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TOWARDS AN INTEGRATED AGRO-CLIMATIC MONITORING: RESULTS AND CHALLENGES IN TWO CENTRAL-AMERICAN PROTECTED AREAS

Fabio Cresto Aleina*, Pablo González-Xiloj°, Estefani Anayté González-García*, Samuel Carlos Secaira-Ziegler°

*Asociación Vivamos Mejor Guatemala, f.cresto@vivamosmejor.org.gt

°Asociación Vivamos Mejor Guatemala, p.gonzalez@vivamosmejor.org.gt

*Asociación Vivamos Mejor Guatemala, e.gonzalez@vivamosmejor.org.gt

°Asociación Vivamos Mejor Guatemala, s.secaira@vivamosmejor.org.gt

Abstract

Climate change threatens the livelihood of small farmers all around the world, as in Guatemala and Honduras. We used long-term, downscaled climate information to understand the local impacts in two protected areas, the Multiple-Use Reserve of the Atitlán Basin in Guatemala and the National Park Pico Bonito in Honduras. We selected two main crops, conducting *in-situ* analysis to assess vulnerabilities to climate change. The aim was to elaborate an agro-climatic monitoring, to understand local responses and adaptive capacities, and to elaborate *ad-hoc* adaptation measures. The results stress the urgency of realizing this monitoring, because climate change effects in the region may be catastrophic, especially in the bordering areas of the Central American Dry Corridor.

Il cambiamento climatico minaccia il sostentamento dei piccoli agricoltori di tutto il mondo, come in Guatemala e Honduras. In questo lavoro si sono utilizzate informazioni climatiche a scala ridotta a lungo termine per comprendere gli impatti locali in due aree protette: la Riserva del bacino di Atitlán (Guatemala) e il Parco Nazionale Pico Bonito (Honduras). Sono state selezionate due colture conducendo un'analisi *in situ* per valutare le vulnerabilità ai cambiamenti climatici, al fine di ottenere un monitoraggio agroclimatico per comprendere le locali capacità di risposta e per elaborare misure di adattamento *ad hoc* efficaci. I risultati sottolineano l'urgenza di mettere in atto questo sistema di monitoraggio, poiché gli effetti del cambiamento climatico nella regione possono essere catastrofici, specialmente nelle aree confinanti con il corridoio secco centroamericano.

Keywords

Adaptation, climate change, agriculture, downscaling, monitoring

Introduction

The rapid change in climate is heavily impacting vulnerable communities everywhere in the Global South. Central American countries are among the most vulnerable to such impacts, because of their exposure to climate change related events and because of the low adaptive capacities of their populations (Bouroncle et al. 2017).

The project described in paper is focused on increasing the resilience of vulnerable populations and ecosystems in two protected areas in Guatemala and Honduras. Both countries are responsible for relatively small contributions to the global greenhouse gas (Ghg) emissions, as Guatemala

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contributes to the 0.08% of the global emissions with 63.55 $MtCO_{2\text{-eq}}$ (Urrutia 2021) and Honduras with 9.7 $MtCO_{2\text{-eq}}$ (less than 0.05%, Friedlingstein et al. 2022). Nevertheless, the impacts of the climate change on these regions are very significant, as both countries rank among the 50 most affected countries by climate change and extreme weather events (Eckstein et al. 2021). Both countries declared adaptation to climate change as a national priority, and their National Adaptation Plans are focused to maintain their natural resources and to improve the resilience of local communities. Further studies are necessary to better understand the impacts of climate change at local scale, especially to establish the magnitude of some impacts in small regions such as protected areas in Central America. Recent regional studies suggested that, besides the general increase in temperature, the region will experience a widespread change in rainfall patterns that is currently leading to a general decrease in precipitation (Pascale et al. 2021). Droughts are expected to be more frequent and more pronounced, especially in the already vulnerable Central American Dry Corridor (Depsky & Pons 2021), as well as a probable increase of hurricane (Kossin et al. 2020). These changes will have a significant impact on the local agricultural practices, especially for small-scale (Imbach et al. 2017) and subsistence farmers (Viguera et al. 2019). Droughts, inundations, and an increase in intensity and frequency of extreme weather events will endanger the livelihood of farmers throughout the region (Ipcc 2022). Commercial crops like coffee (*Coffea arabica*), rambutan (*Nephelium lappaceum*), and cocoa (*Theobroma cacao),* will also be heavily impacted. Recent advances in agro-climate science (de Sousa et al. 2019) showed how vast regions in Central America (from Mexico to Costa Rica) may become unsuitable for coffee and cocoa if any adaptation strategies will be put in place. It is therefore important to elaborate strategic actions to increase the resilience of agroecosystems and adaptive capacities of the farmers (Harvey et al. 2018).

We aim to highlight in this study the vulnerabilities of two protected areas in Guatemala and Honduras: the Reserva de Usos Múltiples de la Cuenca del Lago Atilán (Rumcla, Guatemala), and the National Park Pico Bonito (Pnpb, Honduras). The Ngos Asociación Vivamos Mejor Guatemala (Avm) and the National Park Pico Bonito Foundation (Fupnapib) have been working in these two protected areas since three decades. The goal of these organizations is to improve the wellbeing of the populations and the communities living in these territories, working to protect ecosystems and their services.

The comprehension and the correct communication of the threat posed by climate change and its consequences in Central America has therefore become a priority in order to timely propose adaptive strategies to reduce the vulnerability of human communities and of natural ecosystems of these protected areas. Through an in-depth analysis of the future, long-term climate impacts in these

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territories, we are building an agroclimatic monitoring system in the regions anchored to two locally rooted NGos, to elaborate concrete adaptive actions to diminish such vulnerabilities, and to boost the sustainable development of local communities, along with the conservation of key ecosystems.

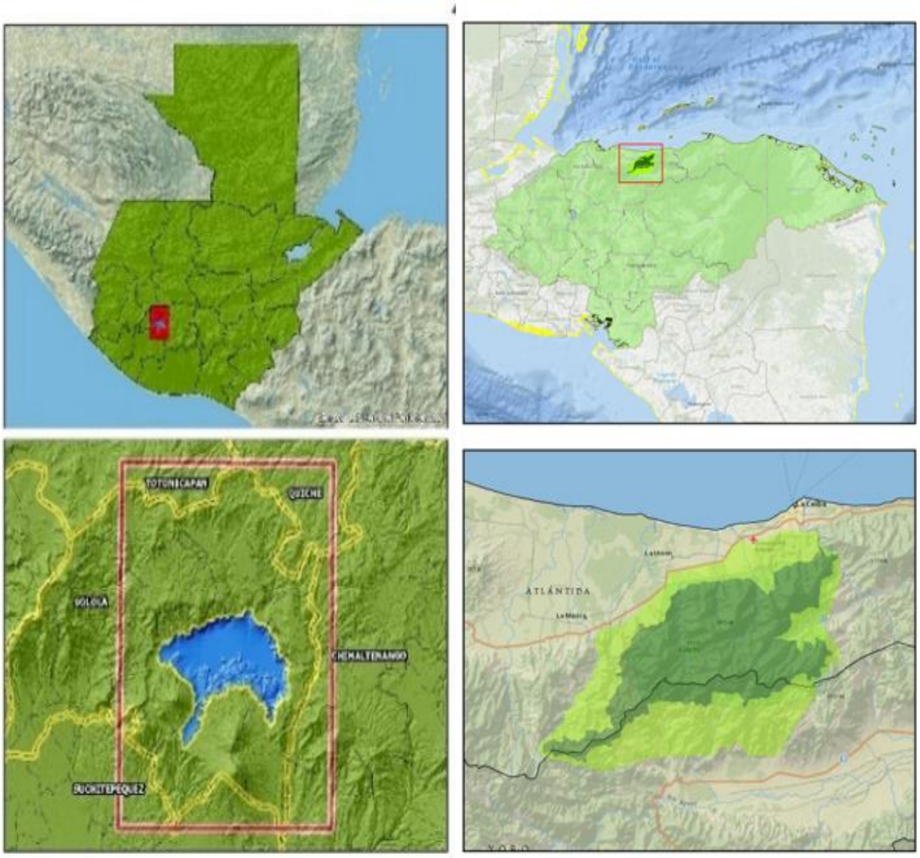

Figure 1 - The Rumcla in Guatemala (left-hand panels) and the Pnpb in Honduras (right-hand panels).

Methods

Agroclimatic modeling and monitoring is a fundamental tool in the analysis of the connections between climate and agriculture (Funk et al. 2019). The meteorological monitoring projects in the two regions led by two long-time locally rooted Ngo's offer the opportunity to establish a long-term, sustainable agroclimatic monitoring system and, above all, to focus on improving climate change adaptation strategies of local communities and agroecosystems. Thanks to the scientific training of the Ngo's technical teams, the appropriate instrumentation, and the active involvement of the communities, we designed an agroclimatic monitoring system to collect climatic and agriculture data to understand how short and long-term climate variations may impact the micro-climate, and the local agricultural practices of the investigated regions. This long-term strategy focuses moreover on anticipating potential climate changes in the next decades, promoting knowledge transfer at multiple levels, empowering farmers and stakeholders, and building resilient

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agroecosystems. In this first phase of the project we focused on the impacts of climate change on agriculture, to implement an efficient agroclimatic monitoring.

We carried out this study in two protected areas (Figure 1): the Rumcla in Guatemala (left-hand panels), and the Pnpb in Honduras (right-hand panels). The Rumcla encompasses 124,722 hectares and it is located between the highlands and the volcanic chain of Guatemala (latitude 14.704, longitude -91.198). The basin of the lake Atitlán is its important tropical ecosystem and agroecosystem, favouring its cultural richness.

The Pnpb is located in the hinterland of La Ceiba, Honduras (latitude 15.609, longitude -86,872), and encompasses around 107,000 hectares of well-connected tropical forests. Its borders are defined by the Cuero river on the west-side, and the Cangrejal river on the east-side. It is one of the biodiversity hotspots of Mesoamerica, and the high pressure caused by human activities is projected to increase in the next decades because of the consequences of climate change.

Downscaling

Generally, a climate model output is available at a scale of 40-130 km, but given the highly heterogeneous territories of the regions, this large-scale information is not enough to formulate local adaptation strategies. The first step towards an agroclimatic monitoring is therefore the downscaling of past and future climate information, as the monitoring system will be focused on long-term climate information (i.e., in the changes projected to the next decades, until 2060).

We selected simulations from a specific General Circulation Model (Gcm), the MPI-ESM-HR2 model. We used outputs from this Gcm produced for the CMIP6 exercise (Eyring et al. 2016), as the model scored higher than other CMIP6 models in Southern Central America (Almazroui et al. 2021). We used downscaled data from the WorldClim 2.1 dataset (Fick & Hijmans 2017), which provides datasets at 30-seconds (of a longitude/latitude degree) spatial resolution (this is about 1 km at the equator).

We analyzed the 1970-2000 climate data, in the dataset version released in January 2020, and we focused in particular on the projection for the 2021-2040 and 2041-2060 periods. We examined two future Ghg emission scenarios, using the Shared Socioeconomic Pathways scenarios (Ssps), which are projecting socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies (Riahi et al. 2017) in the Sixth Assessment Report of the Ipcc (Ipcc 2022).

We analysed the results from SSP2-4.5 (a moderate emission scenario, with stable Co_2 emissions until 2050, then falling but not reaching net zero by 2100) and from SSP5-85 (a very high-emission scenario, with Ghg emissions reaching 3 times pre-industrial levels by 2075). We used these scenarios (a “realistic one”, SSP2-4.5, and a “pessimistic” one, SSP5-8.5) to better understand the

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potential future consequences of the climate change in the two areas. To analyze the relative changes for the maximum temperature in the warmest month, and for the precipitation in the three wettest months, for each pixel we used the Equation 1.

$$Relative\ Change = \frac{(Future\ Value - Historical\ Value)}{Historical\ Value} \qquad \text{(Equation 1)}$$

Selected Crops

To analyse the impacts of climate change on agriculture, we selected two crops in each area: maize (*Zea mays)* and coffee in Rumcla, and rambutan and cocoa in Pnpb. We performed in-depth regional diagnostics for each crop, considering both the means of production, and potential climate related vulnerabilities.

In Guatemala maize is the base for the diet, especially in rural areas (Usaid 2019). Within the Rumcla, corn covers over 17% of the land surface. In the Atitlán region, historical findings (Harvey et al. 2019) document the presence of this crop as far back as the Mayan Preclassic period (1000-300 BCE). It is an integral part of the so-called "*milpa system*", a traditional crop-growing system used throughout Mesoamerica and still widely spread in the Rumcla, which combines maize with beans and squash. On the other hand, the percentage of maize monocultures has been increasing in the southern part of the Rumcla. In the same region, the main commercial crop is coffee, occupying 15% of the land surface. It is a fundamental crop for the economy of the region, and it can be found mainly in agroforestry systems (i.e., the deliberate and simultaneous management of trees within crop systems). Around 95% of the coffee production in Guatemala is under shade, and therefore planted in association with fruit with timber trees (Anacafe 2019).

In Honduras, we chose the rambutan because of its rising economic importance for the communities living in the buffer zone of the Pnpb and at its borders. After its introduction at the beginning of the last century, this fruit has expanded in the Pnpb area, and it has become a viable economic alternative for small-scale farmers to diversify their traditional production (consisting mainly of cocoa or staple grains). Fupnapib is currently promoting the rambutan as a crop to be introduced in agroforestry systems, using it to restore degraded lands or to convert areas once used for cattle. Finally, cocoa is historically widespread in the buffer zone of the national park, and it is also usually cultivated within an agroforestry system.

In general, we face a major challenge in the Pnpb area as, because of the remoteness of the region and of its communities, the data available are much sparser and scarcer than the data available for the Rumcla in Guatemala. To further complement the available information, therefore, we conducted *in-situ* interviews with local farmers in both of the study areas.

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Results and Discussion

We analyzed the downscaled data for the two regions, comparing the historical climatology with the downscaled model in future scenarios. We then used this information to explore the vulnerabilities of the selected crops and to elaborate potential solutions to diminish such vulnerabilities.

In both regions (and scenarios) we see a general increase in the average annual temperature, more pronounced in the SSP5-8.5 (heavy emission scenario), especially towards the end of the period (2041-2060). Results also showed a moderate increase in average annual precipitation towards the mid of the century, and a pronounced decrease towards the end of the century, more significantly in the SSP5-8.5 scenario (2041-2060). The changes are nevertheless heterogeneously projected in the areas (Figures 2 and 3).

Rumcla

In both scenarios, the average temperature and the maximum temperature of the warmest month steadily increase from the present until the 2041-2060 period (Figure 2, panels (a), (b), and (c)). The annual average temperature is projected to a steep increase especially in the densely populated and cultivated area around the lake Atitlán, with average temperature switching from 15.5-17.1 degrees to 17.2-20.4 degrees. The colder pockets in the north of the region and on the top of the volcanoes in the south will tend to diminish, with potentially catastrophic consequences for local ecosystems (e.g., cloud forests), and significant impacts for the local agriculture. On the other hand, the average annual precipitation is not projected to heavy changes, but the analysed data don't give precise information on the distribution of the precipitation throughout the year. In mid-century higher precipitations are expected in the Rumcla, before a drop in the period 2041-2060 (panels (d), (e), and (f), Figure 2).

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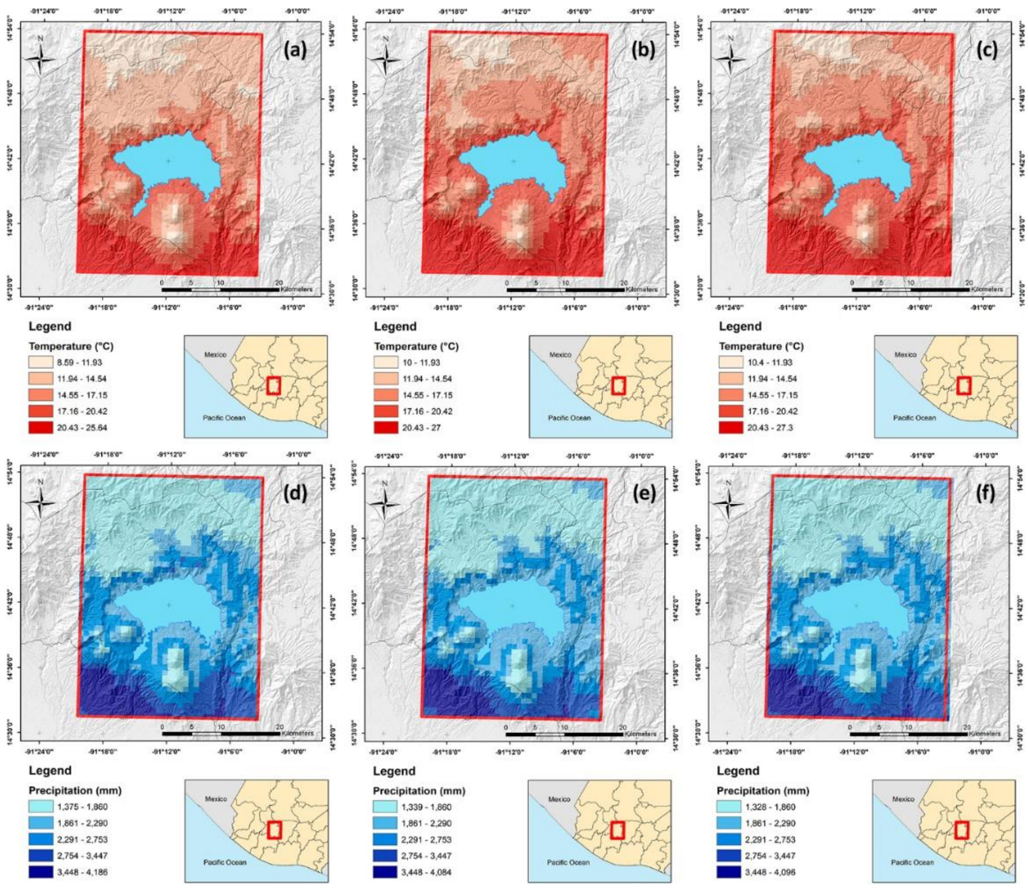

Figure 2 - Average annual temperature and precipitation in the Rumcla forecast. Actual (panels (a) and (d)), in the 2041-2060 period under a moderate Ghg emission scenario (panels (b) and (e)) and a heavy Ghg emission scenario (panels (c) and (f)).

In Figure 3 we study the projected future relative changes in temperature and precipitation. Analyzing the difference in the precipitation in the three wetter months between current and projected values (Figure 3, panels (c) and (d)), we notice that in the warmer, wetter part of the Rumcla, precipitation is expected to have a moderate average decrease (more pronounced in the moderate emission scenario), whereas in the northern, drier part of the Rumcal, precipitation is expected to decrease up to 5-6% of the current values. The two scenarios differ in the projected patterns towards 2060, as the SSP2-4.5 scenario forecasts a stronger decrease in precipitation in the eastern part of the Rumcla that does not appear in the SSP5-8.5, heavy emission, scenario. Looking at the relative change in the maximum temperature of the warmest month, our results highlight that in both scenarios relative changes are stronger in the colder areas, i.e. the northern part of the Rumcla and the top of the volcanoes (Figure 3, panels (a) and (b)). In the heavy emission scenario, changes are much steeper, as they predict almost a 10% temperature increase in the whole northern part of the protected area.

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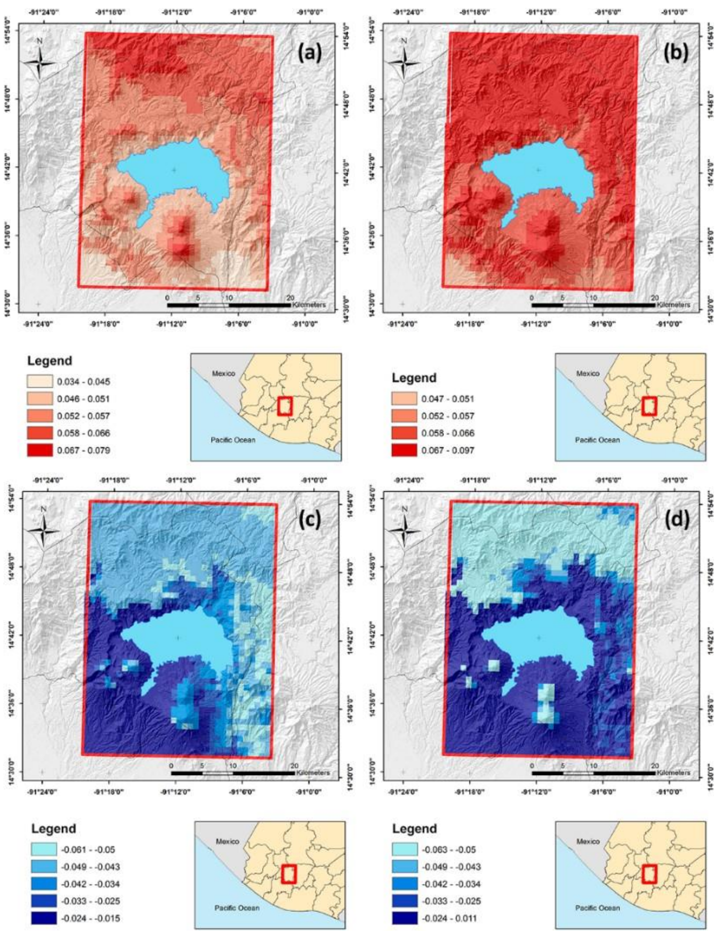

Figure 3 - Relative changes in Rumcla for the maximum temperature in the warmest month with moderate and heavy Ghg emission scenarios (actual panel (a), future panel (b)) and for the precipitation in the 3 wettest months with the same scenarios (actual panel (c), future panel (d)).

Pnpb

The Pnpb is located in a warmer area than the Rumcla, with higher average temperatures and a stronger influence of the near Atlantic Ocean. In both scenarios the annual temperature will increase in the park, especially in the warmer regions, towards the Atlantic coast, and in the southern part of the country. In the basins of the Cuero and the Cangrejal rivers, which delimitate the park on the western and the eastern part respectively, the average annual temperature also increases up to 29 degrees, which can have enormous consequences for the crops cultivated in these areas. In the central zone of the park, with denser vegetation and a higher altitude, the cold pockets diminish in both scenarios, more in the heavy emission scenario (Figure 4, panels (a), (b), and (c)). Analogously to the results for the Rumcla, also the cloud forests of Pnpb are threatened by such changes. More worryingly, the increase in temperature in the southern part of the park is mirrored by a generalized steep decrease in precipitation in the whole park, especially in its center, where there are the priceless water reservoirs for the local agriculture are located (Figure 4, panels (d), (e), and (f)). The decrease is particularly significant because of the proximity of the southern border of the park with

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the Central American Dry Corridor, a semi-desertic region which is currently expanding (Depsky & Pons 2021).

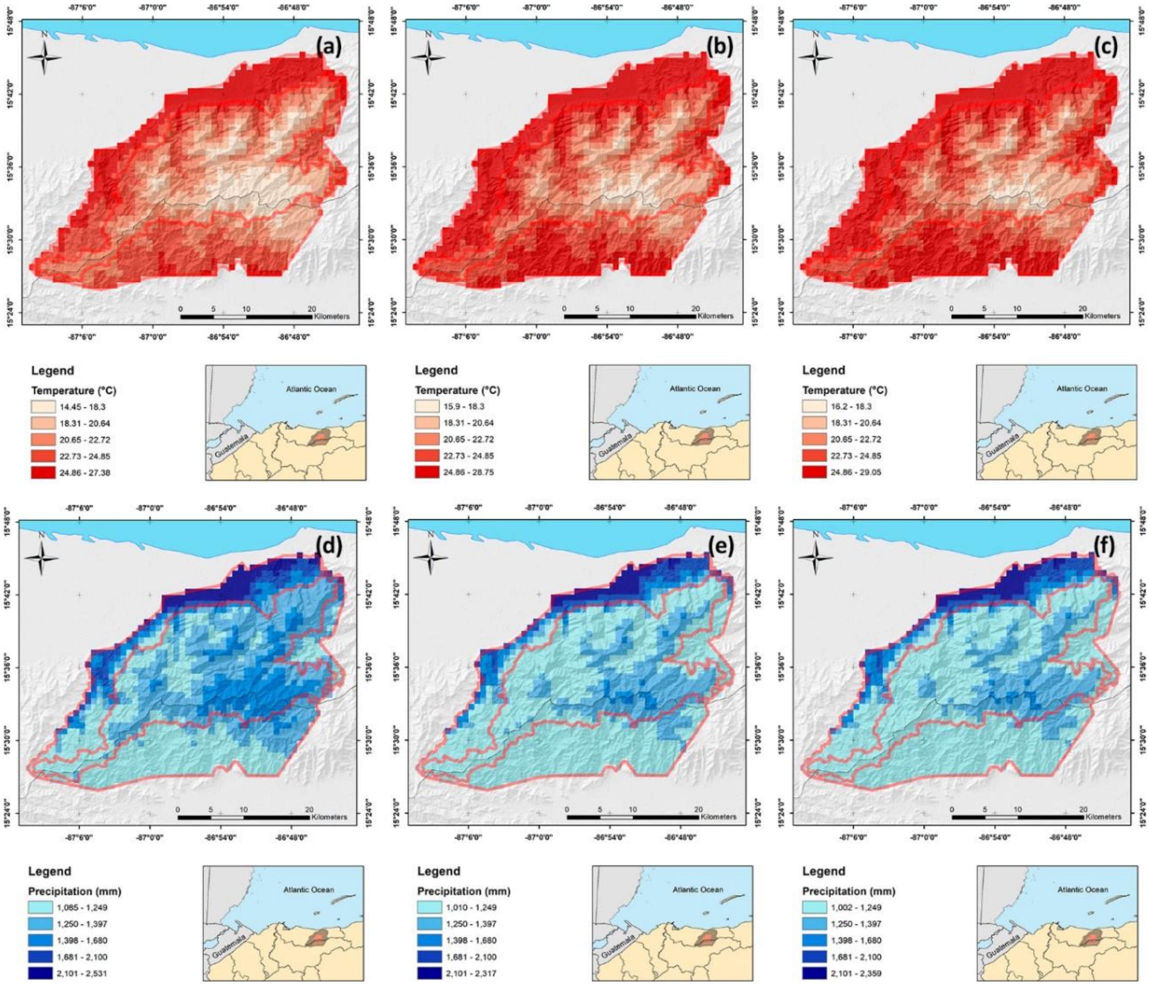

Figure 4 - Average annual temperature and precipitation in Pnpb for the current climatology (panels (a) and (d), respectively), and projected average annual temperature and precipitation in the decades 2041-2060 under a moderate Ghg emission scenario (panels (b) and (e)) and a heavy Ghg emission scenario (panels (c) and (f)).

This issue is even more striking if we analyze the relative changes in the projected precipitation in the three wettest months (Figure 5, panels (c) and (d)). In a moderate emission scenario, the decrease of precipitation is even more intense (up to 12% of the current values). In a heavy emission scenario, the decrease of rainfall in this region is not as strong (between 9 and 10%), but the temperature increases are much higher (up to 9% of the current values) and almost homogeneous in the whole protected area (Figure 5, panels (a) and (b)). Analyzing the relative differences between the current and the future climate, our results show that in both scenarios there is an increase in the highest temperature of the warmest month throughout the whole park. In a moderate emission scenario, in particular, our results show a 6-7% increase in temperature in the

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coldest parts of the park and a 4-5% increase in the warmest areas. In a heavy emission scenario, instead, the climate model forecasts a generalized 6 to 9% increase throughout most of the Pnpb area.

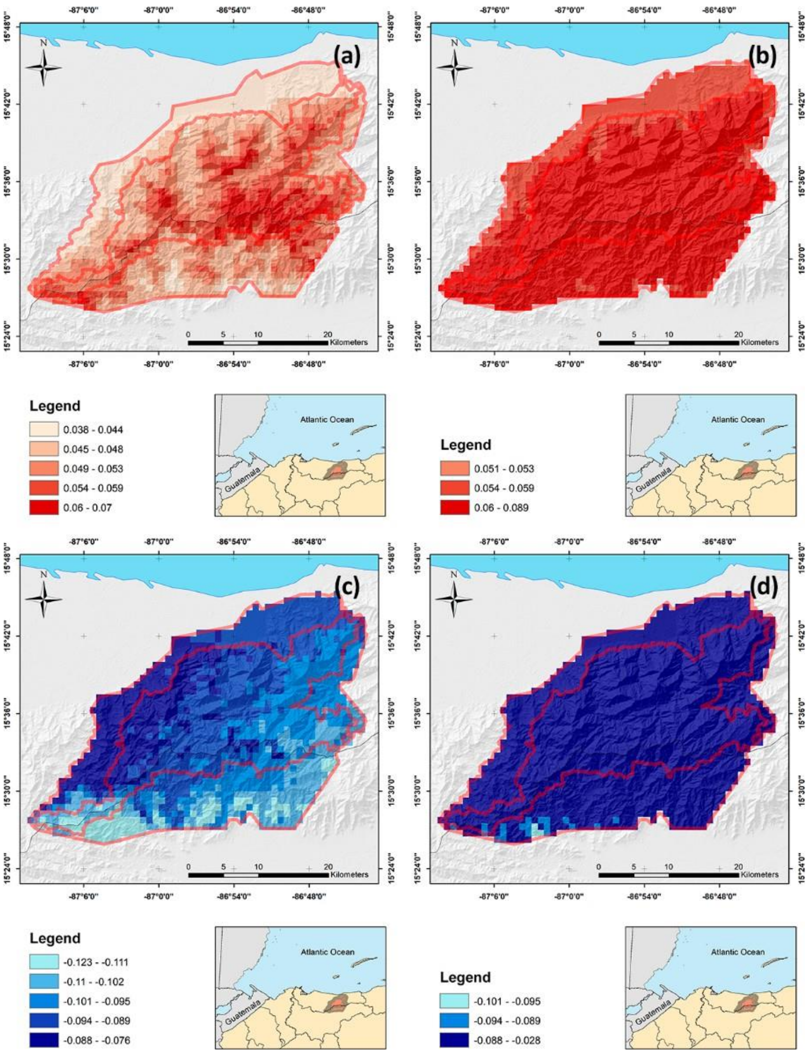

Figure 5 - Relative changes in the Pnpb for the maximum temperature in the warmest month from current and future climate under a moderate and heavy GHG emission scenario (panels (a) and (b), respectively). Panels (c) and (d) show the relative changes in the Pnpb for the precipitation in the 3 wettest months from current climate to future climatology under a moderate and a heavy GHG emission scenario, respectively.

Consequences for the selected crops

The main result of our *in-situ* interviews is that the main climatic variables influencing agriculture in Central America are related to extreme weather events, which have not been completely investigated in the present study. In particular, maize in the Rumcla is heavily impacted by droughts, strong winds, inundations and frost. If frost events are expected to diminish because of the general shift towards higher mean temperatures (a robust pattern that can be seen in the average

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minimum temperatures in both regions and scenarios), our results indicate that other extreme weather events may increase in the next decades. Our *in-situ* investigations with small-scale farmers indicated that farmers are already reporting heavy losses because of recent changes in precipitation patterns. Recent severe droughts, for example, are impacting the productivity of maize in the region because of the almost complete absence of irrigation systems and their dependence on the seasonal rainfall. Further investigation is needed to pinpoint the exact extent of these threats, with a focus on the potential changes of the onset of the rainy season, as well as on potential future changes of the so-called "*canicula*", a relatively rain-free period happening in July-August because of local changes in the intensity of the trade winds in the Caribbean (Orrego León et al. 2022). Potential adaptation measures involve the use of water trapping systems where irrigation is not economically or geographically possible, the inclusion of trees in the plots to decrease soil degradation and to act as wind breaking barriers. Nevertheless, further investigation on extreme weather events is needed to establish a proper long-term climate monitoring and suggest effective adaptation measures with a higher degree of certainty. About the coffee production in the Rumcla, besides the impacts of extreme weather events, a general increase in average temperature, such as the one predicted by our study, may heavily affect productivity, also because of its correlation with the appearance of coffee rust (*Hemileia vastatrix*) and other diseases. Our investigation with local farmers and of the existing literature from the Guatemalan national coffee association (Anacafé) shows that reported daily temperatures higher than 25ºC are dangerous for the crop. Analyzing changes in the maximum temperature of the hottest month, we are observing that under both a heavy-emission scenario and a moderate-emission scenario, regions which are currently cultivated with coffee, especially at the shores of Lake Atitlán, might become less suitable, if not completely unsuitable, for its cultivation by the end of 2060. This is an important finding, as in this part of the Rumcla most of the farmers are low-income small-scale farmers, extremely vulnerable and currently with few possibilities to adapt. Moreover, vast regions towards the Pacific coasts, where larger scale farmers are already switching from coffee to other crops, will experience annual average temperatures between 21 and 28 degrees Celsius, which will make them altogether unsuitable for coffee. A potential switch to cocoa or to fruit trees may be a potential adaptation measure, whereas in the Atitlán basin we plan to explore novel combinations of agroforestry systems (i.e., with different shade trees), more tolerant to higher temperature and lower precipitation.

For the rambutan, our findings showed that if the tree and its fruit can be cultivated in a range between 22 and 35 degrees Celsius, the optimal temperature for its productivity is around 27 degrees. The future mean temperature changes, especially in the Cuero river basin, where average temperature towards year 2060 may rise up to 29 degrees on average and over 33 degrees in the

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hottest months in both emission scenarios, pose a potential limit to rambutan production. Climate simulations showed that precipitation patterns in the region are also expected to undergo drastic changes, especially between 2041 and 2060. The basins of the Cuero and the Cangrejal rivers, in particular, that are now areas of rambutan production, are shown to be particularly vulnerable and exposed to strong rainfall decreases, putting them at the edge of the area where the rambutan agriculture will be possible. To obviate these issues, we are suggesting the association of rambutan (often cultivated as a monoculture in the region) with other trees or crops, in a multilevel agroforestry system, diversifying the income of the farmers and diminishing their dependence on only one produce, while simultaneously increasing the resilience of the rambutan trees to higher temperatures and different precipitation patterns. Agroforestry, on the other hand, will certainly diminish the short-term productivity of the rambutan plots because of the decreased tree density, but we argue that such decisions will offer sustainable long-term benefits, especially in the second half of the century. Further analysis is needed to investigate the impact of extreme weather and climate events, as well as the specific agroforestry systems needed to effectively adapt to climate change impacts. Finally, we analyzed the cocoa cultivations that in the region share similar geographic distributions as the rambutan (i.e., the buffer area at the eastern and western limits of the Pnpb). As for the rambutan, our analysis shows that this crop will become more vulnerable in the future because of the general higher temperatures (especially in the Cuero river basin) and lower precipitation. On the other hand, as cocoa generally tolerates lower precipitation rates than the rambutan and because it is already found in agroforestry systems, we argue that its vulnerability to the projected changes is lower in this region than other crops, with the exception of the southern border of the Pnpb. This region is already presenting some challenges for the cultivation of cocoa, because of the lower rain, the higher temperature, and the so-called Central American Dry Corridor borders.

This region will become extremely vulnerable in the future, with even lower rainfall and even higher temperatures, making it towards 2060 potentially unsuitable not only for cocoa, but for other crops, too. In general, we argue that further, in-depth investigations in the region are needed, to better understand not only the average climate changes, but also changes in extreme weather and climate events.

Conclusions and outlook

Our investigation showed that significant changes in temperature and precipitation are expected in the next decades in the studied regions. In particular, general increases in temperature will be mirrored by a decrease in precipitation.

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The combination of these dynamics will threaten the productivity and the livelihood of local farmers. Under a heavy emission scenario, these changes may have consequences so catastrophic that some regions may become unsuitable for the crops currently cultivated.
Understanding the amplitude of the projected changes, the intensity, the probability, and their geographical extent is vital to elaborate efficient and timely adaptation measures, when and where possible.
This is a first step towards an agroclimatic monitoring system that considers both long-term downscaled climate information, and bottom-up, *in-situ* information collected with the local farmers. After this first climate analysis, we are establishing both in the Rumcla and in the Pnpb a series of control plot to monitor the changes to the selected crops (starting from 2023), to further understand the short and long-term effects of climate change in both regions, and to collect fundamental information to better assist the local farmers in increasing their resilience and their adaptive capacity to climate-related threats.
A limitation of this study is that our results do not consider changes in extreme events, and only focus on average changes. A second step will be therefore to analyze changes of extreme weather events which are often much more dangerous for local farmers than mean changes. In the next year we plan to elaborate this kind of analysis to downscaled time series of climate models.
We also plan to establish a baseline of carefully chosen bio-indicators that will be used to understand the impact of climate change on ecosystems and biodiversity.
Through a niche modelling, land use change analysis and future projections, we plan to include all these components in a holistic and comprehensive agro-bio-climatic monitoring system, the first of its kind in Central America to our knowledge.
This system, when in place, will be a key tool in helping reduce the long-term climate-related vulnerability not only of local communities, but also of local ecosystems and of the local biodiversity.

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List of acronyms

Avm	Asociación Vivamos Mejor Guatemala
Fupnapib	Fundación Parque Nacional Pico Bonito
Gcm	General Circulation Model
Ghg	Greenhouse gas
Fupnapib	National Park Pico Bonito Foundation
Ipcc	Intergovernmental Panel on Climate Change
Pnpb	Parque Nacional Pico Bonito
Rumcla	Reserva de Usos Múltiples de la Cuenca del Lago Atitlán
SSPs	Shared Socioeconomic Pathways scenarios