Own figure based on The World Bank Group (2020b).

**Figure D.3:** Change of average temperature of Ecuador for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



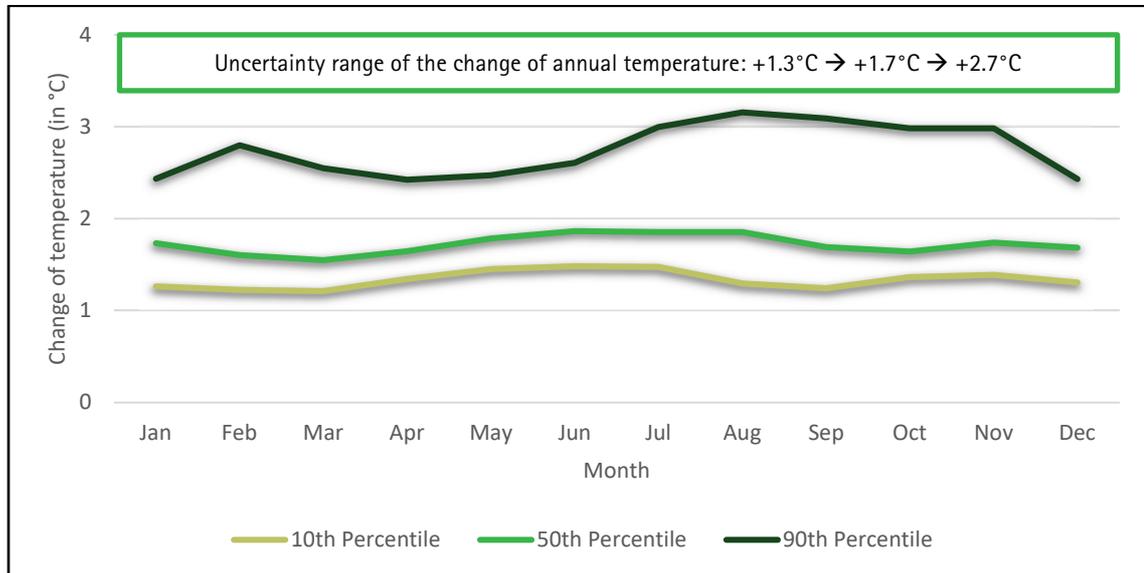
Source: Own figure based on The World Bank Group (2020b).

**Figure D.4:** Change of average precipitation of Ecuador for the year 2070 and the climate change scenario RCP 2.6 compared to 1986–2005



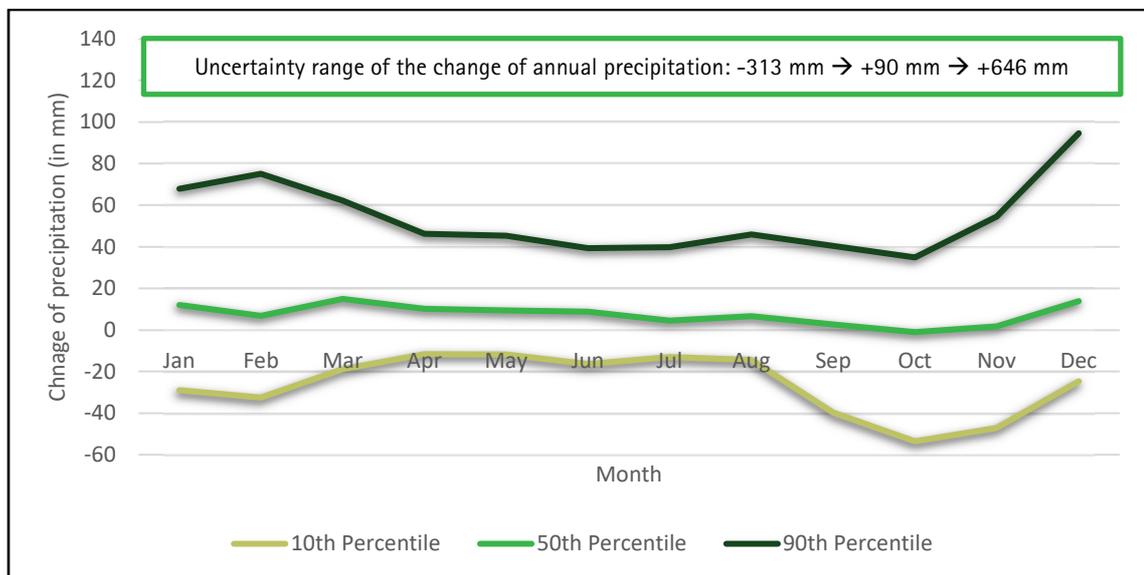
Source: Own figure based on The World Bank Group (2020b).

**Figure D.5:** Change of average temperature of Ecuador for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



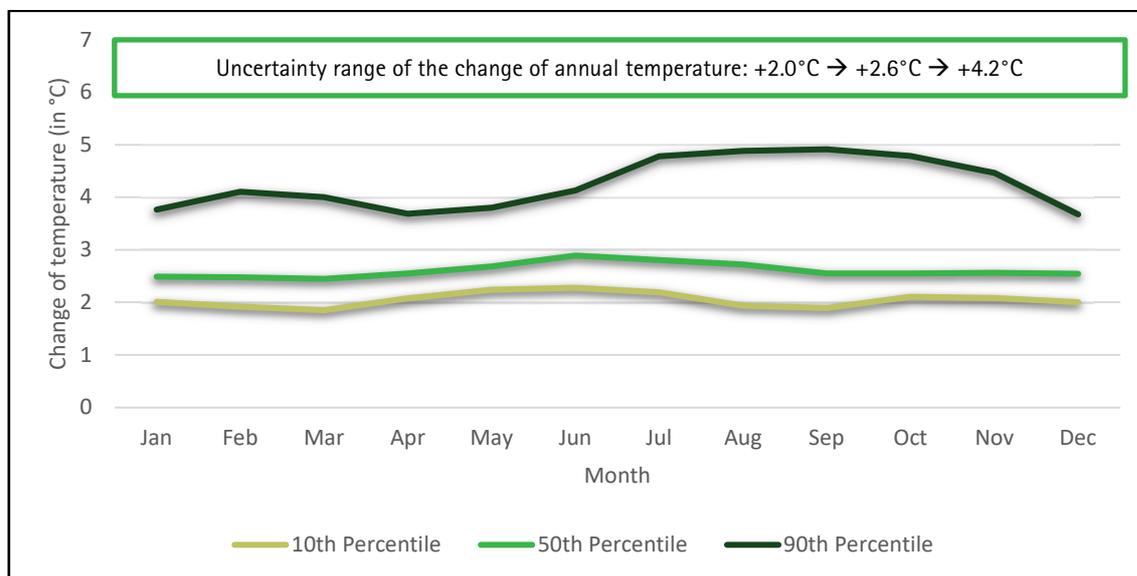
Source: Own figure based on The World Bank Group (2020b).

**Figure D.6:** Change of average precipitation of Ecuador for the year 2050 and the climate change scenario RCP 8.5 compared to 1986–2005



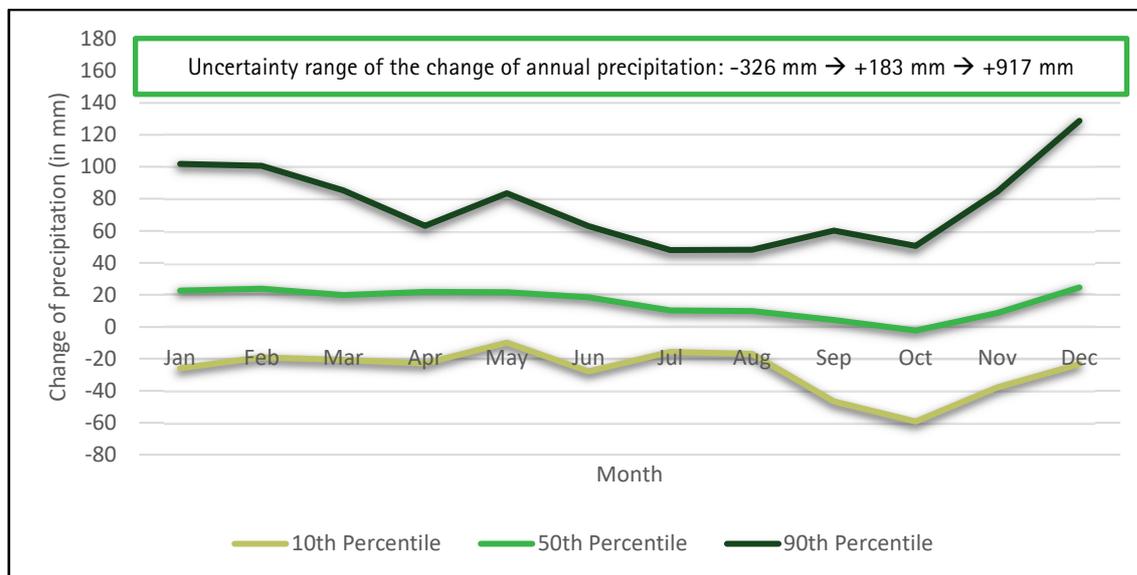
Source: Own figure based on The World Bank Group (2020b).

**Figure D.7:** Change of average temperature of Ecuador for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

**Figure D.8:** Change of average precipitation of Ecuador for the year 2070 and the climate change scenario RCP 8.5 compared to 1986–2005



Source: Own figure based on The World Bank Group (2020b).

## Annex E: Data and methods for the analysis of observed and projected climate developments

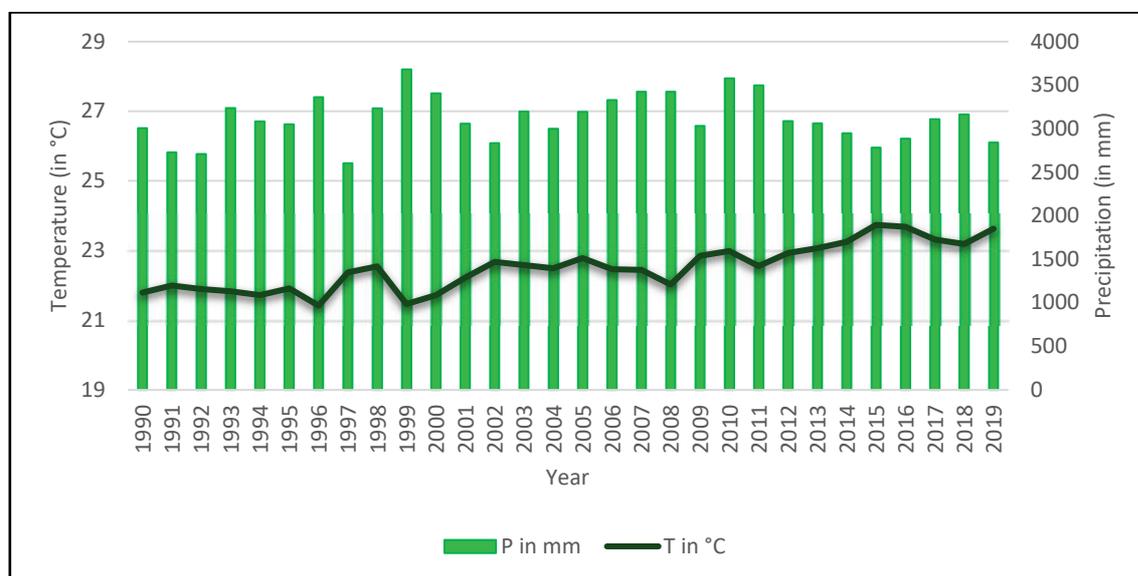
The climate analysis is based on three datasets, which are briefly discussed in the following:

- Current precipitation levels are based on the high-resolution dataset Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) version 2 (see, for instance, Funk et al., 2014). CHIRPS combines a variety of satellite products and in-situ observations and provides daily precipitation data with a spatial resolution of 0.05° for the period from 1981 until today. The annual number of dry months is also calculated from this dataset.
- Current temperature conditions and consequently the temperature-based calculation of PET are based on ERA5, the most recent reanalysis product of the European Centre for Medium-Range Weather Forecasts (ECMWF) (see, for instance, Hersbach et al., 2019). Reanalysis data is produced by combining a numerical weather prediction model with observational data from satellites and ground observations, therefore providing optimized global estimates of climate data without spatial or temporal gaps. ERA5 is available with 0.25° spatial and daily temporal resolution, which is higher than the resolution of purely observational temperature datasets and makes ERA5 a suitable choice for regions with diverse topography.
- The projected climate conditions are based on the recently published Coordinated Regional Climate Downscaling Experiment (CORDEX) – COmmon Regional Experiment (CORE) dataset (CORDEX, 2020), and within that, in particular on the data from the Central America domain. We use data from the Regional Climate Model (RCM) Remo with forcing from three different global General Circulation Models (GCMs). The three GCMs are NCC-NORESM, MPI-ESM-LR and HadGEM-ES. These models were particularly chosen to cover the whole range of equilibrium climate sensitivity within the Coupled Model Intercomparison Project 5 (CMIP5) ensemble. Accordingly, simulations for RCP 2.6 and RCP 8.5 are available to cover the whole range of RCP scenarios. More precisely, the CORDEX-CORE project provides daily climate data until 2100 with a spatial resolution of 0.22°. This high resolution is crucial in regions of complex terrain and when comparing changes in comparatively small regions.

To analyze the particularly small regions in our study our analysis is conducted on the finest grid of the three datasets, the 0.05° grid of CHIRPS. All data was re-gridded to this resolution using first order conservative remapping. To avoid the influence of inter-annual variability when analyzing projected changes, we based this analysis on time-periods of 29 years – namely 1990–2018 for current climate conditions, 2036–2064 for climate conditions around the year 2050 and 2056–2084 for climate conditions around the year 2070. The variables analyzed from these datasets are annual sums of precipitation, annual average temperatures, the annual numbers of dry months, and the annual sum of PET. As PET is not a direct output of climate models, we calculated it following the method of Thornthwaite (1948). The main limitation of this method is that it considers PET as a function of temperature only, while more realistically it also depends on other factors, in particular wind. However, since wind data is highly uncertain, including it into the PET calculation would introduce another (different) type of uncertainty.

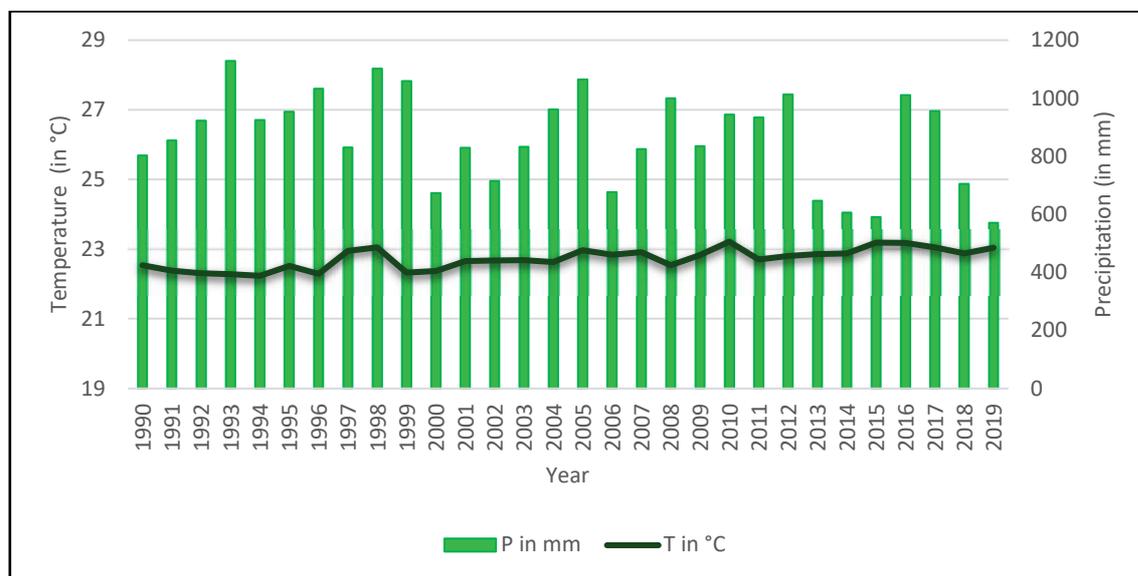
## Annex F: Regional observations of temperature and precipitation

Figure F.1: Observed annual temperature and precipitation in Antioquia, 1990–2019



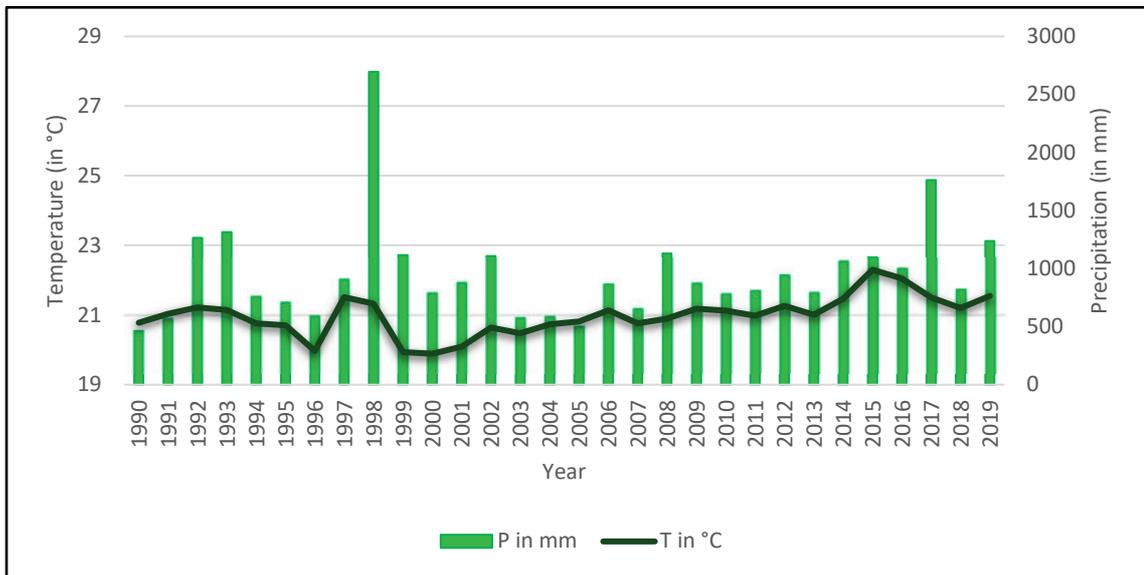
Source: Own figure.

Figure F.2: Observed annual temperature and precipitation in Azua, 1990–2019



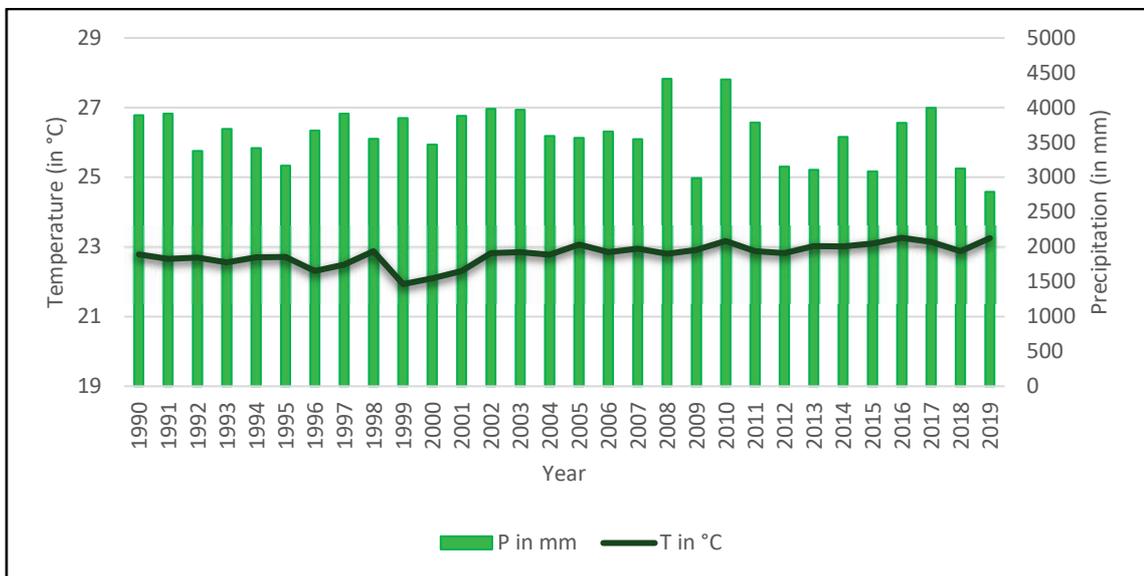
Source: Own figure.

**Figure F.3:** Observed annual temperature and precipitation in El Oro, 1990-2019



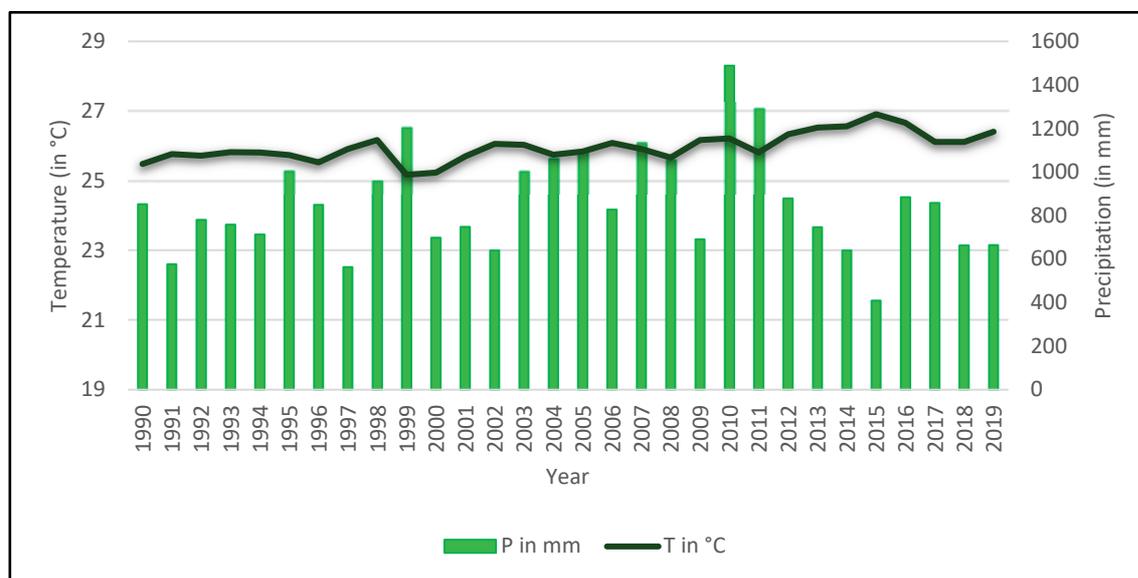
Source: Own figure.

**Figure F.4:** Observed annual temperature and precipitation in Heredia, 1990-2019



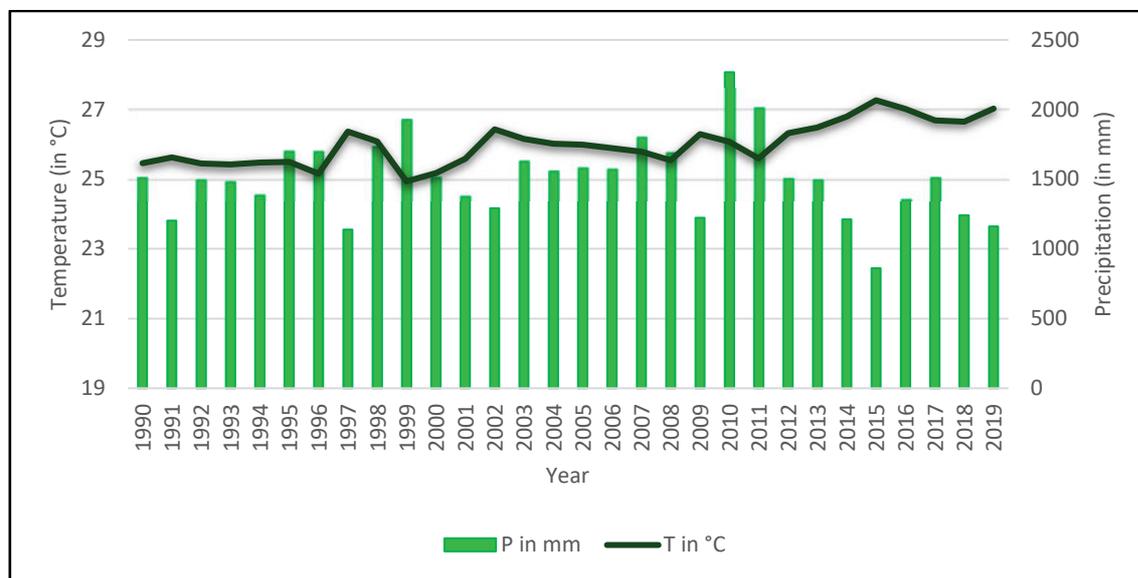
Source: Own figure.

**Figure F.5:** Observed annual temperature and precipitation in La Guajira, 1990-2019



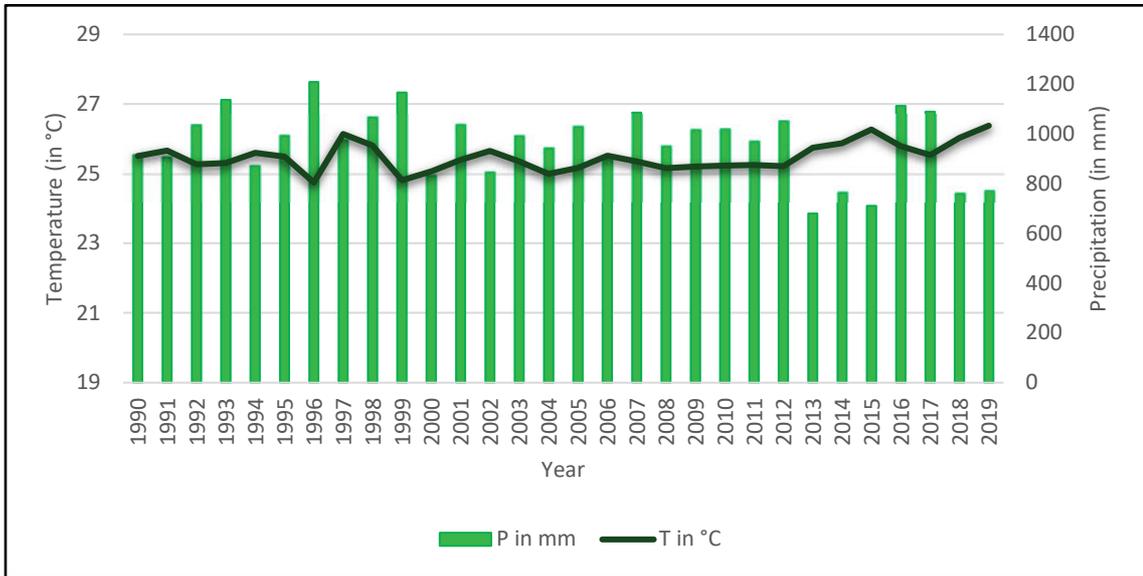
Source: Own figure.

**Figure F.6:** Observed annual temperature and precipitation in Magdalena, 1990-2019



Source: Own figure.

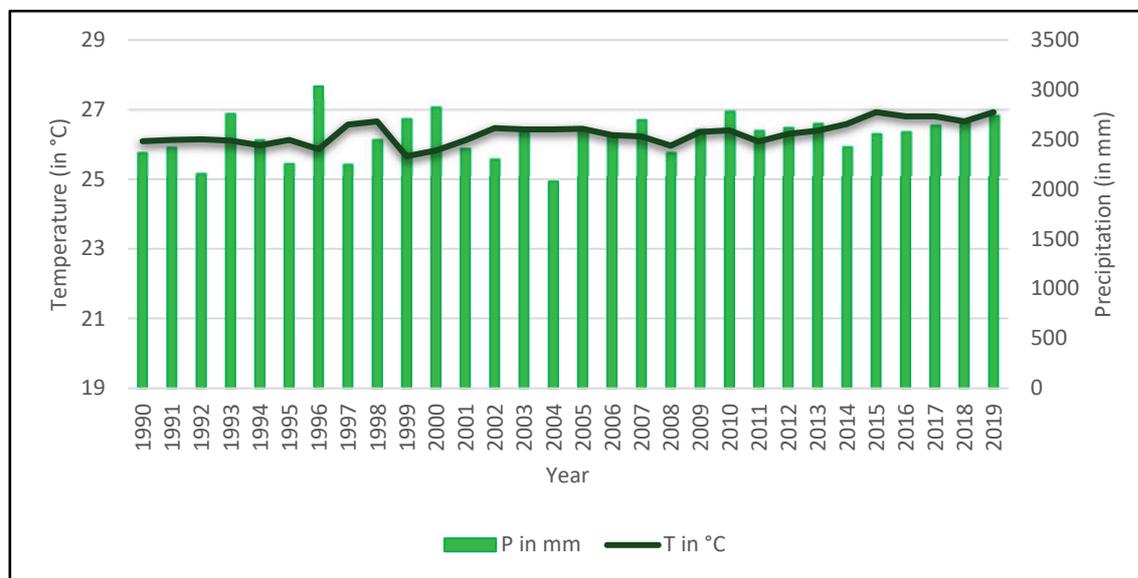
**Figure F.7:** Observed annual temperature and precipitation in Valverde, 1990–2019



Source: Own figure.

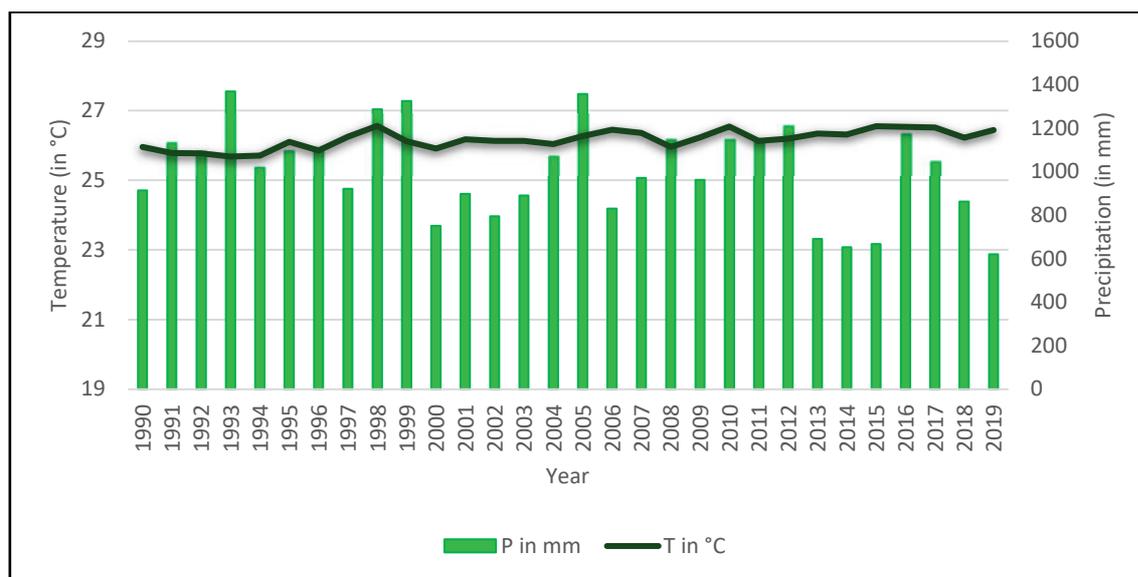
## Annex G: Area observations of temperature and precipitation

**Figure G.1:** Observed annual temperature and precipitation in a banana production area of Antioquia, 1990–2019



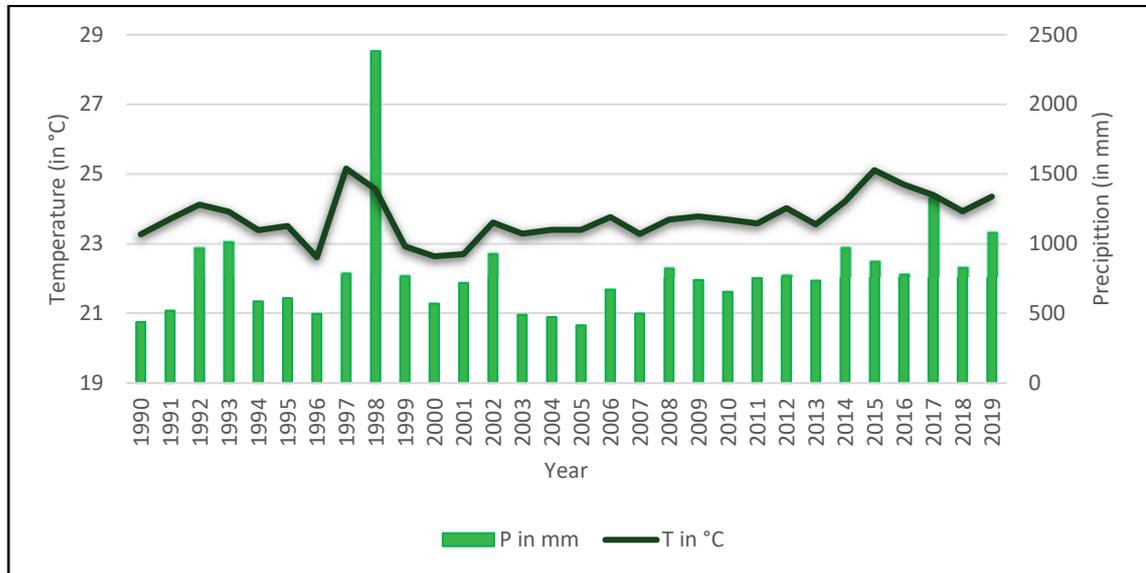
Source: Own figure.

**Figure G.2:** Observed annual temperature and precipitation in a banana production area of Azua, 1990–2019



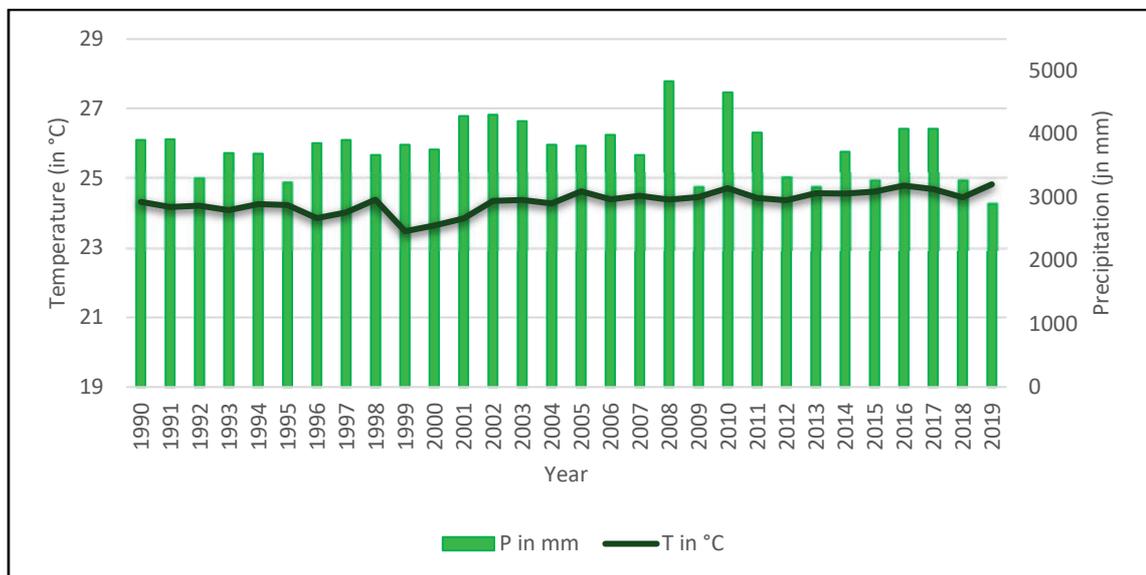
Source: Own figure.

**Figure G.3:** Observed annual temperature and precipitation in a banana production area of El Oro, 1990–2019



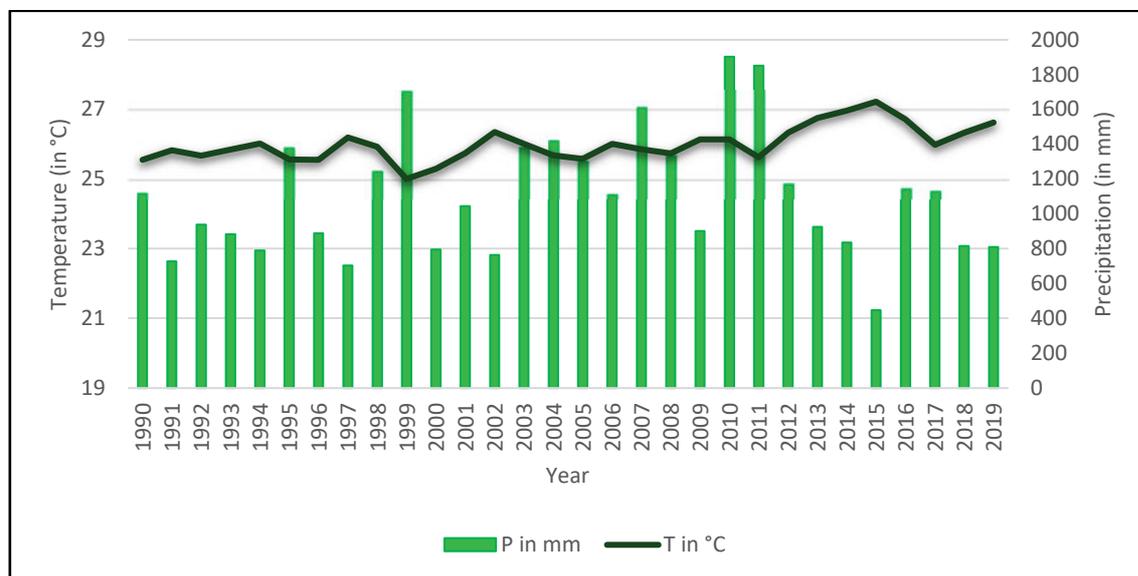
Source: Own figure.

**Figure G.4:** Observed annual temperature and precipitation in a banana production area of Heredia, 1990–2019



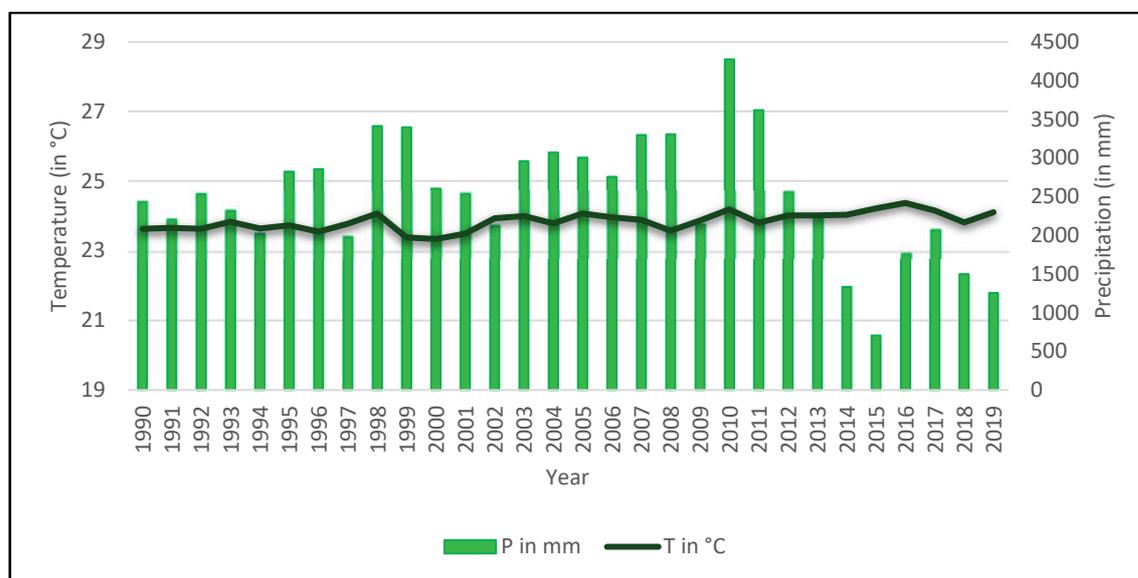
Source: Own figure.

**Figure G.5:** Observed annual temperature and precipitation in a banana production area of La Guajira, 1990–2019



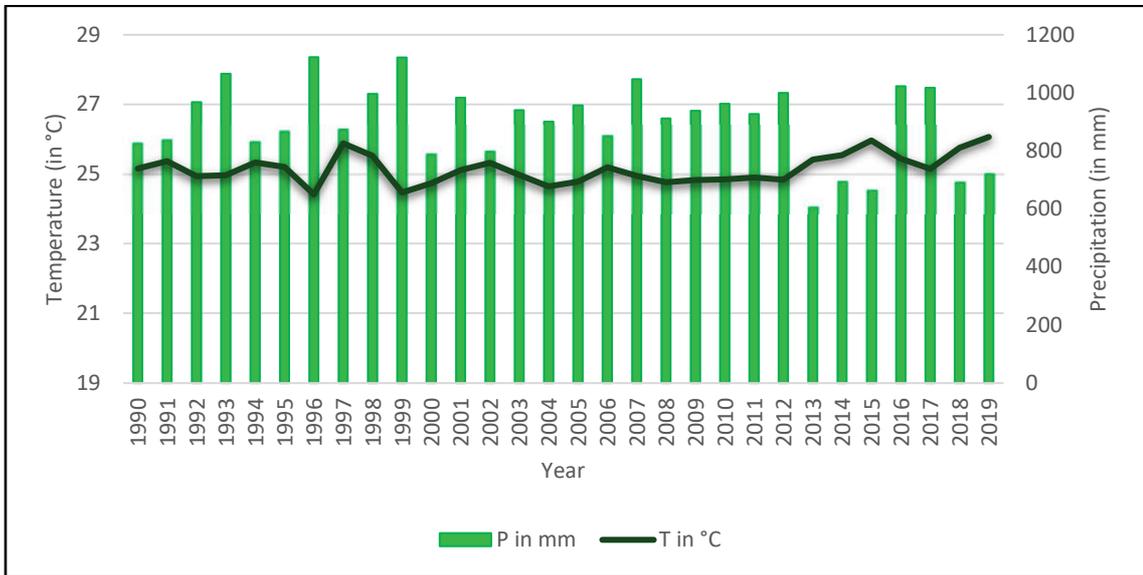
Source: Own figure.

**Figure G.6:** Observed annual temperature and precipitation in a banana production area of Magdalena, 1990–2019



Source: Own figure.

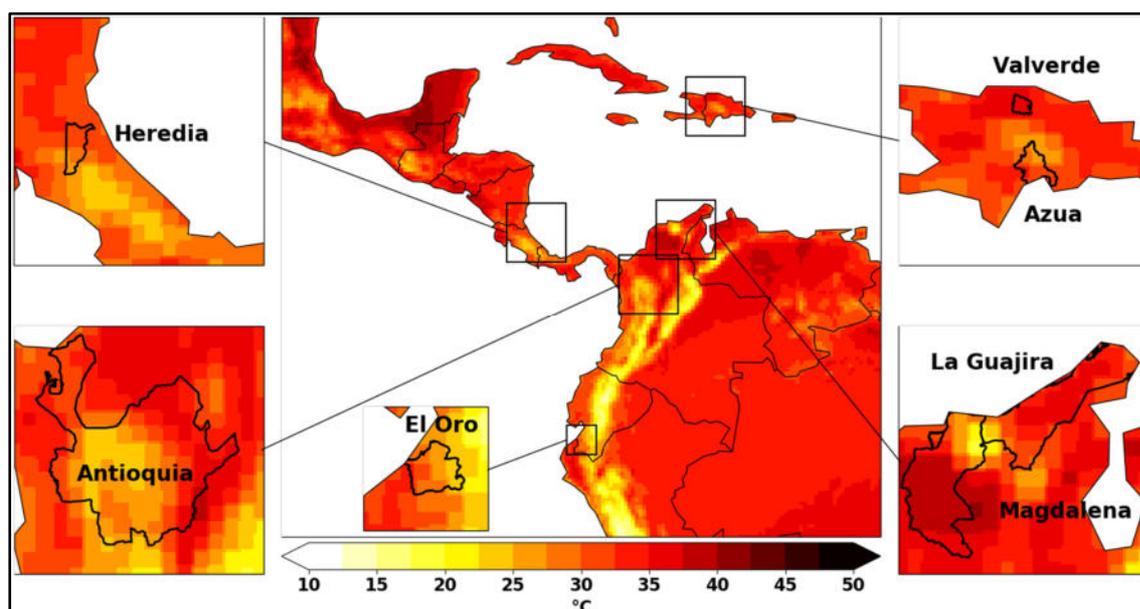
**Figure G.7:** Observed annual temperature and precipitation in a banana production area of Valverde, 1990-2019



Source: Own figure.

## Annex H: Observations of and projected changes in maximum temperatures

**Figure H.1:** Observed annual maximum temperature averaged over the period from 1990 to 2018 in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



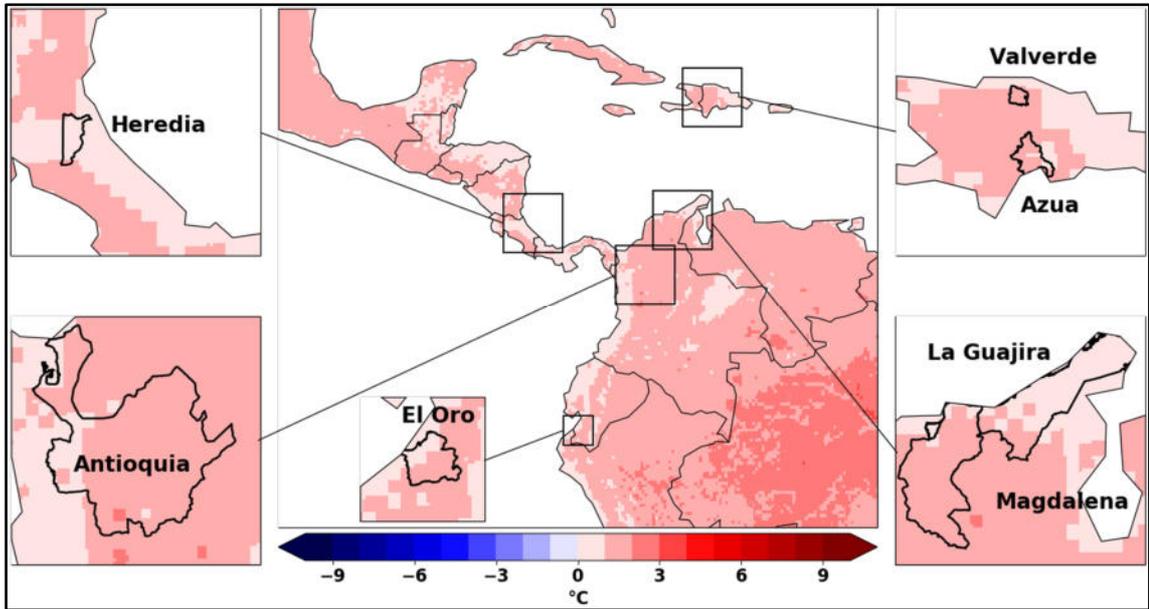
Source: Own figure.

**Figure H.2:** Calculated difference of the maximum temperature, compared to 1990–2018, for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Region	2050 – RCP 2.6	2050 – RCP 8.5	2070 – RCP 2.6	2070 – RCP 8.5
Antioquia	1.29°C	2.40°C	1.55°C	3.86°C
Azua	1.02°C	2.19°C	1.05°C	3.62°C
El Oro	1.04°C	1.91°C	1.21°C	3.08°C
Heredia	0.78°C	1.32°C	0.78°C	2.15°C
La Guajira	0.85°C	1.70°C	1.10°C	2.80°C
Magdalena	1.25°C	2.45°C	1.54°C	4.17°C
Valverde	1.26°C	2.22°C	1.10°C	3.69°C

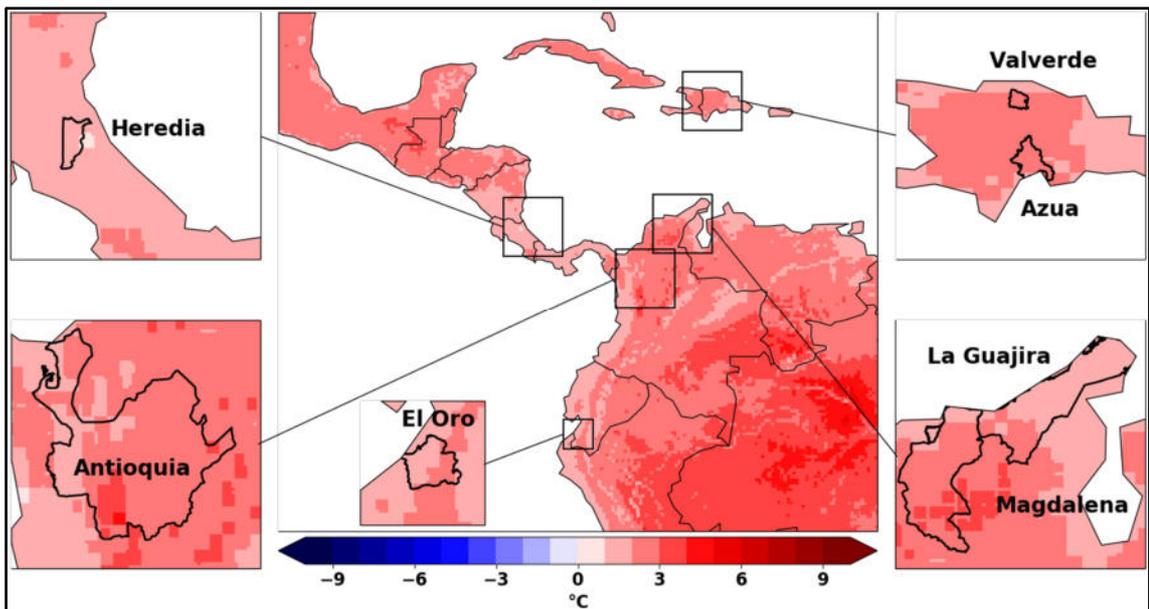
Source: Own figure.

**Figure H.3:** Projected change in maximum temperature by 2050 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



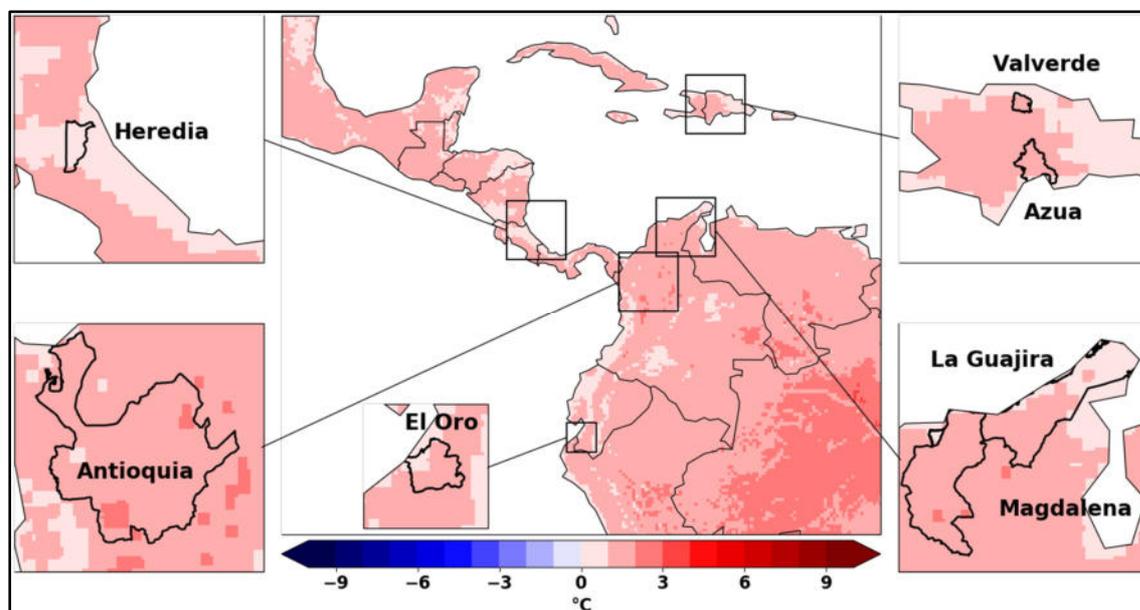
Source: Own figure.

**Figure H.4:** Projected change in maximum temperature by 2050 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



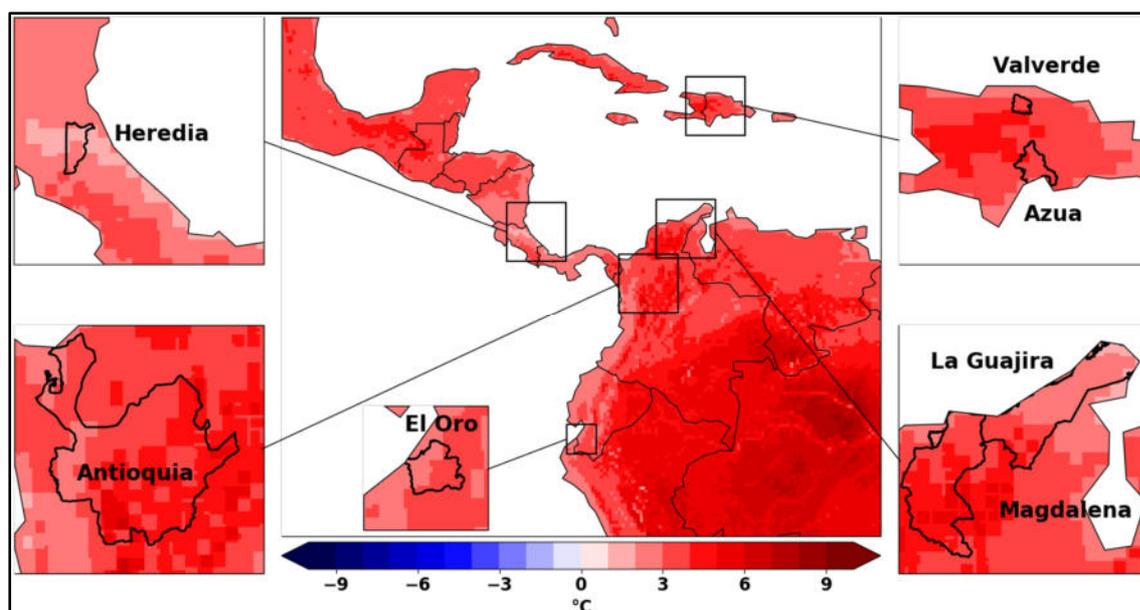
Source: Own figure.

**Figure H.5:** Projected change in maximum temperature by 2070 for the RCP 2.6 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

**Figure H.6:** Projected change in maximum temperature by 2070 for the RCP 8.5 scenario in the broader LAC region as well as in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador



Source: Own figure.

## Annex I: Calculated difference of selected climate variables

**Figure I.1:** Calculated difference of the near-surface temperature, compared to 1990–2018, for specific banana production areas in selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Banana production area in ...	2050 / RCP 2.6	2050 / RCP 8.5	2070 / RCP 2.6	2070 / RCP 8.5
... Antioquia	0.82°C	1.59°C	0.92°C	2.57°C
... Azua	0.77°C	1.49°C	0.79°C	2.83°C
... El Oro	0.84°C	1.50°C	0.90°C	2.39°C
... Heredia	0.76°C	1.37°C	0.78°C	2.16°C
... La Guajira	0.84°C	1.59°C	0.95°C	2.59°C
... Magdalena	0.91°C	1.81°C	1.03°C	2.98°C
... Valverde	0.97°C	1.84°C	0.97°C	2.93°C

Source: Own figure.

**Figure I.2:** Calculated difference of the annual precipitation, compared to 1990–2018, for specific banana production areas in selected regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador

Banana production area in ...	2050 / RCP 2.6	2050 / RCP 8.5	2070 / RCP 2.6	2070 / RCP 8.5
... Antioquia	4.05 %	0.17 %	2.11 %	-6.69 %
... Azua	5.09 %	-10.17 %	-0.14 %	-21.86 %
... El Oro	-2.21 %	2.90 %	3.01 %	10.46 %
... Heredia	5.06 %	4.72 %	3.75 %	8.92 %
... La Guajira	5.02 %	-0.43 %	-3.63 %	-10.84 %
... Magdalena	11.60 %	-7.28 %	1.03 %	-16.83 %
... Valverde	-4.69 %	-12.02 %	-5.48 %	-22.71 %

Source: Own figure.

## Annex J: Regional yield data and the climate-yield coefficient

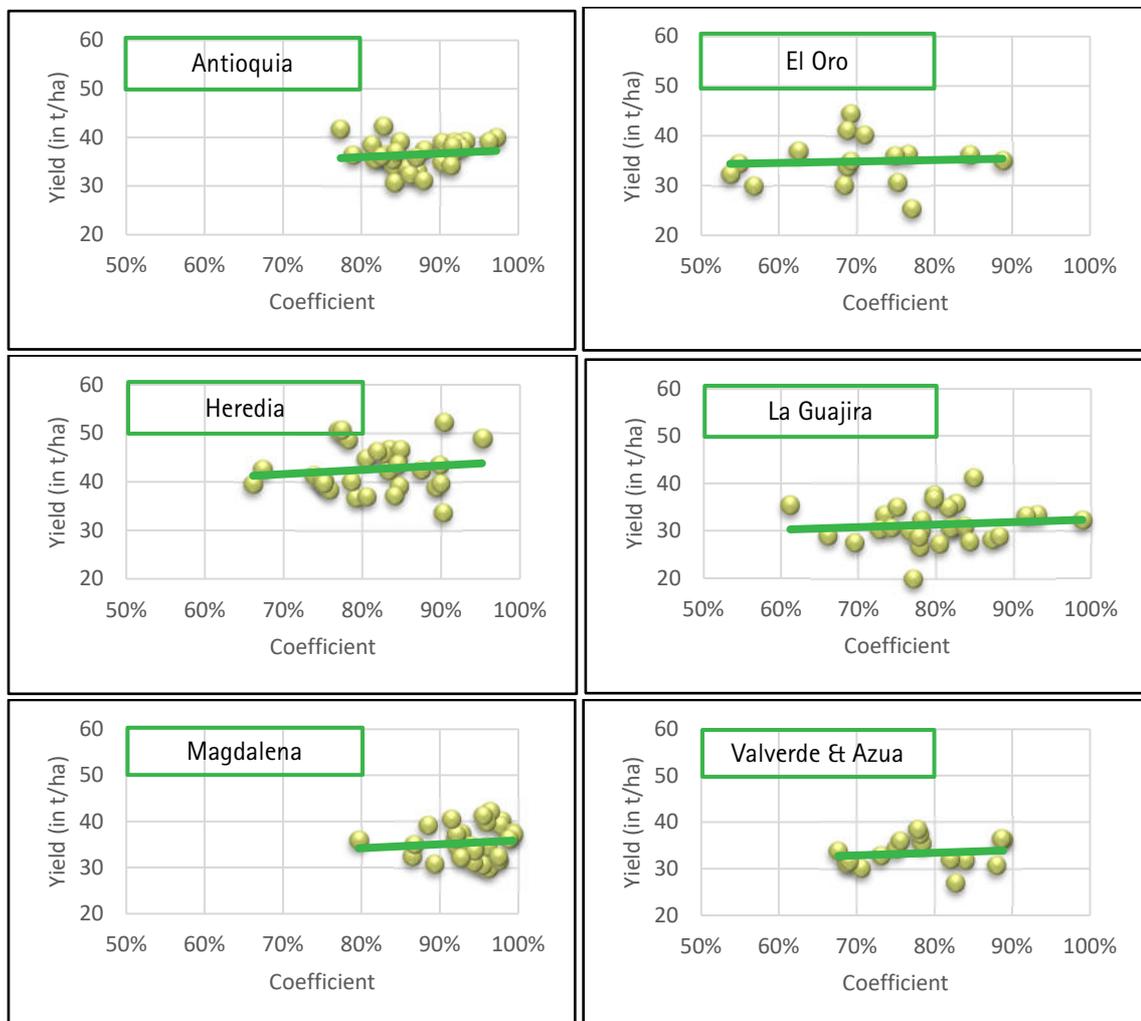
**Figure J.1:** Observed yield data for the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador (in tons per hectare)

Year	Antioquia	Azua	El Oro	Heredia	La Guajira	Magdalena	Valverde
1990	33.9			48.5	30.0	33.6	
1991	38.8			38.3	33.3	37.3	
1992	32.9			39.1	35.7	40.0	
1993	35.3			36.6	34.8	39.0	
1994	36.3			37.1	37.5	42.0	
1995	30.6			42.4	30.8	34.5	
1996	36.3			40.0	26.6	29.8	
1997	39.0			40.2	28.9	32.4	
1998	37.2			44.2	27.2	30.5	
1999	41.5			41.2	28.2	31.6	
2000	38.3			36.9	30.3	34.0	
2001	33.5			40.2	30.7	34.3	
2002	34.8	14.0		39.6	27.5	30.8	
2003	32.2		34.4	50.4	30.5	34.2	
2004	31.1		30.0	46.6	30.9	34.7	
2005	35.7		32.3	42.2	27.7	31.1	
2006	35.2		30.1	45.7	30.0	33.6	
2007	36.0		36.9	46.6	33.3	37.4	
2008	42.1		36.3	39.5	33.1	37.1	
2009	38.8		33.8	33.6	32.2	36.1	
2010	39.0		34.9	42.6	32.2	36.1	
2011	36.8		44.4	44.6	28.8	32.3	
2012	36.7	27.0	36.0	43.4	28.7	32.1	30.7
2013	38.5	30.1	41.1	38.8	36.7	39.7	34.2
2014	34.1	31.1	30.7	43.5	34.9	34.9	35.4
2015	39.8	31.5	36.1	39.6	35.4	35.8	35.8
2016	38.9	31.8	25.4	46.1	20.0	37.2	36.2
2017	37.7	31.9	34.9	50.6	41.1	41.1	36.3
2018	38.0	32.8	40.2	52.1		40.3	37.3
2019		33.7		48.8		39.0	38.3

Source: Own figure and calculations based on Ardila Parrado (2020), CLAC (2019), Damiani (2002), Giraldo (2020), Inec (2020), Rodriguez (2020), and Sanchez (2020).

Looking at figure J.1, it becomes obvious that gathering regional yield data from 1990 until most recently for the seven selected regions considered in this study has been a challenge. Finally, we have been able to identify – with the support of local experts and therefore not in a methodologically uniform way, i.e. slightly biased – 150 data points on regionalized annual banana yields. Using this information and additionally data of annex F, it can be checked if there is a relationship between annual banana yield information/observations for the seven regions of this study and the calculable climate–yield coefficient as the product of equations (1) and (2). Working hypothesis is that such a relationship exists although it cannot explain yearly yield manifestation in total since annual average temperature and precipitation are only one yield determinant and many other factors would need to be considered to fully explain yield developments. Figure J.2 shows the relation per region<sup>129</sup>.

**Figure J.2:** Yields and climate–yield coefficients in the selected banana producing regions of Colombia, Costa Rica, the Dominican Republic, and Ecuador, 1990–2019



Source: Own figure and calculations.

<sup>129</sup> Due to the limited yield data base, information for Azua and Valverde were merged.

A positive relationship can be observed in all regions. This means that climate – in terms of annual average temperature and precipitation – obviously has an impact on yield, in the sense that the closer the annual average temperature and precipitation are to the optimal temperature and precipitation, the higher the climate–yield coefficient, and subsequently the higher the observed yield in relation to the achievable yield. Assuming a linear relationship, one percent of the climate–yield coefficient acts to improve regional yields by 76 kg in Antioquia, 56 kg in Azua and Valverde, 30 kg in El Oro, 89 kg in Heredia, 55 kg in La Guajira, and 84 kg in Magdalena. This is not trivial since other yield determining factors apart from annual average temperature and precipitation are still not accounted for and surely explain the rather huge spread visible in figure J.2. In fact, the partially wide distance of single yield observations from the “trend” demonstrates that over time many more factors determine the observed yield. These factors are other climate indicators, especially the occurrence of extreme events, but also managerial and technological factors which are also subject to change over time. Analyzing all these factors is beyond the scope of this study and its underlying workload, but points to further research.

## Annex K: Yield impact assessment for various drivers of climate change

**Figure K.1:** Qualified assessment of the yield impact of various drivers of climate change for the RCP 2.6 scenario in 2050

Banana production area in ...	Impact of ...			
	... temperature & precipitation	... weather variability	... pests and diseases	... suitability of area
... Antioquia	-	-	-	-
... Azua	-	-	-	-
... El Oro	+	-	-	+
... Heredia	-	-	-	-
... La Guajira	-	-	-	-
... Magdalena	+	-	-	+
... Valverde	-	-	-	-

Source: Own figure. "+" indicates a potential positive impact and "-" refers to a potential negative impact.

**Figure K.2:** Qualified assessment of the yield impact of various drivers of climate change for the RCP 2.6 scenario in 2070

Banana production area in ...	Impact of ...			
	... temperature & precipitation	... weather variability	... pests and diseases	... suitability of area
... Antioquia	-	-	-	-
... Azua	-	-	-	-
... El Oro	+	-	-	+
... Heredia	-	-	-	-
... La Guajira	-	-	-	-
... Magdalena	+	-	-	+
... Valverde	-	-	-	-

Source: Own figure. "+" indicates a potential positive impact and "-" refers to a potential negative impact.

**Figure K.3:** Qualified assessment of the yield impact of various drivers of climate change for the RCP 8.5 scenario in 2070

Banana production area in ...	Impact of ...			
	... temperature & precipitation	... weather variability	... pests and diseases	... suitability of area
... Antioquia	-	-	-	-
... Azua	-	-	-	-
... El Oro	+	-	-	+
... Heredia	-	-	-	-
... La Guajira	-	-	-	-
... Magdalena	-	-	-	-
... Valverde	-	-	-	-

Source: Own figure. "+" indicates a potential positive impact and "-" refers to a potential negative impact.

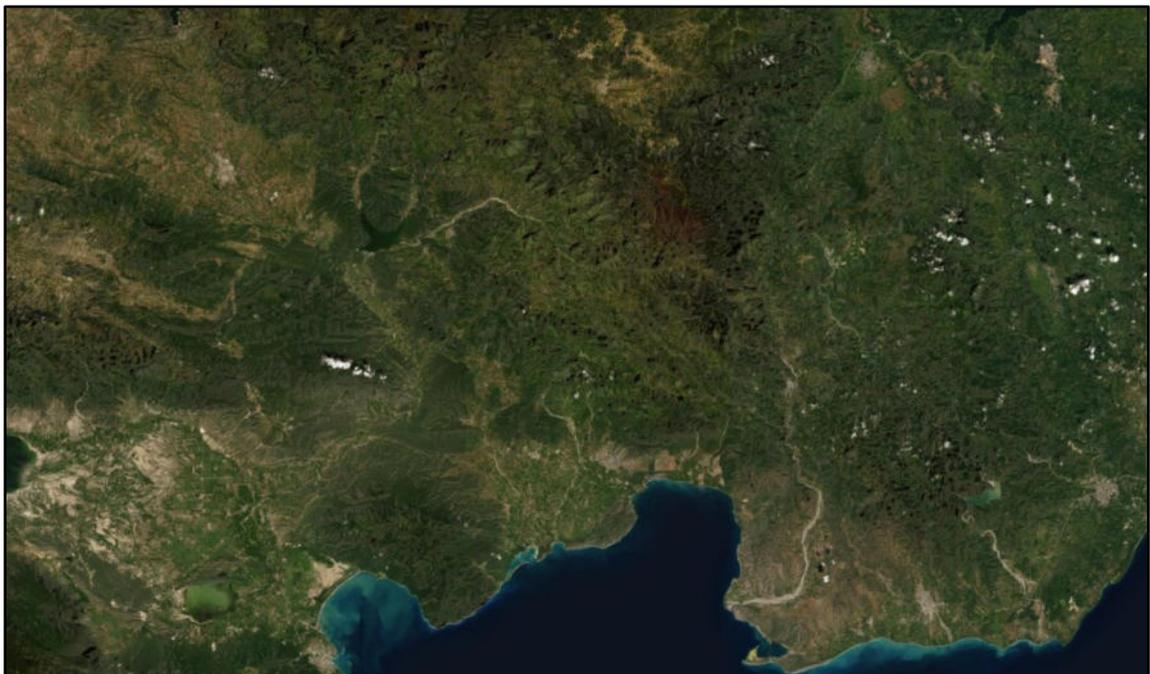
## Annex L: Topographic maps of banana producing regions

Figure L.1: Map of Antioquia and its neighboring areas



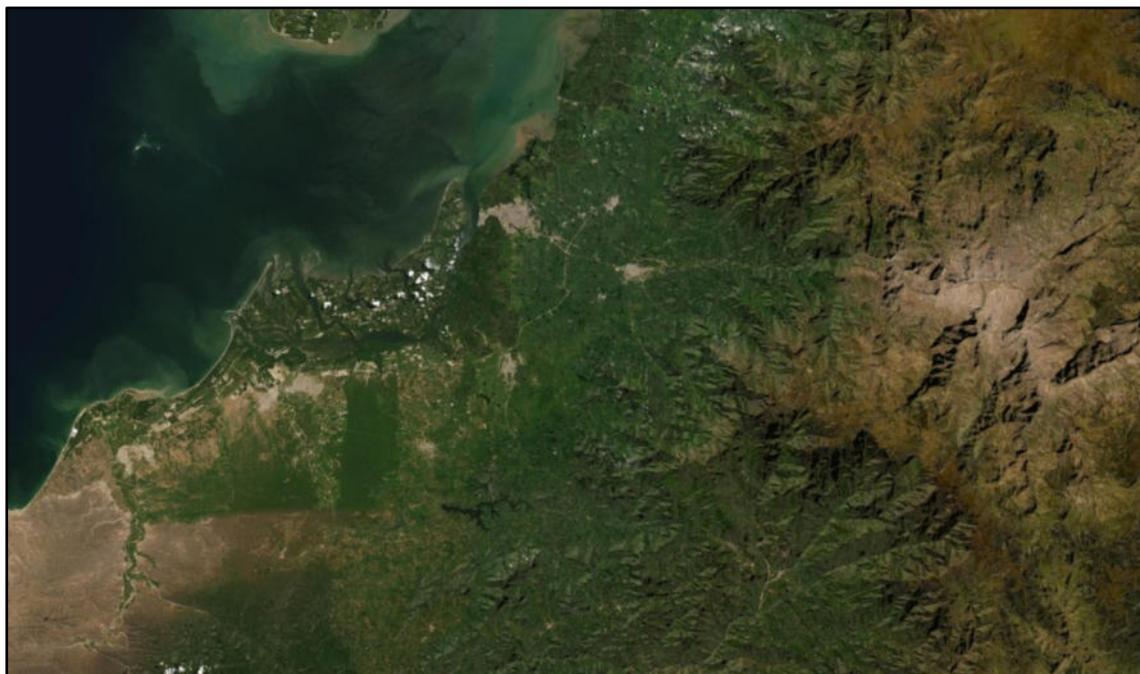
Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community, ESRI; courtesy of the U.S. Geological Survey (in: <https://earthexplorer.usgs.gov/>; last access: 20/11/2020).

Figure L.2: Map of Azua and its neighboring areas



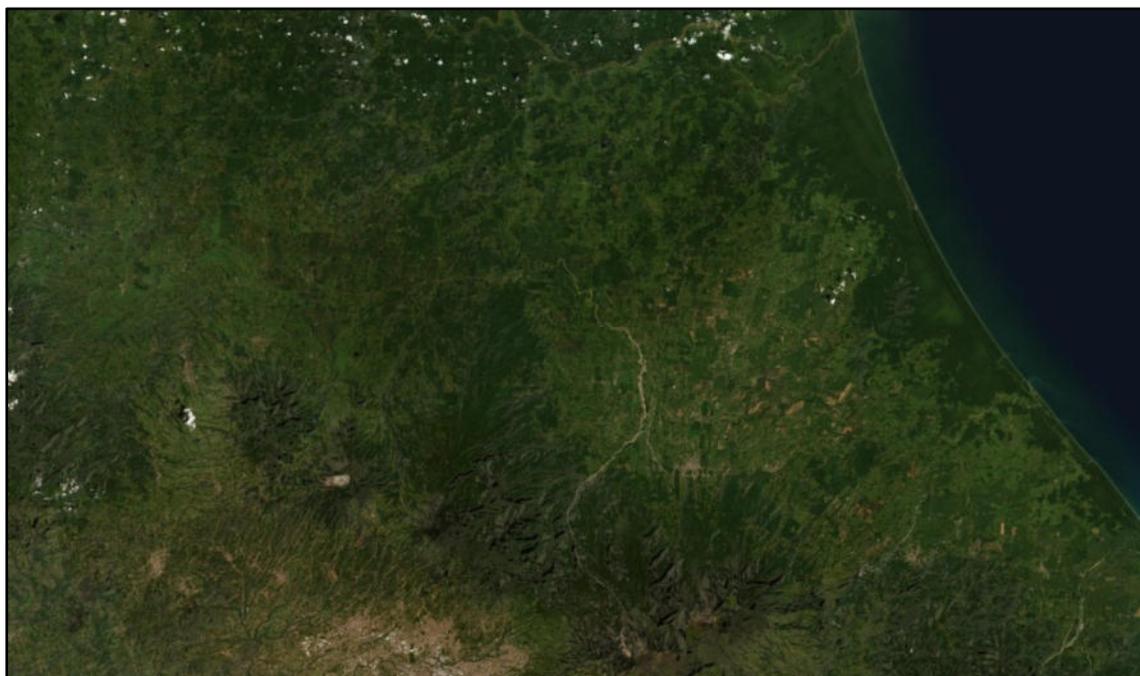
Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community, ESRI; courtesy of the U.S. Geological Survey (in: <https://earthexplorer.usgs.gov/>; last access: 20/11/2020).

**Figure L.3:** Map of El Oro and its neighboring areas



Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community, ESRI; courtesy of the U.S. Geological Survey (in: <https://earthexplorer.usgs.gov/>; last access: 20/11/2020).

**Figure L.4:** Map of Heredia and its neighboring areas



Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community, ESRI; courtesy of the U.S. Geological Survey (in: <https://earthexplorer.usgs.gov/>; last access: 20/11/2020).

**Figure L.5:** Map of La Guajira and its neighboring areas



Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community, ESRI; courtesy of the U.S. Geological Survey (in: <https://earthexplorer.usgs.gov/>; last access: 20/11/2020).

**Figure L.6:** Map of Magdalena and its neighboring areas



Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community, ESRI; courtesy of the U.S. Geological Survey (in: <https://earthexplorer.usgs.gov/>; last access: 20/11/2020).

**Figure L.7:** Map of Valverde and its neighboring areas



Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community, ESRI, courtesy of the U.S. Geological Survey (in: <https://earthexplorer.usgs.gov/>; last access: 20/11/2020).



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## Imprint

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Colombia, Costa Rica, the Dominican Republic, and Ecuador

Steffen Noleppa, Christoph Gornott,  
Sophia Lüttringhaus, Isabel Hackenberg, Stephanie Gleixner

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