Climate Adaptation Turning Points in cacao production in the Peruvian Amazon

M.Sc. Thesis by

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Water Systems and Global Change Group

Frontpage image: Cacao blossoms on tree.. S. Korswagen Eguren, San Martin, 2013.

Back cover image: Cacao flower on tree.. P. Korswagen Eguren, San Martin, 2013.

Climate Adaptation Turning Points in cacao production in the Peruvian Amazon

Master Thesis Water Systems and Global Change Group in partial fulfillment of the degree of Master of Science in Climate Studies at Wageningen University, the Netherlands

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Acronyms and abbreviations

APPCACAO	Peruvian Association of Cacao Producers (guild)	Asociación Peruana de Productores de Cacao (gremio)
ATP	Adaptation turning points	
BI-CIAT	Alliance Biodiversity International - CIAT	Alianza Biodiversity International - CIAT
CABI	Centre for Agriculture and Bioscience International	
CIAT	International Center for Tropical Agriculture	Centro Internacional de Agricultura Tropical
CIRAD	French Agricultural Research Centre for International Development	Centre de coopération internatio-nale en recherche agronomique pour le développement
Clima-LoCa	Climate Low Cadmium Project	
CMIP5	Fifth phase of the Coupled Model Intercomparison Project	
CCN 51	Colección Castro Naranjal 51, cacao clone know for its high productivity	Colección Castro Naranjal 51, clon de cacao conocido por su alta productividad
DEEIA	Office for Economic Studies and Agrarian Information	Dirección de Estudios Económicos e Información Agraria
DGA	General Directorate for Agriculture	Dirección General de Agricultura
DRA	Regional Agricultural Office in San Martín	Dirección Regional de Agricultura de San Martín
ENSO	El Niño Southern Oscillation	
NDC	Nationally Determined Contributions	
ENBCC	National Strategy on Forests and Climate Change	Estrategia Nacional sobre Bosques y Cambio Climático
ENCC	National Climate Change Strategy	Estrategia Nacional ante el Cambio Climático
GADM	Global Administrative Area Database	Base de datos global de áreas administrativas
GCM	General Circulation Model	Modelo de Circulación General
GHG	Greenhouse gas	
GIS	Geographic Information Systems	
GIZ	German Agency for International Cooperation	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GTM	Multisectoral Working Group	Grupo de Trabajo Multisectorial
IIAP	Peruvian Amazon Research Institute	Instituto de Investigación de la Amazonía Peruana
INEI	Peruvian National Institute for Statistics and Informatics	Instituto Nacional de Estadística e Informática
IPCC	International Panel on Climate Change	
LMCC	Framework Law on Climate Change	Ley Marco sobre Cambio Climático
MINAGRI /	Peruvian Ministry for Agricultural Development and Irrigation (Previously	Ministerio de Desarrollo Agrario y Riego

MIDAGRI	MINAGRI and MINAG)	(antes MINAGRI y MINAG)
MINAM	Peruvian Ministry of the Environment	Ministerio del Ambiente
MINCETUR	Peruvian Ministry of International Commerce and Tourism	Ministerio de Comercio Exterior y Turismo
MINEDU	Peruvian Ministry of Education	Ministerio de Educación
NAP	National Adaptation Plan	Plan Nacional de Adaptación al Cambio Climático
NGO	Non-governmental organization	Organización no gubernamental
PIPCACAO	Public Investment Project on Cacao in San Martin	Proyecto de Inversión Pública en Cacao en San Martín
PESEM	Sectoral Strategic Multianual Plan	Plan Estratégico Sectorial Multianual
PLANGRACC-A	Risk Management and Climate Change Adaptation Plan in the Agricultural Sector	Plan de Gestión de Riesgos y Adaptación al Cambio Climático en el Sector Agrario
RCP	Representative Concentration Pathways	
SECO	State Secretariat for Economic Affairs of the Swiss Cooperation	Secretaría de Estado para Asuntos Económicos de la Cooperación Suiza
SENAMHI	Peruvian National Service for Meteorology and Hydraulics	Servicio Nacional de Meteorología e Hydráulica
UNFCCC	United Nations Framework Convention on Climate Change	Convención Marco de las Naciones Unidas para el Cambio Climático
USAID	United States Agency for International Development	
WGS	World Geodesic System	Sistema Geodético Global
WUR	Wageningen University & Research	Universidad de Wageningen

Abstract

Cacao (*Theobroma cacao*) has a high social and economic relevance at the local scales where it is produced. Climate change impact on cacao, as well as on cacao's main pests and diseases, are of concern to diverse stakeholders in the Peruvian cacao landscape. This research estimates thresholds in time and space for cacao production in the Peruvian Amazon, by modelling its suitability under present and future climate change scenarios.

First, goals and challenges of cacao producers were identified. Second, the acceptable thresholds for cacao production, i.e. performance thresholds, together with the critical climate variables behind them, were estimated based on stakeholders' perceptions and literature research. Third, the suitable habitat of cacao and selected pests (*Carmenta sp., Monalonion dissimulatum*) and diseases (*Moniliophthora roreri, Moniliophthora perniciosa, Phytophthora sp.*) were projected with an ensemble modelling approach. Species presence data available for Peru and 35 bioclimatic, soil and terrain variables, were used as predictors. Ensemble suitability models were produced under future climatic conditions using five General Circulation Models, two Representative Concentration Pathways (RCP 4.5 and RCP 8.5) and three time horizons (2030, 2050, 2070). Finally, the adaptation turning points for cacao production in San Martin were analysed considering the performance thresholds and suitability models.

Cacao farmers in Peru aim to have an economic activity that delivers sustained income and allows them to achieve an acceptable quality of life. Their main challenges comprise drought, pests and diseases. For farmers, droughts of two weeks during the harvest season are critical, because they reduce the yield that could be harvested and commercialized. Drought stress also turns cacao trees more vulnerable to attacks of pests and diseases.

The climate conditions where farmers perceive undesirable conditions were identified at a precipitation <100 mm/ month and temperatures >32°C in the study area located in San Martin. Further critical climatic variables are: precipitation of the driest month, maximum temperature of the warmest month, as well as precipitation of the driest quarter and mean temperature of the driest quarter.

In San Martin cacao already faces current maximum temperatures that exceed its optimum range and reach an average maximum of 32°C during the warmest month of the year. Climate projections show a clear increasing trend in temperature for the future. Models project an average of 34.8°C for 2050 under RCP 4.5 and up to 37.9°C by 2070 under RCP 8.5. Some localities in the study area also receive precipitation lower than 100 mm/ month during the driest month and the driest quarter under current conditions. Although there is variability among projections and RCP, models project a decrease in precipitation for the driest month and driest quarter under RCP 8.5.

The suitability models show that the distribution range of cacao is mostly projected to remain suitable. Areas that may gain in suitability are located along a narrow NNW - SSE stripe along the Andes at higher elevations. In contrast, losses are projected along the Andean foothills and lower Amazon basin, especially towards 2070. Diseases follow a similar geographic trend. However, for some diseases the loss of suitable areas is prominent along large areas at the eastern Andean slopes and towards the lower Amazon. Insects' responses vary under future scenarios. *Carmenta sp*. maintains large suitable areas in San Martin and *Monalonion sp*. gains in suitable areas under RCP 8.5.

This work shows the added value of integrated approaches, especially by adding performance thresholds and incorporating stakeholders' perceptions into ecological modelling. In addition, to the author's knowledge, this work is the first to model cacao together with varied cacao pests and diseases in a single modelling exercise.

There is a diversity of stakeholders in the Peruvian cacao sector, who require practical information on climate change impacts on cacao, its pests and diseases, as well as adaptation possibilities. Thanks to scientific platforms as well as stakeholder networks, there is an opportunity and momentum to share the results of this work.

Keywords

- Climate change
- Ensemble suitability modelling
- Performance thresholds
- *Theobroma cacao*
- *Moniliophthora roreri*
- *Moniliophthora perniciosa*
- *Carmenta sp*

1. Introduction

Agriculture is one of the most vulnerable sectors to climate change (Porter et al., 2014). Food production is affected by water availability, climate hazards, the temperature tolerance of crops and species shifts. Further impacts comprise increased food prices and reduced access to food and markets, which altogether affect food security, rural economies and markets for agricultural commodities (Oppenheimer et al., 2014; Porter et al., 2014). In this context, adaptation to climate change is critical for rural livelihoods and smallholder farmers (Lee et al., 2014; Searchinger et al., 2019).

In South America, agricultural productivity is expected to decrease in the next decade due to increased temperature and decreased rainfall in the Andes (Magrin et al., 2014; Porter et al., 2014). Significant trends in precipitation and temperature have already been observed, as well as changes in climate variability and extreme events (CIAT, 2014; Magrin et al., 2014). Additionally, agricultural expansion coupled with deforestation at the edges of tropical rainforests may asseverate climate change impacts. Social conditions, particularly poverty, increase the vulnerability to climate variability and change (Magrin et al., 2014).

In this sense, the case of cacao (*Theobroma cacao*) is of particular interest. Cacao production is especially important for local communities as a source of income and to get out of poverty (Cerda et al., 2014; Medina & Laliberte, 2017; Ortega et al., 2017; MINAGRI, 2018). The cacao value chain offers opportunities to innovate, gain access to knowledge, empower communities and access new markets (Jacobi et al., 2014; Nash et al., 2016). Recently, strategies such as agroforestry, organic certification or CO2 sequestration, offer opportunities to transform cacao production into a more sustainable option, as well as to mitigate greenhouse gases and adapt to climate change (Vaast et al., 2016; Maas et al. 2020).

Cacao in South America is projected to be directly and indirectly affected by climate change (CIAT, 2014; Ortega et al., 2017). Apart from impacts on tree growth and production, climate change may also modify the geographic range of pests, diseases and pollinators, which are critical for crop production and higher yield. On top of this, international trade of plant material can also accelerate the introduction and spread rate of invasive species (Bailey & Meinhardt, 2016; CABI, 2021). Last but not least, cacao production has a high social and economic relevance at local scales where it is produced and along its value chain.

1.1 The importance of cacao in Peru as a case study

Peru represents an important case study for climate change and cacao. Climate impacts on cacao are of concern to the Peruvian Government (MINAGRI, 2013, 2018), individual farmers, farmer associations, the academia and the cacao guild[1]. The spread of pests and diseases, the emergence of new or invasive pests and diseases, together with a higher potential to damage crops and or pollinators, are the most striking concerns to the cacao stakeholders[2]. Doubts also arise on adaptation strategies, specifically on how to adjust production to changing climatic conditions and identifying resilient genotypes (Medina & Laliberte, 2017; Lahive et al., 2019; Ceccarelli et al., 2021).

Cacao is the 6th most important crop to the country in terms of number of producers and harvested area (MINAGRI, 2018), as well as the 6th national agroexportation good (INIA, 2019). In 2016, nearly 140 000 farmers were growing cacao, of which 111 000 harvested and commercialized it. Two thirds of cacao producers are smallholders owing less than 10 ha and in family agriculture systems. Cacao surface is about 200 000 ha, representing 3.4 % of the country's agricultural surface (MINAGRI, 2018). The largest and best-known cacao producing region is San Martín, which scores highest in terms of agricultural surface, number of cacao producing units, total yield and number of producers (MINAGRI, 2018).

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[1] Manager of APPCACAO, personal communication, January 2020.

[2] Personal communications during workshop and interviews (February – May 2020).

Due to its importance for family agriculture, local and international markets, the cacao value chain has received attention and support from governmental institutions and NGOs, and is gaining interest as a commodity for the private sector (APPCACAO, 2013; Chávez, 2016; MINAGRI, 2013, 2018; MINCETUR, 2018). For instance, Peru is nowadays the 2nd largest exporter of organic cacao (MINAGRI, 2018; MINCETUR, 2018). Besides, cacao cultivation is incentivised to replace illegal coca plantations since the 1980s (MINAGRI, 2015).

The Peruvian public policies aim to prioritize adaptation to climate change (MINAGRI, 2013; MINAM, 2015a; Peruvian Government, 2019). In 2020, Peru was fine-tuning its National Adaptation Plan (NAP), which contains indicators on cacao agricultural surface and exportation (GTM-NDC, 2018). Meanwhile, the National Institute for Agrarian Innovation (INIA) has highlighted the key role of climate in cacao production, as well as the importance of considering current and future climate change impacts and reinforcing farmers' adaptation capacity, among other adaptation strategies (INIA, 2019). Since 2020, relevant stakeholders are working on a National Action Plan on Cacao, which aims to bring together goals of all stakeholders in the cacao value chain and plan future actions[3]. In addition, key stakeholders regularly dialogue during the "Mesa Técnica de Cacao y Chocolate", and several national and international fora and events are held around the cacao value chain.

The impacts and challenges driven by climate change lead to many questions and uncertainties in the Peruvian cacao sector. The main question is about the future suitability of cacao. Is cacao resilient to climate change or to the impacts of pests and diseases in the future? Is there a moment in time where it reaches an ecological threshold? Or does the production become not profitable or socially beneficial anymore? And what are the best adaptation strategies?

Considering these questions, stakeholders' concerns, the NAP and the National Action Plan on cacao, there is a momentum to contribute to planning processes in the cacao value chain in Peru. In this context, it is relevant to analyse future suitability for cacao and its main pests and diseases in Peru under climate change in order to support and advice the stakeholders depending on the cacao economy[4].

1.2 The research gap

Several studies analyse climate change impacts on cacao production worldwide. However, the majority of studies focus on Africa (Ojo & Sadiq, 2010; Nwachukwu et al., 2012; Nkobe et al., 2013; Läderach et al., 2013; Schroth et al., 2016, 2017; Asante et al., 2017; Bunn et al., 2019) and Latin America broadly (Moraes et al., 2012; Hutchins et al., 2015; Ortega et al., 2017; Gateau-Rey et al., 2018; de Sousa et al., 2019). Only recent study has modelled cacao suitability under climate change for Peru, differentiating between cultivated and wild cacao (Ceccarelli et al., 2021).

Regarding cacao pests and diseases, research in the context of climate change or contemplating weather parameters is scarce. A few studies focus on key species, mostly fungi, in cacao producing regions like Brazil, Nigeria and Costa Rica (Moraes et al., 2012; Agbeniyi et al., 2015; Leandro-Muñoz et al., 2017; Etaware et al., 2020). Only one study was found to analyse climate change impacts jointly on cacao and a pathogenic fungus (Ortega et al., 2017). Most literature around cacao pests and diseases consists of biological or ecological descriptions of the species, followed by management guides.

The lack of climate studies applied on cacao in South America is evident (Bunn et al., 2016). Some studies focus on physical and ecological impacts on the cacao tree and production yield. Other qualitative studies focus on farmer's perceptions on climate change (Jacobi et al., 2013). Few studies apply a spatial approach in analysing climate impacts on cacao. Agricultural or ecological modelling under climate change scenarios have been applied in

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[3] C.R. Chávez, personal communication (February-April, 2020).

[4] During the research, contact was established with multiple public and private stakeholders, who found this research interesting and with a large potential. The researcher fully compromised to give back the results from this study.

West Africa (Läderach et al., 2013; Schroth et al., 2016, 2017; Bunn et al., 2019), Latin America (Moraes et al., 2012; Ortega et al., 2017; de Sousa et al., 2019) and the Caribbean (Eitzinger et al., 2015a, 2015b). Only four studies address the future suitability for cacao in Peru (CIAT, 2014; Bunn et al. 2016; Ortega et al., 2017; Ceccarelli et al., 2021).

Suitability modelling is a biophysical approach that models a species' potential niche from an ecological perspective. Most of the times, stakeholders' concerns or other on-farm issues are not incorporated in the modelling. An opportunity arises to complement and contrast suitability modelling with stakeholder relevant thresholds. In this sense, the adaptation turning points (ATP) approach provides a basis to frame stakeholder relevant thresholds. The ATP approach identifies a moment in time when a threshold of concern is met due to climate change (Werners et al., 2013). Beyond this threshold, undesirable conditions or an unsustainable situation arise, and it becomes necessary to adopt adaptation strategies (Werners et al., 2013). The threshold of concern can be defined as a performance threshold according to a group of stakeholders and is context specific (Werners et al., 2018a). The definition of such a threshold requires consultative processes to determine what is an acceptable or undesirable situation (Werners et al., 2018). Thus the approach approximates suitability from the perspective of the stakeholders.

The ATP are relatively recent in the scientific literature and belong to a flexible adaptation planning approach (Kwadijk et al., 2010; Haasnoot et al., 2013; Werners et al., 2013; Werners et al., 2015). They have been applied to varied case studies and continents (Kwadijk et al., 2010; Bölscher, 2011; Haasnoot et al., 2012, 2013; Bölscher et al., 2013; Smolenaars, 2018; Werners et al., 2018a, b; Arce Romero, 2019; Gómez Álvarez, 2019). However, to date, no assessment has focused on performance thresholds for cacao, and only one study has explored limits to adaptation for cacao in West Africa (Schroth et al., 2016).

To put it into a nutshell, the following thematic and methodological research gaps were found in current literature:

i) identifying stakeholder-relevant thresholds for cacao;
ii) analysing climate change impacts on cacao with its main pests and diseases in a single modelling exercise;
iii) explicitly incorporating stakeholders' concerns in suitability modelling; and
iv) further exploring the ATP approach and performance thresholds in Latin American case studies.

By developing suitability maps for different time periods and climate scenarios, suitability modelling allows to identify when and where ATP arise. In addition, the modelling allows to analyse several species together. Developing suitability maps for cacao and its main pests and diseases under climate change scenarios helps to bridge the gap on climate change and cacao in Peru. In addition, combing performance thresholds with suitability modelling into one methodological approach adds to the literature on how to operationalize ATP.

1.3 Research objectives and questions

Facing the thematic and methodological gaps mentioned above, the main research objective is to approximate the adaptation turning points for cacao production in the Peruvian Amazon. The research objectives are:

Main objective: Approximate the adaptation turning points for cacao production in the Peruvian Amazon.

1. Identify the local cacao stakeholders' landscape and identify farmer's goals and challenges regarding cacao production.
2. Identify and analyse the critical climate-relevant variables for cacao production.
3. Analyse the climatic and ecological suitability for cacao production under climate change scenarios.
4. Estimate adaptation turning points for cacao production with time and spatial approaches.

To approximate the ATP for cacao production in the Peruvian Amazon, the perspectives of key stakeholders in the cacao landscape are considered and contrasted with suitability modelling approaches. The research questions are:

Main question: Where and when do adaptation turning points arise for cacao production in the Peruvian Amazon?

1. How is the local cacao stakeholders' landscape and which are the farmers' goals and challenges regarding cacao production?
2. Which are the critical climate variables and performance thresholds for cacao production according to local stakeholders, scientific literature and climate-ecological models?
3. How do climatic and ecological suitability for cacao, and its main pests and diseases, change under climate change scenarios?
4. What are the adaptation turning points in time and space for cacao production in the Peruvian case study?

1.4 Reader's guide

The framework on thresholds and adaptation turning points is presented in chapter 2. Chapter 3 introduces the study area in Peru as well as some background on cacao ecology and production. The methodology is described in chapter 4, paying attention to the stakeholder analysis, interviews and field visit; identification of critical climate variables for cacao production; and the ensemble suitability modelling under climate change scenarios.

The study then identifies the stakeholders in the cacao landscape and the cacao farmers' goals and challenges regarding cacao production (chapter 5). Then, it identifies critical climate variables for cacao production, according to the interviewees, the literature and the models (chapter 6). Afterwards, the research looks at the future suitability of cacao and its main pest and diseases under climate change scenarios to estimate the ATP in the study area (chapter 7) .

The discussion contrasts the findings with the scientific literature, the uncertainties that arise from the data and methods used, as well as conceptual implications and the added value of integrated approaches (chapter 8). Furthermore, adaptation options and recommendations are addressed. The concluding remarks address the main results and implications of the study (chapter 9).

2. Theoretical framework

This section explains key concepts used in this report. It begins by defining adaptation and resilience, which set the ground to understand discussions on thresholds, and later the concept of adaptation turning points. Working definitions and examples applied to cacao are given in Box 1.

2.1 Adaptation and resilience

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2001, in Nelson, 2011: 113). Under this perspective, adaptation comprises activities, measures, projects or actions that seek to cope with climate change impacts on natural and human systems. An objective of adaptation is to avoid risks for human or ecological systems that society considers intolerable (Klein et al., 2014). Adaptation takes place at several spatial and temporal scales, by a multiplicity of actors and sectors, and several interactions and trade-offs take place (Nelson, 2011). After Adger et al. (2005), adaptation is based on three cornerstones: reduce sensitivity, reduce exposure and increase resilience of both social and ecological systems.

Adaptation and resilience are related and complementary (Nelson, 2011). Resilience refers to a "system's ability to anticipate, reduce, accommodate, and recover from disruptions in a timely, efficient, and fair manner" (IPCC, 2012, in Denton et al., 2014). In this sense, resilience allows a system to continue operating –delivering goods and services- after a disturbance, because the system maintains its structure and functions (Nelson, 2011). Resilience requires long-term perspective in management, the need to avoid or overcome tipping points (Nelson, 2011) and openness to transformational adaptation, as opposed to incremental adjustments, to manage potential limits (Klein et al., 2014).

2.2 Thresholds and limits to adaptation

In a system, however, adaptation and resilience are not unlimited. This has raised discussions in the literature on varied thresholds.

In the resilience framework, several factors can push a system to a threshold or to the system's boundary. If the boundary is crossed, the system can either collapse or transit to a new system state with a new equilibrium (Nelson, 2011).

A more common understanding of thresholds refers to tipping points. Tipping points are increasingly being used as a metaphor in climate change communication (Russill & Nyssa, 2009). A tipping point is a threshold beyond which negative impacts affect both human and natural systems, where the change is usually abrupt and irreversible (Oppenheimer et al., 2014). Approaching a tipping point can be slow, but after crossing it, changes can develop in a non-linear way and rapidly.

Key risks may lead to tipping points. After the IPCC, a key risk indicates "dangerous anthropogenic interference with the climate system" as phrased by the Article 2 of the UNFCCC. Key risks bring "(…) severe adverse consequences for humans and social-ecological systems resulting from the interaction of hazards linked to climate change and the vulnerability of exposed societies and systems" (Oppenheimer et al., 2014: 1043). Some examples of tipping points include the arctic ice melting, the slowing down of the termohaline circulation or extensive biodiversity loss (Klein et al., 2014; Oppenheimer et al., 2014). These dangerous global tipping points can also be referred to as planetary boundaries.

Overall, key risks and thresholds are related to the concept of limits to adaptation. Literature shows growing evidence about the existence of adaptation limits (Nelson, 2011; Klein et al., 2014). Since climate change interacts and adds pressure to biophysical and social systems, systems face more challenges to cope with stressors. Adaptation limits arise because “the capacity of societal actors and natural systems to adapt is finite” (Klein et al., 2014: 902). Limits to adaptation imply “that, for a particular actor, system, and planning horizon of interest, no adaptation options exist, or an unacceptable measure of adaptive effort is required, to maintain societal objectives or the sustainability of a natural system” (Klein et al., 2014: 902). In other words, adaptation limits imply that no options are available or feasible in the near term, and certain objectives, practices or ecosystems may not be sustained in a climate change context (Klein et al., 2014). They differ from adaptation constraints, which are barriers or obstacles that “make adaptation planning and implementation more difficult” (Klein et al., 2014: 906).

Limits to adaptation can be hard or soft (Oppenheimer, 2014). A hard limit means that no adaptation action is possible to avoid intolerable risks; whereas a soft limit means that the options are currently not available, but could become available or feasible in the future, for example due to technological change (Adger et al., 2009). Hence, limits to adaptation can change in time and across space.

Critique has pointed also to the existence of social, cultural, governance or cognitive limits, related to perceptions, values, decisions, learning capacity and the ability to act (Adger et al., 2009; Nelson, 2011). In this sense, adaptation limits are social constructions (Adger et al., 2009). Adger et al. state: “what is or is not a limit to adaptation becomes a contingent question. It all depends on goals, values, risk and social choice” (2009: 338). Adaptation limits are then defined by societies depending on their values and resources. The ethical and social definition of limits can be found back in the UNFCCC’s Article 2, in the sense that thresholds are “politically or ethically undesirable” outcomes (Adger et al., 2009).

2.3 Adaptation turning point

A different understanding of thresholds, but yet related to the conception that thresholds are social constructions, can be found under the adaptation turning points approach. Here, thresholds have been defined as “performance thresholds that specific groups of actors do not want to transgress” (Werners et al., 2018a:4). In other words, a performance threshold defines a condition below which a system delivers undesirable outcomes according to certain stakeholders.

Regarding the adaptation turning points approach, Werners et al. explain:

> "The assessment of adaptation turning points (ATP) starts from identifying the performance thresholds that specific groups of actors do not want to transgress. This sets it apart from many other risk and impact assessments. The threshold of concern will have to be determined for each specific context. To be able to define what is ‘acceptable’ and ‘not acceptable’, consultative processes need to be followed to understand properly where the limits stand for what, to whom, and when." (2018a: 4).

This definition and consultative approach to defining performance thresholds was used in this research.

The ATP approach arised as part of the adaptation pathways approach, proposed as a method for decision making under deep uncertainty (Haasnoot et al., 2012, 2013; Werners et al., 2013). Adaptation pathways are an analytical approach to explore and sequence events that could occur under future plausible scenarios over time (Haasnoot et al., 2013). Under this approach, time and different scenarios lead to specific thresholds. The moment in time when a threshold is met is known as an ATP (figure 1). When an ATP is met, stakeholders should take decisions to lead development through an alternative pathway (Haasnoot et al., 2012). Note that adaptation options are, in theory, still possible after reaching a threshold.

Under the ATP framework, different concepts have been used to operationalize the thresholds. For instance, “adaptation tipping points” have been used in contrast to biophysical tipping points. Socio-political thresholds, also known as the “sell-by-date” of a particular policy or level of concern, are also common in the ATP literature (Kwadijk et al., 2010; Haasnoot et al., 2013; Werners et al., 2013). A socio-political threshold expresses conditions where climate change makes current policy unattainable or where it renders undesirable conditions for society (Werners et al., 2013). A social-political threshold can be formally defined, e.g. by political objectives or management plans, or informally, as described by societal interests. Note that performance thresholds and social-political thresholds are, in essence, equal in the sense that undesirable outcomes are defined according to stakeholders' preferences and values.

The time dimension is key in the ATP approach, since estimating its timing is important to design anticipatory adaptation measures. The time- and scenario-bound representation allow for flexible and progressive planning, to identify strategies that perform well under wide variety of futures (Haasnoot et al., 2012; 2013), and to hold a more salient and credible dialogue at the science-policy interface (Werners et al., 2013).

For this study the ATP are seen as an overarching goal. On the field, talking about "trigger" situations to change production practices helped to identify the critical climate variables leading to thresholds. Then, performance thresholds and suitability modelling were used to operationalize and identify the ATP for cacao production in the Peruvian Amazon.

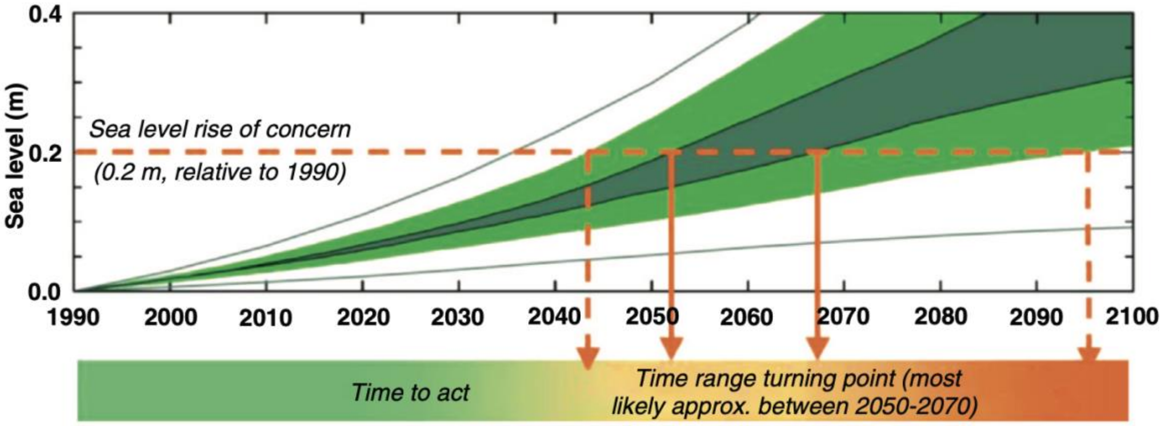

Figure 1. Adaptation turning points (ATP) for sea level rise in the Netherlands.

The performance threshold refers to the sea level rise of concern (dashed orange line). The projected averages for sea-level rise for the 21st century from the IPCC assessment report are shown in green shades. The moments in time (horizontal axis) where the threshold may be reached, according to different scenarios, represent the ATP. Source: Werners et al., 2013.

Box 1: Key concepts and applied examples

For clarity, working definitions of key concepts used throughout this report are given below:

Tipping point: A (biophysical) threshold beyond which negative impacts affect human and natural systems.

- A tipping point for cacao production could be a climatic condition where cacao trees are not able to resist and die, thus a point of no-return for the trees. For example, a long and severe drought.

Threshold: A value that defines a tipping point or performance threshold.

- A threshold to define a cacao tipping point could be a climatic value. For example, in Zuidema et al.’s model simulations, they found that cacao plantations “that receive less than 50 mm of rain during the two driest months, would produce less than 60% of their potential under optimal water supply.” (2005:215).

Performance threshold: A condition or situation threshold beyond which stakeholders perceive undesirable outcomes. In other words, a situation that is not acceptable or not desirable by stakeholders (Werners et al., 2018a).

- The performance threshold may appear before a tipping point. Since cacao farmers are interested in the amount and quality of harvested cacao pods, from the moment on that cacao trees start to show signs of wilt and yellowing leaves during the maturation process, this becomes a reason for concern. These signs may indicate the possibility of a low harvest with reduced profit, i.e. a performance threshold.
- Such critical situations where stakeholders are motivated to change their cacao production practices are further understood in this study as trigger situations.
- Note that a performance threshold may arise even when a cacao tree is still within its range of ecological tolerance, or expressed differently, within a suitable habitat.

Adaptation turning point: The moment in time when, due to climate change, a performance threshold is met.

- The moment in time when, due to climate change, cacao production is not a desirable or profitable economic activity for local cacao stakeholders, for example, by consecutive low harvests. From that moment, cacao producers may consider a different strategy or adaptation actions.

Suitability: Degree to which an area or habitat is optimal for a species, i.e. a species’ ecological niche or potential niche.

- The definition of cacao suitability in Läderach et al.’s study is a valid example here: “Climatic suitability for cocoa in the context of this analysis refers to the probability (…) that cocoa grows well, judged from the combined presence of favorable climatic variables. Not all areas identified (…) as climatically suitable actually grow cocoa since some may be occupied by human settlements, protected areas or different crops.“ (2013: 845).

3. Case study: cacao in San Martin

This chapter presents background information on cacao and the study area. First, it introduces the ecology of cacao, followed by insights on cacao production worldwide and in Peru. Then, details on the study area and criteria for its selection are given. This background is a cornerstone to identify the farmer's challenges and perceived performance thresholds.

3.1 Cacao ecology

Cacao (*Theobroma cacao)*, also known as cocoa, is a tropical tree native to the Amazon basin (Motamayor et al., 2002). Cacao beans, seeds or grains, contained in the fruits known as pods, are the essential ingredients of chocolate and other cacao derivates.

Theobroma cacao is a perennial tree up to 10 m tall. The tree is known for its cauliflorous nature, meaning that flowers and pods develop directly from the tree trunk and branches (De Almeida & Valle, 2007; Lahive et al., 2019) (figure 2). The tree begins fruit production at years 5 - 7, although improved varieties produce since years 2 - 3 (INIA, 2019). Each cacao pod contains 30 - 40 beans surrounded by mucilage (INIA, 2019).

Figure 2. Mature cacao pods growing directly from the stem. Tarapoto, March 2020.

Cacao grows in warm and moist tropical forests between 200 - 900 meters above sea level. It requires an optimum mean temperature of 25ºC (23 - 32ºC) (Leguía et al., 2010; CIAT, 2014; Eitzinger et al., 2015a; Ortega et al., 2017; MINAGRI, 2018; Romero, 2019). However, there are some seasonal variations in optimal and critical temperature ranges according to cacao vegetative cycle (Romero, 2019). The optimum annual precipitation is 1250 - 2500 mm, which should be distributed throughout the year (Leguía et al., 2010; Eitzinger et al., 2015a; INIA, 2019). Long dry seasons are known to affect cacao, especially during pod maturation

(Zuidema et al., 2005; Eitzinger et al., 2015a; Lahive et al., 2019). An optimal relative humidity should be 70 - 80% throughout the year (Romero, 2019).

Light is a further critical factor. Cacao needs varying low intensity light according to its growing stage, which can be achieved by managing shadow trees. Cacao requires 40 - 50% direct light in its early stages and 60 - 75% for mature trees, although experts advise that shadow should not exceed 25 – 30 %[5] (Zuidema et al., 2005). A best practice is to implement shadow trees for young cacao plantations (INIA, 2019) or grow cacao in agroforestry systems, in contrast to monocrop plantations (Vaast & Somarriba, 2014; Delgado et al., 2016) (figure 3). Agroforestry offers multiple benefits for farmers, who can grow additional crops for subsistence or to elevate their income (Cerda et al., 2014, Somarriba et al., 2014; Vaast & Somarriba, 2014; Maas et al., 2020).

Figure 3. Cacao trees grown in an agroforestry system in Pachincao farm. Chazuta, March 2020.

Additionally, cacao requires deep and permeable soils, slightly acidic (pH between 4.5 – 6.5) and rich in organic matter, as well as good drainage and non-flooded areas (Ortega et al., 2017; MINAGRI, 2018; INIA, 2019; Romero, 2019).

Cacao flowering is critical for productivity. A mature tree may produce thousands of flowers per year, but less than 5% are pollinized and only 0.5 – 2 % grow to pods and are harvested (Alvim, 1966, in García, 2017). The time from flowering to harvest is around 3.5 – 6 months, depending on the environmental conditions and the cacao genotype or variety.

Cacao is pollinized naturally by small diptera that visit the flowers to feed from sugary secretions (García, 2017). The principal and best-known pollinators are diptera from the gender *Forcipomyia* (Fam. *Ceratopogonidae*) (García, 2017). Other pollinators belong to the Berytidae genus (*Parajalysus andinus*) (Schaefer & Panizzi, 2000; Rengifo & Gonzales, 2011), although aphids (*Toxoptera aurantii)* and ants (*Crematogaster sp., Solenopsis sp.*) have also been reported (Valarezco et al., 2012).

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[5] Personal communication, E. Arévalo, February 2020.

Cacao is host to several pests and diseases[6]. Pest and diseases may attack the whole plant or part of it, such as the roots, stem, leaves, pods or flowers (CABI Plantwise, 2021). Typically, cacao diseases are caused by fungi or viruses. The most important diseases in the Americas and Peru are Moniliasis, Witches' broom and Black pod, respectively caused by the fungi *Moniliophthora roreri*, *M. perniciosa* and the pseudo-fungus *Phythophthora palmivora* (Evans, 2002; Philips-Mora & Wilkinson, 2007; Phillips-Mora et al., 2007; Moraes et al., 2012; Arévalo et al., 2017; Cubillos, 2017; Jaimes et al., 2017; Ortega et al., 2017; Bailey et al., 2018; Bailey & Meinhardt, 2016; Marelli et al., 2019; Norandino, 2020).

Insects, nematodes and other plants, including common weeds and parasitic plants, are considered pests. While nematodes attack the cacao root system, pest plants may compete with cacao for resources. Insects typically feed on cacao leaves, stems or pods, leaving behind both physical damage and sugary secretions which in turn can lead to fungal growth. Some important insects are, for instance, the cocoa mirid (*Monalonion dissimulatum*), mealybugs (Coccidae and Pseudococcidae), as well as Hemiptera such as Aphididae, Membracidae, leaf- and grasshoppers (Valarezco et al., 2012; Ferrari et al., 2014; CABI Plantwise, 2021). Recently, the Lepidoptera Carmenta bug or "Mazorquero del cacao" (*Carmenta sp.*) has been reported as a very important pest (Delgado Puchi, 2005; Cabezas et al., 2017; Jorge Panduro, 2018; Norandino, 2020; Murrieta & Palma, 2020c).

Finally, there are differences in cacao quality due to genetic varieties. There are four natural genetic groups of cacao, and at least one artificial variety (García, 2010; MINAGRI, 2018; INIA, 2019). Two varieties produce fine and aromatic cacao, being Ecuador and Peru the leading countries in their production (*cacao criollo* is grown mainly in the northern part of Peru and *trinitario* is grown in Junín). Other varieties (*forastero*, grown mostly in Cusco and Ayacucho; and *nacional*) are for bulk production and are produced worldwide (MINCETUR, 2018).

3.2 Cacao production

Africa produces 77% of global cacao, being Ivory Coast and Ghana the leading countries (Huamán & Romero, 2021). The Americas and Asia-Oceania account for 17% and 6% of global production, respectively. The global market is around 12 billion USD per year. Worldwide, 80% of cacao production comes from smallholders (Vaast el al., 2016). The crop represents an income source for 50 million rural households and is cultivated in 10 million hectares around the world.

Peru is the 8th largest producing country and largely participates in international markets (Huamán & Romero, 2021). The Netherlands is the largest importer of Peruvian cacao: nearly half of the cacao export value were destined to the Netherlands in 2015 (Armando & Urrego, 2016; Chávez, 2017). The Peruvian cacao sector has been strongly incentivized the last ten years and national production has been growing by 12.6% yearly (Huamán & Romero, 2021). Production recorded an historical peak in 2020 with 151 600 TM.

As a commodity, cacao price is deeply linked to the international markets and prices have been oscillating the last five years (Huamán & Romero, 2021). Early in 2020, stakeholders expected that the coronavirus crisis would affect the international markets and cacao prices, but also the local cacao network[7]. Indeed, 2020 saw international cacao markets affected and a decreasing trend in prices, but the latter recovering in 2021 (Huamán & Romero, 2021).

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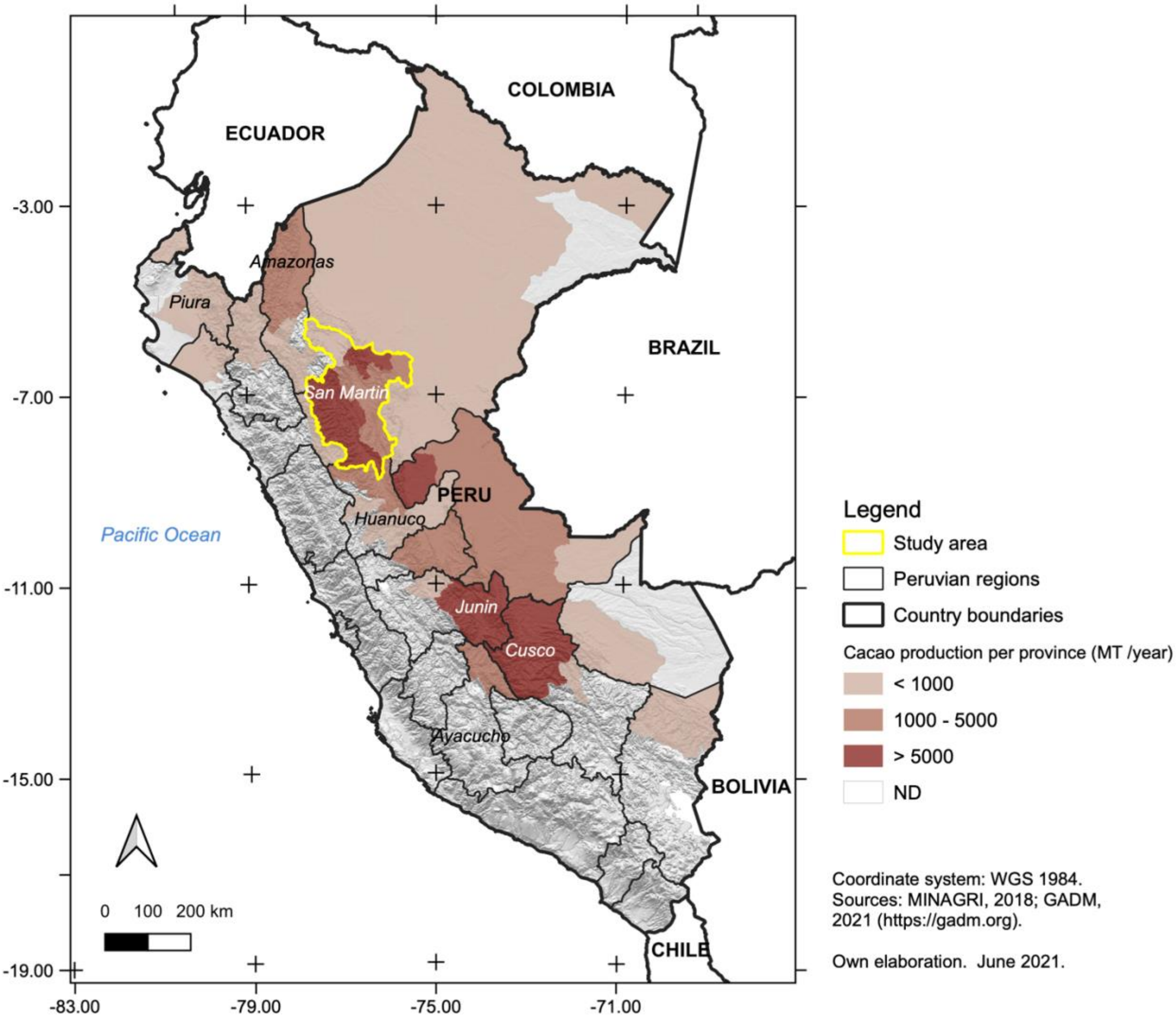
[6] A comprehensive list of relevant cacao diseases, pests, nematodes and weed was elaborated and discussed with experts to identify and evaluate the key cacao pests and diseases in Peru. Discussions took place between February – May 2021, with M. Dita (Senior Scientist at Alliance Bioversity CIAT, Bogota), E. Murrieta (Agrobusiness Specialist at Peru Cacao Alliance, Lima), L. Bagny Beilhe (Researcher on pest management in Perennial Crops at Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), Montpellier) and colleagues from their organizations.

[7] Personal communications from MIDAGRI, farmers and cooperatives, March – April 2020. Problems were later experienced in local transportation services. Due to the lockdown, farmers were not able to transport and commercialize their products. In addition, later during the coronavirus pandemic, changes in worldwide consumption were observed (Foro del cacao y chocolate latinoamericano, 2020).

Cacao is grown in 16 regions in Peru but 86% of national production is concentrated in few regions (figure 4) (Chávez, 2017; Romero, 2019). Production zones are located on the Amazon rainforest along the eastern Andean slopes and on the northern coast limiting with Ecuador (figure 4, figure 5). Of the three large productive clusters, the northern part (San Martin, Amazonas and Cajamarca) is the largest producer (MINCETUR, 2018). San Martin region accounts for 36 % of national cacao production (Huamán & Romero, 2021).



Coordinate system: WGS 1984.
Sources: MINAGRI, 2018; GADM, 2021 (https://gadm.org).

Own elaboration. June 2021.

Figure 1. Peruvian cacao production.

Cacao is produced in Peru along the eastern Andean slopes and western Amazonia, and in the northwestern dry forests although under irrigation. The map shows cacao production in metric tones (MT) per province (pink – red tonalities), as registered by the Ministry of Agrarian Development and Irrigation (MIDAGRI) for the year 2017.

The cacao cycle in Peru depends deeply on the precipitation seasonality (for historical climate data in San Martin, see annex 11). Broadly, the rainy season extends from October to March; cacao flowering occurs from October to February and fructification from November to April[1]. Most regions do show a marked seasonality. The main harvest occurs between May and July and the secondary harvest between October and December. The highest harvested yields are achieved between April and June (Huamán & Romero, 2021). National averages are

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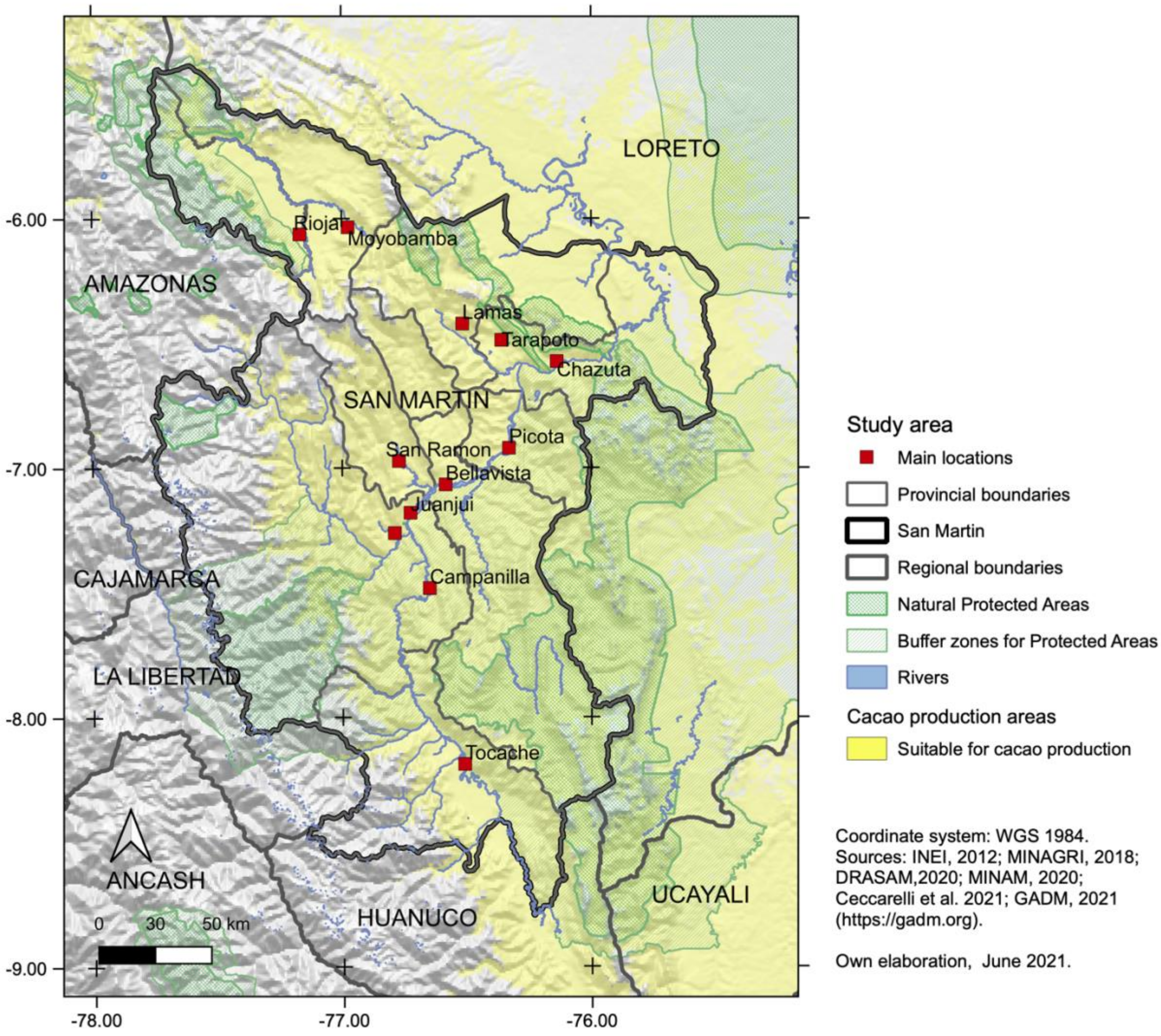
[1] Personal communication, E. Trigozo, March 2020.

hence influenced by the main harvest in San Martín, Junín, Ayacucho, Piura and Huánuco (Romero, 2019). However, cacao can be harvested throughout the year, especially in regions that do not experience a marked seasonality[2] (Cusco, Cajamarca and Amazonas) (Chávez, 2017; Romero, 2019).



Coordinate system: WGS 1984.
Sources: INEI, 2012; MINAGRI, 2018; DRASAM,2020; MINAM, 2020; Ceccarelli et al. 2021; GADM, 2021 (https://gadm.org).

Own elaboration, June 2021.

Figure 2. Study area: San Martin.

The study area consists of the San Martin region (in thick gray borders). Main localities (red dots) are relevant for the cacao value chain in the region and representative of climatic and topographic variability in San Martin. The coordinates of localities are given in table 3; the historical climate is analyzed in annex 11; and corresponding values of bioclimatic variables under present and future scenarios are analyzed in annex 9. Interviews were conducted in Lamas, Tarapoto and Chazuta. Areas suitable for cacao production, i.e. considering only cacao ecology (Ceccarelli et al., 2021), are shaded in light yellow. Natural Protected Areas (in green patterns) are established officially by the government for nature conservation; some economic activities are restricted in these areas. Low impact agricultural production is allowed in the buffer zones (light green pattern).

3.3 San Martin region

San Martin was selected as the case study by a combination of criteria. First, a literature research on projected climate impacts on cacao indicated that impacts follow similar trends

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[2] Personal communication, W. Céspedes, March 2020.

for most regions (Bunn et al., 2016; Ceccareli et al., 2021). The recommendations of this study can be, hence, extender to further regions (Box 5).

Second, San Martin is the most important cacao region in Peru in both social and economic terms. The region has the largest cacao surface (29.6%), as well as the highest number of producers (27%). In San Martin, 25 927 farmers grow cacao as their single main crop, which corresponds to a planted surface of 46 915 ha (14% of the regional agricultural surface) (INEI, 2012). Additional 4 717 farmers grow cacao in association with other crops, which equals a planted surface of 8 456 ha (INEI, 2012). Increases in cultivated surface and yield improvements allowed the region to multiply its production by factor five in the last 10 years (MINAGRI, 2018). By 2018, over 37 000 cacao farmers in San Martin produce over 56 000 TM (MINAGRI, 2018; Romero, 2019). The agricultural background in the study region is further described in Box 2.

Third, San Martin displays accumulated experience in cacao. Several programmes and interventions have helped in acquiring good practices, strengthening farmer organizations, certifying products, participating in cacao and chocolate competitions, etc (annex 5). A study revealed, for instance, that 45% of producers have more than 25 years of experience on cacao, which is the largest percentage the country (MINAGRI, 2018: 17). Since cacao and coffee are grown in the same regions, cooperatives and associations usually produce and commercialize both crops (MINCETUR, 2018).

At least 26 farmer cooperatives, 10 associations, 17 enterprises and 6 traders, together with public stakeholders, research centres and NGOs, participate in the Regional Discussion Table on cacao and chocolate in 2020[1]. The local experience and entrepreneurship is also expressed in the fact that farmer associations, enterprises or individual farmers venture into tourism. Tourism routes are being organized to show around cacao and coffee farms and processing plants.

There is also experience and willingness to implement climate change mitigation and adaptation measures[2]. For instance, the Agrarian Cooperative for Coffee and Other Services Oro Verde LTDA. performs reforestation to mitigate emissions. Ten cooperatives also measure and report their carbon footprint.

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[1] Personal communication, International Conservation, March 2020.

[2] Personal communication, L. Mendoza, APPCACAO, February 2020.

Box 2. Agricultural background in San Martin

Population & agriculture

- Total population is projected to be 899 648 in 2020 (53% men, 47% women) (INEI, 2020).
- 32% of working people are farmers and qualified workers in agriculture, forestry and fisheries (INEI, 2017). 47% of businesses in San Martin are dedicated to agriculture, forestry and fisheries; in comparison, the national average is 19% (INEI, 2017).
- These ciphers clearly demonstrate the importance of the agricultural sector in San Martin.

Heterogeneous land ownership

- Yet, the land tenure distribution shows the importance of small scale agriculture. While the regional agricultural surface accounts for 446 713 ha, individual farmers own a total of 428 345 ha, societies 16 590 ha and agrarian cooperatives 844 ha (INEI, 2012).
- It is important to note that 17.8% farmers own parcels ranging from 0.5 – 5 ha, while more than 99.5% of societies and cooperatives own parcels > 20 ha (INEI, 2012).

Cacao planted surface

- 25 927 farmers grow cacao as their single main crop, which corresponds to a planted surface of 46 915 ha (14% of the regional agricultural surface).
- 4 717 farmers grow cacao in association with other crops, which equals a planted surface of 8’456 ha (2% of the regional agricultural surface) (INEI, 2012).

Farmer associativity

- In San Martin, only 14% of farmers belong to an association, committee or cooperative (INEI, 2012). Especially farmers with larger agricultural parcels tend to be organized.
- Of those who are associated, 6% are associated to Cacao Producer Associations. Other agricultural associations, such as coffee cooperatives, also manage cacao.

Productivity issues

- Productivity is the main problem that cacao producers face. It can be related to inappropriate agricultural practices, although cacao genetic varieties, tree age and the farmers’ expertise also explain differences in yield and productivity (INIA, 2019).
- A typical cacao producer in Peru has the following characteristics: owns an average of 2 ha; produces 600 -700 kg/ha; 20% of producers fertilize; 30% perform adequate pruning; 20% receive technical assistance; and 20% have access to credits (INIA, 2019).

4. Methodology

This section, first, gives an overview of the research process. Second, it indicates how the stakeholder analysis, interviews and the field work phase in Peru took place. Third, it presents the process of identifying the critical variables and thresholds for cacao. Fourth, it details the ensemble suitability modelling for cacao and its main pests and diseases under climate change scenarios. Finally, the chapter points at analysing the ATP, discussing methods and results.

4.1 Overview

Broadly, the research consisted of a combination of literature and desktop research, discussions with key stakeholders and modelling future suitability to analyse the ATP in the study area (figure 6).

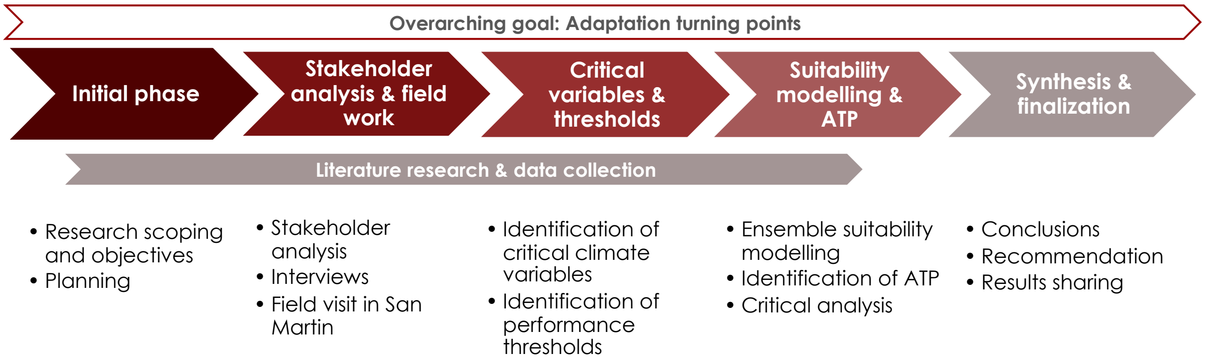

Figure 1. Research process.

The adaptation turning points frame the research. The main research phases, shown as block arrows, contribute towards estimating the ATP. Literature research and data collection is shown as a process underlying and supporting from the initial phase to the critical analysis. Key activities for each phase are indicated below.

The adaptation turning points approach functioned as an overarching goal involving the research. Main phases, from interviews and field work to the critical analysis after the suitability modelling, contributed towards estimating the ATP for cacao production. Literature research and data collection were constant and supported the research phases.

The initial scoping and planning phase focused on structuring the research project, including objectives, methods and selecting a study area. Literature research and discussions with experts were conducted. The second phase involved the preparation for field work; the actual field work in Peru, comprising interviews in Lima and San Martin; and data processing.

To identify the critical climate variables, as well as performance thresholds, interview results were analysed and contrasted with literature. In addition, bioclimatic variables were collected to prepare the suitability modelling. The ensemble suitability modelling of cacao and selected pests and diseases was conducted following Ceccarelli et al. (2021).

The identification of ATP comprised comparing the performance thresholds based on stakeholders' perspectives with the suitability projections for present and future scenarios. Afterwards, methods used, results and their implications, were critically assessed and contrasted with relevant literature.

Finally, recommendations and conclusions were elaborated. An important final step consisted in sharing the results and recommendations with the contacted stakeholders.

4.2. Stakeholder analysis, interviews & field visit

This first step consisted in conducting literature research, consulting maps, governmental reports and statistics to gain an overview of cacao in Peru and identify key stakeholders and organizations. With this background, the stakeholder landscape was analysed and a study area selected. Initial contact with key stakeholders was taken. To prepare the fieldwork, the interview questions were elaborated and translated, in addition to elaborating Spanish summaries of the research.

Fieldwork took place between 18th February 2020 and 21st May 2020[3] in Peru. During the stay in Peru, establishing connections, creating a network to exchange ideas and information, as well as to understand the stakeholders' perspectives on their problems and needs, were essential.

A meeting was organized with 15 key stakeholders from the public and private sectors and international cooperation[4] in Lima (19th February 2020). It aimed at presenting the research, coordinating research priorities and needs on cacao and climate change, and manage expectations. During two participatory spaces, participants were asked to reflect individually, write their ideas on post-its and then share them. The first question addressed what each public and private institution considered as their priorities and needs for research on cacao in the context of climate change. The second question, after presenting the research proposal, addressed recommendations from each institution's perspective, as well as their advise for sharing the final results. In the meeting, the stakeholder landscape was validated and later improved according to the participants' suggestions. Agreements for sharing information, facilitating contacts for the interviews and sharing results were made. The meeting's systematization was shared and validated by the participants (annex 2, annex 3).

4.2.1 Interviews

Interviews and follow-up discussions were held while in Peru. They were held in person, otherwise via phone and Skype calls[5]. Interviews were organized with an invitation email, attaching a brief research summary and WUR presentation letter. A directory of contacts, a fieldwork calendar and notes of all interviews were kept.

A questionnaire was previously elaborated, but its strict application proved counterproductive. Instead, a guideline was used to cover relevant topics (Box 3). The interviews developed as semi-structured conversations (30 – 60 minutes). Depending on the setting, additional materials (drawings, summaries or presentations) were used by both the researcher and the interviewee. The communication always aimed at being transparent and the possibility of asking for further information and feedback was mentioned. Permission was asked to mention the interviewees' name and refer to the interview for the research purposes. Interviews were transcribed and systematized in an Excel database.

Interviewees were representatives from the public sector (MIDAGRI and its dependencies, Regional Government), the private sector (cacao farmers, farmer associations and cooperatives), as well as public and private universities and research institutions, NGOs and international cooperation (APPCACAO, 2013; MINAGRI, 2018; MINCETUR, 2018).

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[3] Fieldwork was initially planned until 20.03.2020. But that was not possible due to the coronavirus pandemic, strict lockdown in Peru and flight cancellations. Staying in Peru gave the opportunity to hold follow-up discussions with the advantages of local time and telephone.

[4] Participants were representants of: MIDAGRI (General Directorate of Agriculture; General Directorate of Environmental Agrarian Issues); MINAM (General Directorate for Natural Resource Strategies); INIA; SENASA, National Water Authority; IICA, PNUD, Proyecto Cacao Seguro and Netherlands Senior Experts (PUM).

[5] All interviews were held in person until 15.03.2020; after the 16.03.2020, interviews were per telephone or Skype, because Peru declared a state of sanitary emergency and lockdown.

International stakeholders working on cacao projects in Peru were also included. Annex 1 gives an overview of the interviews.

Box 3. Interview topics and structure

1. Introduction & research
    - Personal background
    - Aim and uses of the research
2. Cacao production system & case study (if relevant)
    - Aspects such as associativity, yield, price, etc.
3. Farmers' goals & challenges
    - Aims and problems of farmers and of cooperatives (if relevant)
    - Subtle verification if these variables were considered as problems: weather (temperature, rain, dry season), low yield, plagues, prices, others
4. Climate variables
    - Which seasons or variables (temperature, rain, dry season) affect cacao production and how
5. Climate trends, projections and impacts
    - Perceived changes on climate, rainfall, dry seasons, etc.
    - Past events and their impacts
    - Climate projections (if relevant)
6. Thresholds and adaptation turning points
    - Triggers: Cases and reasons for abandoning cacao production
    - Changing practices and alternatives
7. Closure
    - If the stakeholder knows about the National Action Plan on Cacao
    - Open space for comments or suggestions
    - Stay in contact and commitment to share results back

4.2.2 Field visit in San Martin

The field visit to San Martin took place between 11 - 14 March 2020. Interviews were held in Tarapoto, the regional capital, Lamas and Chazuta, two cacao-producing towns (table 3, figure 5). In Tarapoto, institutional and research stakeholders were interviewed, as well as farmers and cooperatives in Lamas and Chazuta. The visits comprised the Regional Agricultural Office; the Institute for Tropical Crops (ICT), which maintains research parcels for cacao; the local INIA office, including their cacao nursery (figure 7); and the local IIAP office.

A representative of the cooperative Oro Verde was interviewed in Lamas. In Chazuta, the visit comprised the women's Association Mishky Cacao at their local manufacturing plant, as well as the cacao parcels in the agrotourism farm Pasikiwi (figure 7). It's worth noting that cacao production is so common in Chazuta, that farmers let the cacao beans dry outside their houses (figure 7). Due to time limitations and large distances, other cooperatives in the region could not be visited. The field visit allowed to become familiar the varied realities of different cacao producers and stakeholders along the value chain.

Figure 2. Different images of cacao during the field visit in San Martin. March 2020.

Top left: Cacao nursery for research at INIA, outside of Tarapoto. Top right: Cacao trees growing under agro-forestry systems at Pasikiwi, Chazuta. Bottom left and right: Cacao beans drying under the sun, Chazuta.

4.3. Critical variables and thresholds for cacao

Critical variables for cacao were identified, on the one hand, from the interviews, and on the other hand, from further literature.

Interviews allowed to gain insights into most striking problems that cacao producers face, as well as on which situation they consider a trigger to change cacao production practices. Changing practices could involve abandoning cacao or switching to other crops. Thus, trigger situations lead to what could be considered a performance threshold for cacao production (Werners et al., 2018a). From these critical situations, those related to weather and climate were selected. Then, the climatic variables leading to the performance threshold were identified and contrasted with literature.

Finally, further data was obtained on cacao's ecological range, as well as complementary information for main cacao pests and diseases in Peru.

4.4. Suitability modelling under climate change scenarios

Ensemble suitability modelling allowed to indicate where potential performance thresholds are met due to climate change, in which time periods or under which scenarios.

In ecology, suitability refers to how optimal an habitat is for a species, i.e. an area is suitable for a species if it is equal to the species' ecological or potential niche. The potential niche differs from the realized niche in the sense that not all suitable areas may be indeed occupied by a species (Phillips et al., 2006; Phillips & Dudik, 2008; Läderach et al., 2013). For this study's purpose, unsuitable areas approximate areas where a performance threshold has been crossed.

Future suitability for cacao and selected pests and diseases under climate change scenarios were analysed. The methodology and R script developed by Ceccarelli et al. (2021) were used and adjusted for this specific research jointly with Alliance Bioversity-CIAT (BI-CIAT) (annex 7). Suitability modelling involves modelling the likely distribution of a species based on observed species presence data and a series of environmental layers used as predictors (figure 8) (Philips et al., 2006).

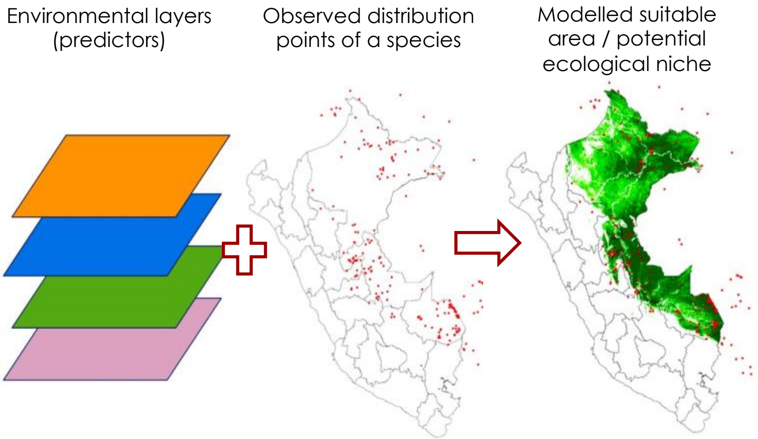

Figure 3. Suitability modelling method.

Suitability modelling consists in using a series of environmental layers as predictors to identify environmental conditions where a species is likely to be present, using a set of observed and georeferences presence points of a species. Areas where the species is present and absent are then calculated by the modelling algorithms. The output is a continuous map indicating suitable areas for the species acoording to the environmental layers used. The output can be interpreted as the likelihood or probability that the species is present (Phillips & Dudik, 2008). Future suitability projections can be generated by using future climatic conditions as predictors. Source: Ceccarelli et al. (2020).

Briefly, the R script used for suitability modelling produced an ensemble modelled suitability map under present conditions, as well as suitability maps under future conditions as specified by the climate change scenarios and time periods selected. Here, two Representative Concentration Pathways (RCPs) were used: RCP 4.5 and RCP 8.5.

The output maps are ensembles, i.e. averages, of a number of climate models. Here, five General Circulation Models (GCM) of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) were used (Emori et al., 2016). The GCM selected belong to different "model families", give a range of diverse responses to RCPs and perform notably better than the previous model generation: gfdl_cm3, mohc_hadgem2_es, miroc_miroc5, mpi_esm_lr, cesm1_cam5 (Knutti et al., 2013). The ensemble models were adjusted to show results where >75 % of the GCM agree in the direction of change.

In addition, eight different statistical algorithms were used to calculate the species' suitability: MAXENT[6], GBM, GBMSTEP, RF, GLM, GLMSTEP, RPART, NNET (annex 8). These algorithms use only species presence data and calculate random pseudo absences (Phillips et al., 2006; Phillips & Dudik, 2008). To reduce geographic bias in the presence data, the points were filtered at a resolution of 5 arcmin. Jointly with BI-CIAT, the algorithms were evaluated among other algorithms available to select those performing better for the study area and the given species.

Environmental variables used as predictors consisted of bioclimatic, soil and terrain variables. Bioclimatic variables are variables derived from temperature and precipitation values, which represent annual trends, seasonality and extreme monthly values, and are meaningful for organisms (Hijmans et al., 2005). Bioclimatic variables are widely used in ecological and suitability modelling, both under present and future RCP scenarios. (for example in Schroth et al., 2016; 2017; Ortega et al., 2017; de Sousa et al., 2019). The bioclimatic variables were obtained from WorldClim[7] and complemented with potential evapotranspiration and an aridity index (Ceccarelli et al., 2021). Here, 21 bioclimatic variables were used (table 1A). These bioclimatic variables were also used to identify the performance thresholds for cacao production.

Terrain and soil variables were incorporated as predictors (Danielson & Gesch, 2011; Hengl et al., 2017). Soil also plays an important role in especially plant and fungi's ecology (table 1B). Since soil and terrain variables are assumed to remain constant in this century, these were only used to model suitability under present conditions and calibrate the models.

Cacao in Peru is also grown under irrigation in the northern coast. This region, however, has a different climate from the main cocoa producing regions in the Amazon. Therefore, one categorical variable indicating where cacao grows only under irrigation was added (Ceccarelli et al., 2021). This categorical variable indicates in the script that those presence points for cacao in irrigated areas should not be considered for modelling suitable areas.

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[6] Phillips, S.J. M. Dudík, R. E. Schapire. [Internet] Maxent software for modeling species niches and distributions (Version 3.4.1), http://biodiversityinformatics.amnh.org/open_source/maxent. Accessed on 2020-1-16.

[7] Hijmans et al. (2005), www. worldclim.org.

Table 1. List of variables used for modelling the habitat suitability of cacao and its pest and diseases.

A

Bioclimatic variables		
Variable	**Description**	**Unit**
Bio1	Annual Mean Temperature	*10º C
Bio2	Mean Diurnal Range (Mean of monthly (max. temp. - min. temp.))	*10º C
Bio3	Isothermality (Bio2/Bio7 * 100)	%
Bio4	Temperature Seasonality (standard deviation * 100)	%
Bio5	Maximum Temperature of Warmest Month	*10º C
Bio6	Minimum Temperature of Coldest Month	*10º C
Bio7	Temperature Annual Range (Bio5-Bio6)	*10º C
Bio8	Mean Temperature of Wettest Quarter	*10º C
Bio9	Mean Temperature of Driest Quarter	*10º C
Bio10	Mean Temperature of Warmest Quarter	*10º C
Bio11	Mean Temperature of Coldest Quarter	*10º C
Bio12	Annual Precipitation	mm
Bio13	Precipitation of Wettest Month	mm
Bio14	Precipitation of Driest Month	mm
Bio15	Precipitation Seasonality (Coefficient of Variation)	Coefficient
Bio16	Precipitation of Wettest Quarter	mm
Bio17	Precipitation of Driest Quarter	mm
Bio18	Precipitation of Warmest Quarter	mm
Bio19	Precipitation of Coldest Quarter	mm
PET	Annual potential evapotranspiration	mm
Aridity	Aridity index	Index

B

Soil and terrain variables		
Variable	**Description**	**Unit**
bdod	Bulk density (density of fine earth) of soil	kg/cm3
clay	Clay content mass fraction	%
silt	Silt content mass fraction	%
sand	Sand content mass fraction	%
cec	Soil cation exchange capacity	cmol/kg
soc	Soil organic carbon content (fine earth fraction)	g/kg
phh2o	Soil pH in water	pH
nitro	Soil nitrogen content	g/kg
cfvo	Coarse fragments volumetric fraction	%
slope	Slope (terrain)	Degree
aspect	Aspect (terrain)	Degree
flow	Direction of surface waterflow	Factor
TPI	Topographic position index	m
TRI	Terrain roughness index	m
Irrigation	Area where cacao grows under irrigation	Binary

A) bioclimatic variables for present and future habitat suitability; and B) soil and terrain variables for present habitat suitability.

For A): bioclimatic variables are available for present and future conditions, as modelled by different Global Climate Models (GCM). The data represents downscaled and bias corrected GCM projections (CMIP5). The temporal resolution used is 2020-2049, 2050-2069 and 2060-2089. Note that a quarter is equal to 4 months; temperature variables are given in *10º C to avoid handling with decimals. Bioclim variables (Bio1 to Bio19) were obtained from Worldclim (Hijmans et al., 2005; https://www.worldclim.org/data/bioclim.html) and PET and Aridity were derived by BI-CIAT (Ceccarelli et al., 2021).

For B): Soil and terrain variables were only used to model present habitat suitability, under the assumption that soil and terrain variables are more stable and will not change significantly in the coming decades. Soil variables were obtained from Hengl et al. (2017). Terrain variables were calculated by BI-CIAT in the raster package for R (Hijmans & van Etten, 2020) using the GMTED2010 digital elevation model (Danielson & Gesch, 2011). The Irrigation variable was developed as a categorical variable, indicating where cacao is rainfed (0) or only grows under irrigation (1).

For A) and B): The spatial resolution is 30 arcsec (pixel size of 0.0083 degrees), which equates about 1 km at the Equator.

Table 2. List and description of modelled species.

Species taxonomy				Common names		General distribution	Sources	Georeferenced presence data	
Kingdom	**Family**	**Genus**	**Scientific name**	**English**	**Spanish**			**Number of records**	**Sources**
Plantae	Malvaceae	**Theobromae**	*Theobroma cacao*	Cacao, cocoa	Cacao	Cacao is native to the Neotropics, but is now cultivated along the tropical areas of the Americas, Africa and Asia.	De Almeida & Valle, 2007	9976	SENASA, BI-CIAT, DRASAM, Alianza Cacao, GBIF, TROPICOS, scientific publications
Fungi	Marasmiaceae	**Moniliophthora**	*Moniliophthora roreri*	Frosty pod rot, moniliasis	Monilia, moniliasis	Native from South America, it has extended to South and Central America. Africa, Asia and the insular Caribbean are still free of the pathogen.	Evans, 2002; Bailey & Meinhardt, 2016; Phillips-Mora et al., 2017; Bailey et al., 2018; CABI, 2021	2705	SENASA, BI-CIAT, DRASAM, Alianza Cacao, scientific publications
			Moniliophthora perniciosa	Witches' broom	Escoba de bruja	Native from South America, it has extended to most of the tropical Americas.	Evans, 2002; Bailey & Meinhardt, 2016; Bailey et al., 2018; CABI, 2021	1951	SENASA, BI-CIAT, DRASAM, Alianza Cacao, scientific publications
Chromista	Peronosporaceae	**Phytophthora**	*P. palmivora,* *P. megakarya,* *P. capsici,* *P. citrophora*	Black pod rot, black pod	Mazorca negra, pudrición parda, podredumbre del fruto / del tronco	Among Phytophthora species, only P. palmivora is found worldwide. P. megakarya has only been reported in West Africa, P. capsici in the Americas and the Caribbean, and P. citrophthora in Brazil and Asia.	Acebo-Guerrero et al., 2011; Bailey & Meinhardt, 2016; CABI, 2021	713*	SENASA, BI-CIAT, DRASAM, Alianza Cacao, scientific publications
Annimalia	Sesiidae	**Carmenta**	*C. theobromae,* *C. foraseminis*	Carmenta	Mazorquero, perforador del fruto	Carmenta is native to the Neotropics. Interestingly, the species may have co-evolved with local species, but is just recently resported as a pest in Peru and South America.	Delgado Puchi, 2005; Murrieta & Palma, 2020c	1371**	SENASA, BI-CIAT, DRASAM, Alianza Cacao, scientific publications
	Miridae	**Monalonion**	*Monalonion dissimulatum*	Cocoa bug, cocoa mirid	Chinche / mírido del cacao, chinche / mosquilla amarilla	Mirids are present worldwide. Monalonion sp. Are known to affect cacao in South America.	Valarezco et al. 2012; Gamboa, 2020	322***	SENASA, DRASAM, GBIF, scientific publications

The table does not aim to be exhaustive of the species taxonomy nor characteristics. It rather aims to provide an overview of the taxa and species' distributions. The number of records shows registries available for Peru, after correcting geographic coordinates and cleaning the data.

*No records were found for Peru for P. megakarya, only 1 record was found for P. capsici and hence removed. Records for P. palmivora and Phytophthora sp. were joined for modelling.

**Only few registries specifying the species name were found: 7 registries for C. theobromae and 0 for C. foraseminis. Thus, registries were joined as Carmenta sp. for modelling.

***Similarly as with other species, many records only register "chinche" and thus it was not possible to assign more records under M. dissimulatum.

Georeferenced presence data on cacao and its main pests and diseases was compiled and analysed to understand the species' ecology and distribution (table 2). A variety of sources was consulted, such as scientific papers, reports, guides for agricultural best practices and integrated pest management, and global databases. Discussions with experts in cacao pests and diseases[8] helped to improve the understanding of the species' ecology and, more importantly, of their priorities regarding pests and diseases' impact and potential risks. As a result, the pest and diseases later included in the modelling were defined by their social and economic importance, as mentioned by stakeholders, and data availability of geographic registries in Peru. Sometimes, the available data was not detailed enough to distinguish a genus at species level. Therefore, records for two related species were merged and modelled at genus level.

The large majority of geographic registries were shared directly by the stakeholders network: DRASAM for registries in San Martin (DRASAM, 2020b); BI-CIAT and Alianza Cacao shared their private project registries from surveys in Peruvian regions; and the Peruvian National Service for Agrarian Sanitation (SENASA) facilitated the national database of cacao pests and diseases. Few georeferenced data was found in global species databases for Peru, except for cacao (GBIF[9], Tropicos[10]), and finally some records were extracted from publications. The records were compiled and cleaned by removing duplicates, transforming and correcting geographic coordinates, verifying species names and the correspondence of the registered location and the coordinates. The final number or records and sources are also shown in table 2.

Briefly, after data collection, modelling the species suitability under future scenarios comprised:

- adjusting the species distribution datasets in the correct format for modelling and loading them into R and RStudio[11];
- loading bioclimatic and non-bioclimatic variables into R;
- revising and adjusting the scripts in R;
- conducting trials to select the best performing modelling algorithms;
- conducting trials to select the best method to generate pseudoabsences from presence records (random pseudoabsences) (Mateo et al., 2010);
- conducting trials to select the best spatial resolution to filter the presence points (geographic or environmental filtering, either at 30 arcsec, 10 arcmin or 5 arcmin);
- running the final suitability models for present conditions (2010) and for future scenarios under RCP 4.5 and RCP 8.5 for 2030, 2050 and 2070; and
- producing the final maps per species, per RCP and per time period.

The suitability algorithms used for the ensemble suitability modelling were selected by evaluating their performance by comparing the Area Under the Curve (AUC) of the output models[12]. The AUC is a statistical metric commonly used in evaluating species distribution models (Phillips & Dudik, 2008). The selection of the method to generate pseudoabsences, the filtering and spatial resolution were done by comparing the AUC, and the actual presence points used as input with the modelled distribution for present conditions (figure 9, annex 10). The filtering and spatial resolution that produced maps closest to the actual presence points of most species, but that did not produce an overfitted distribution, were chosen. The future suitability script was run after having selected the parameters based on the models for current conditions.

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[8] The experts from BI-CIAT, Alianza Cacao and CIRAD who helped in this phase became co-authors for a presentation that will be held at the 2nd International Agrobiodiversity Congress, organized by the Alliance Biodiversity International – CIAT, in Nov. 2021: "Climate change impacts on habitat suitability of cacao (Theobroma cacao) pests and diseases in Peru" (abstract sent for review in July 2021).

[9] Global Biodiversity Information Facility (GBIF) (2020), www.gbif.org.

[10] Missouri Botanical Garden (2020), www.tropicos.org.

[11] The R Foundation for Statistical Computing (2014); RStudio Inc., Version 1.1.383 (2017).

[12] This evaluation was done in cooperation with BI-CIAT.

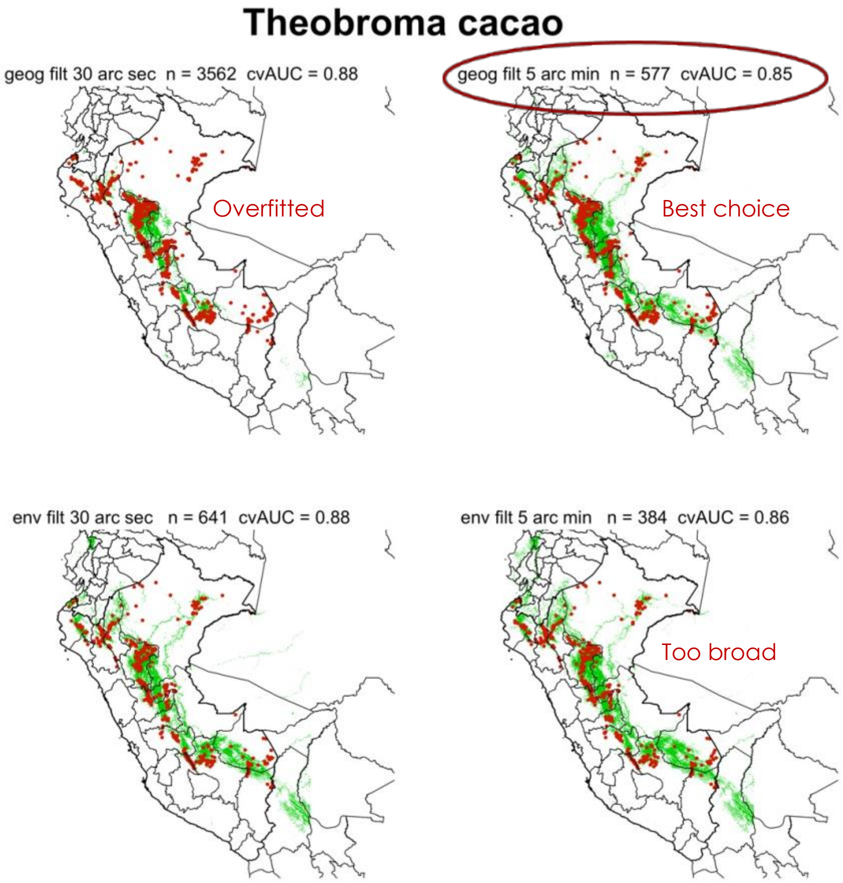

Figure 1. Example for the evaluation of model performance for present suitability for *T. cacao*.

AUC values and modelled suitability (light green areas) against input presence points (n=x) (dark red dots) were compared between the different maps, produced with different filters and resolutions. In general, a higher AUC value (0.0 – 1.0) indicates better model performance. A good model is one that achieves good correspondence between modelled suitability and presence points, but does not produce an overfitted or a too generalized distribution. Note that, since presence points are selected and filtered randomly, the maps show different n used for generating the models.

Table 1. Locations in San Martin selected for interviews and the analysis of bioclimatic variables.

Location	Coordinates		Altitude (m)
	Longitude	Latitude	
Rioja	-77,1678	-6,0626	840
Lamas *	-76,5162	-6,4218	765
Tocache	-76,5102	-8,1886	501
Tarapoto **	-76,3598	-6,4877	331
Campanilla	-76,6498	-7,4826	321
Bellavista	-76,5848	-7,0669	253
Picota	-76,3303	-6,9206	219
Chazuta *	-76,1380	-6,5737	199

Interviews were held at localities marked with * and **. Tarapoto** was not analysed for bioclimatic variables due to its closeness to other places. Coordinates are in degrees and the geographic coordinate system is WGS 1984. Sources: INEI, 2017.

4.5. ATP analysis

The ATP analysis consisted of bringing together the results from previous phases to identify for which time periods and where performance thresholds for cacao were reached.

On one hand, the critical values leading to performance thresholds were identified looking at the projections for the bioclimatic variables. Thresholds were identified for the GCM ensembles under current conditions and for each RCP and time period. The values for localities selected in the study area (table 3, figure 5, annex 9) were interpolated in QGIS[1].

On the other hand, the areas that become unsuitable were also identified for the GCM ensembles under current conditions and for each RCP and time period. Altogether, both methods allowed to approximate the ATP for the study area from complementary angles.

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[1] QGIS (Open Source), Version 2.6-Brighton, https://qgis.org/es/site/.

5. Goals and challenges for cacao production

This chapter presents the stakeholder landscape around cacao in Peru and San Martin. Afterwards, it details farmer's goals and challenges regarding cacao production according to the interviews and field work. Attention is paid to key challenges, such as yield and income, pests and diseases. Additional information on the political framework relevant for cacao, development projects in San Martin, and other issues discussed during the field visit, can be found in Box 4 and annex 5 and annex 6, respectively.

5.1 Stakeholder landscape

The initial step to approach stakeholders' goals and challenges consisted in understanding and mapping the national and local stakeholders. Figure 10 shows stakeholders belonging to the public sector, private sector, international cooperation and NGOs, and research centres and academia[1] (INIA, 2019). Multi-stakeholder discussion spaces are also indicated. Stakeholders in the public sector, especially MIDAGRI-DGAAA and MINAM, followed by international cooperation and NGOs, are also active stakeholders in climate change adaptation in agriculture (CIAT, 2014).

A. Public sector

The public sector is mainly composed of ministries, their attached organisms and regional governments. Key stakeholders are the Ministry of Agricultural Development and Irrigation[2] (MIDAGRI) and its Regional Agricultural Office in San Martin (DRASAM). MIDAGRI is the national authority on agricultural policies and guidelines (MINAGRI, 2015). Locally, the DRASAM implements these policies in the case study area. The latter also plays a pivotal role in coordinating regional stakeholders, reach out to the private sector and international cooperation and execute public projects and funding. Public projects are financed by agricultural or regional plans, or by national contested funds. In addition, the Regional Government of San Martin (GORESAM) sets regional priorities, manages funding and coordinates among actors. Local municipalities are also involved in some projects and facilitation services.

At national level, the General Directorate for Environmental Agrarian Issues (DGAAA) from MIDAGRI coordinates environmental issues, among the climate change, with the Ministry of Environment (MINAM). MINAM is the leading political authority in climate change mitigation and adaptation, as well as on deforestation and agroforestry through the National Service for Forestry and Wildlife (SERFOR). They coordinate with national and local stakeholders in climate related aspects.

The National Service for Agrarian Health (SENASA) also has relevant national and local incidence by performing capacity building and information services. SENASA plays an acknowledged key role in cacao pest management and control. Additionally, the National Service for Meteorology and Hydrology (SENAMHI) delivers key information services for the agricultural sector. A further relevant actor is the National Commission for Development and Life without Drugs (DEVIDA), which supports farmers' transition to cacao as an alternative to illegal coca cultivation.

B. Private sector

The private sector is the largest and most heterogeneous stakeholder group. Cacao producers can be grouped into small individual non-organized farmers, small organized farmers and medium or large enterprises (MINCETUR, 2018). Individual and non-organized

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[1] INIA (2019) showed a similar grouping for the National Agrarian Innovation System (SNIA).

[2] Until November 2020, the official name was Ministry of Agriculture and Irrigation (MINAGRI).

farmers account for 70% of cacao farmers in San Martin (Encomenderos, 2020). They sell their production as dried and fermented cacao beans to the local market or to intermediaries. Small organized farmers (30% of regional cacao producers) are organized into associations, cooperatives or societies (INEI, 2012).

Cooperatives play several roles for their members: they buy cacao beans from their members, negotiate better prices with their clients, provide information and technical assistance, manage and obtain certifications, among others. The largest cooperatives and enterprises also export cacao beans or manufacture products. A key issue in the cacao value chain is achieving standardized protocols for cacao post harvest and fermentation in order to achieve a homogeneous quality of cacao (INIA, 2019). In this sense, cooperatives play a fundamental role for their members. However, associations and cooperatives may suffer from instable management or are effective in their price negotiations (Encomenderos, 2020).

Medium and large enterprises commercialize cacao for the national and international market (Armango & Urrego, 2016; MINCETUR, 2018). Some of them also own appropriate infrastructure for manufacture and process cacao derivates (MINCETUR, 2018). In Peru, 95 registered enterprises export cacao beans (Armando & Urrego, 2016). 82 are formal enterprises, of which only 7 are responsible for 77% of the exported cacao volume. Only 10 cooperatives export cacao; being the first two located in San Martin (Cooperativa Agraria Cacaotera ACOPAGRO and Cooperativa Agroindustrial Tocache Ltda.).

Further important stakeholders are centralized organizations representing the private sector. There are both a cacao guild, which is the Peruvian Association of Cacao Producers (APPCACAO), and organizations that function as brokers between cooperatives, enterprises and international buyers, such as the National Coffee and Cacao Chamber (CAMCAFÉ) and the Central de Café y Cacao del Perú (APPCACAO, 2013; INIA, 2019). They promote improvements along the whole cacao value chain and negotiate with the international markets. These organizations, together with the larger export enterprises, are the most dynamic actors in the cacao value chain (INIA, 2019).

C. Research centres and academia

Cacao-related research centres and academia are public and private universities or institutions. Two main actors are the National Institute for Agrarian Innovation (INIA), which is the national authority on agrarian innovation and research, and the Research Institute for the Peruvian Amazon (IIAP). Both have several offices in Peru and focus on different products or problems according to the office's location. In San Martin, they investigate varied aspects on cacao, for example INIA currently studies how to enhance cacao productivity and protect its pollinator, while IIAP studies possibilities for organic pest control. The Institute for Tropical Crops (ICT) in Tarapoto is a further key stakeholder. In addition to research, it helps to coordinate among stakeholders, offers capacity building, field assistance and technology transfer. Currently, ICT focuses on cadmium mitigation technologies (INIA, GORESAM & ICT, 2019). Finally, the Cacao Innovation Centre (CIC) is a relatively new institution. IIAP, INIA and ICT influence other stakeholders through their activities.

Universities conducting relevant research on cacao are found all across the country. Main research cases contemplate enhancing cacao productivity through improved varieties and technology, as well as the post harvest phase (INIA, 2019). Worth mentioning are the National University of San Martin (UNSM) in Tarapoto and the National University of the Peruvian Amazon (UNAS) in Huánuco region. The UNAS, for example, actively involves students in research on cacao (Jáuregui, 2001; Perdomo Vela, 2014; Jorge Panduro, 2018). Other universities, among them the lead National Agrarian University of La Molina, are not included here since no relationship to the case study was found during the research[3].

Some public stakeholders, NGOs and international cooperation also conduct research. In fact, a formal collaboration network on cacao in San Martin coordinates, offers mutual support

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[3] For more information on research cases and activities per university or stakeholder see INIA (2019).

and conducts research (INIA, GORESAM & ICT, 2019). The network is composed of the DRASAM, INIA, IIAP, ICT, UNSM and some cooperatives.

D. International cooperation & NGOs

Many organizations are locally present through temporal projects supporting cacao. Their support, scientific input and, most of the times, funding, are highly valued by local stakeholders. Activities and projects range from capacity building and field technical assistance to promoting research with public actors and academia. They have a key role in knowledge generation and sharing. The Peruvian Cacao Alliance, supported by USAID, is one of the current main programmes in San Martin. It aims at positioning Peru as an international leader in fine and aromatic cacao, together with improving producers' life conditions and promoting a sustainable business model (INIA, 2019). In addition, the Alliance Bioversity International – CIAT is currently implementing the project *Climate Low Cadmium* across Peru, Ecuador and Colombia, which aims, among other objectives, to develop and scale up climate-innovative practices[4].

E. Multi-stakeholder dialogue platforms and processes

The multistakeholder dialogue platform and processes play key roles in coordination, knowledge sharing and influencing the regional agenda. The Regional Technical Discussion Table on cacao and chocolate, lead by DRASAM, is an official platform for public and private coordination and it is considered a mechanism to strengthen regional development. Its aim is to promote the competitivity of the cacao value chain in an articulated manner. Although participation is voluntary, there is an action plan approved by all members. The platform can also influence the political agenda locally and of international cooperation (GORESAM, 2018).

Since the end of 2019, the elaboration process for the National Action Plan on Cacao has recently generated an articulation space. However, participation is dominated by public stakeholders (MIDAGRI) and the international cooperation supporting the plan (UNDP and IICA), together with a reduced number of large enterprises or cooperatives. The IICA supports an online participatory management platform which hosts the plan's progress[5].

Finally, figure 10 mentions the National Agrarian Innovation System (SNIA). The SNIA integrates institutions, norms, principles, methodologies and instruments which the Peruvian Government uses to promote research, capacity building and technology transfer in agricultural matters (Consorcio APOYO Consultoría S.A.C. & AC Pública S.A.C., 2018). As a collective system, it integrates MIDAGRI, INIA, SENASA, other public institutions, regional and local governments, universities, enterprises and producer associations.

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[4] See https://ciat.cgiar.org/clima-loca/ or https://climaloca.org/es/acerca-de-nosotros/donde-trabajamos/

[5] See https://gestionparticipativa.pe.iica.int/Procesos/Plan-Cacao/Inicio.aspx

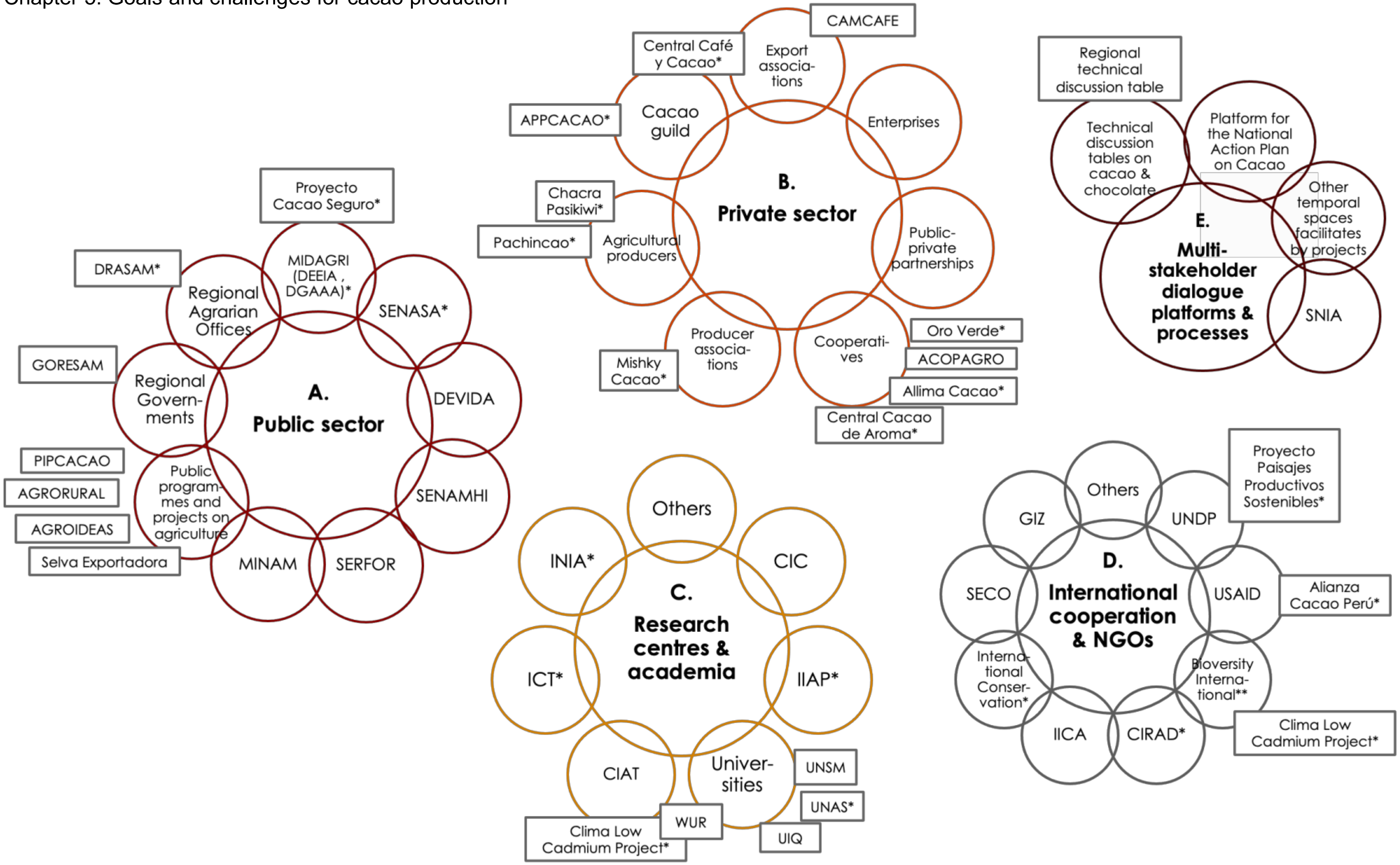

Figure 1. Stakeholder landscape in the case study.

The large circles show the stakeholder groups and smaller circles show specific stakeholders. Rectangles indicate stakeholders present in or related to the case study area. Stakeholders marked with * were interviewed, discussions were held or information exchange per email took place. With stakeholders marked with **, intensive collaboration took place. Own elaboration based on literature, interviews and discussions. An early version of the figure was discussed with stakeholders during a coordination meeting. This picture is not an exhaustive list of all private stakeholders in the study area, it rather presents a practical overview for the case study

In total, 27 interviews were conducted between February and March 2020, as well as 1 multi-stakeholder meeting (annex 1). Table 4 summarizes the interviews conducted per stakeholder group. The majority of interviews represent individual views and are not institutional responses. Most collective views represent cooperatives and associations.

Table 1. Summary of interviews per stakeholder group.

Stakeholder group	**Interviews**		**Interviewees' perspective**	
	Number of interviews	Interviewees who conduct research	Individual	Collective
A. Public	7	3	7	3
B. Private	8	0	2	6
C. NGO / Cooperation	8	5	8	1
D. Academia	4	4	4	0
Total	**27**	**12**	**21**	**10**

The table shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. Note that some stakeholders have dual roles (e.g. academia and other institution), and thus have been included in more than one category. The interviewees' answers were classified afterwards for visualization purposes. Own elaboration from interviews and discussions.

5.2 Goals

Interviewees indicated main goals regarding cacao production in Peru (figure 11). Responses were open answers to keywords such as "goals", "objectives" or "aims of cacao farmers".

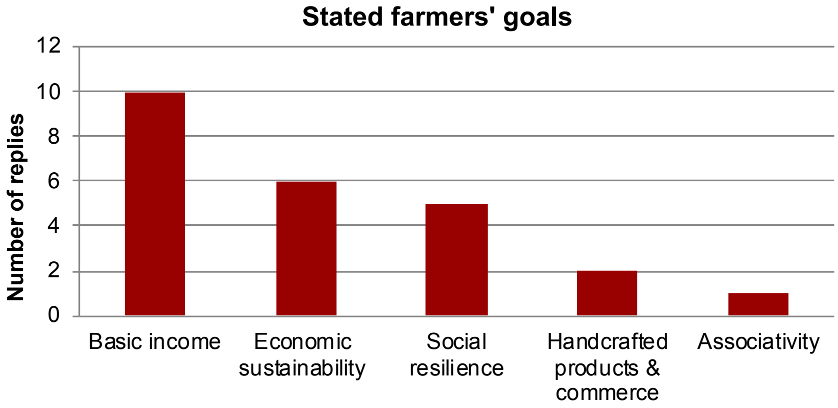

Figure 2. Stated farmers' goals.

The graph shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. The interviewees' answers were classified afterwards for visualization purposes. Own elaboration from interviews and discussions.

There is a clear agreement among all stakeholder groups that cacao producers aim for a basic income. As a main economic activity, cacao production must satisfy the farmers' basic needs and allow achieving an acceptable quality of life. Some stakeholders also highlighted that cacao production should generate profit, allowing the farmer to reinvest the surplus in the agricultural activity.

Stakeholders also brought into the conversation economic sustainability, referring to the continuity of cooperatives, associations or businesses. It was noted that the survival of these organizations depends on their members' income and happiness. Small enterprises need a guaranteed market and clients for their business continuity.

In this sense, collective goals play a key role. Cooperatives, for example, aim to position themselves and compete in international markets, mostly with organic and fair trade certifications. To be competitive, they seek to generate income for their members and assist them by improving cacao management practices on farm and increasing productivity.

Social resilience captures the farmers' goal to reduce vulnerability to economic crisis, to climate events or even to biodiversity loss, and also to the dependence of rural families on cacao production. Pests and diseases are critical. Associations and cooperatives see their subsistence threatened after severe attacks of pests and diseases, since they could lose members who become demotivated after low harvests.

Farmer associations and cooperatives also highlighted their objective of maintaining and expanding their production of cacao derivates, commercialize them and / or export them. In order to reach these objectives, maintaining associativity was a key factor and an aim in itself. Other stated goals were complementing cacao production with other activities on farm, such as agrotourism and education.

To synthesize, the primary implication that can be extracted from the interviews is that a performance threshold for cacao production is the one that allows a sustainable / continuous production, i.e. production for a good quality of life. For this, not only climate, but also pests and diseases are critical.

5.3 Challenges

This section presents farmers' main challenges, which directly respond to on farm-production. The interviews revealed what interviewees stated as perceived or observed problems, difficulties or challenges (figure 12). Further problems perceived by stakeholders and related to the broader cacao value chain can be found in annex 6.

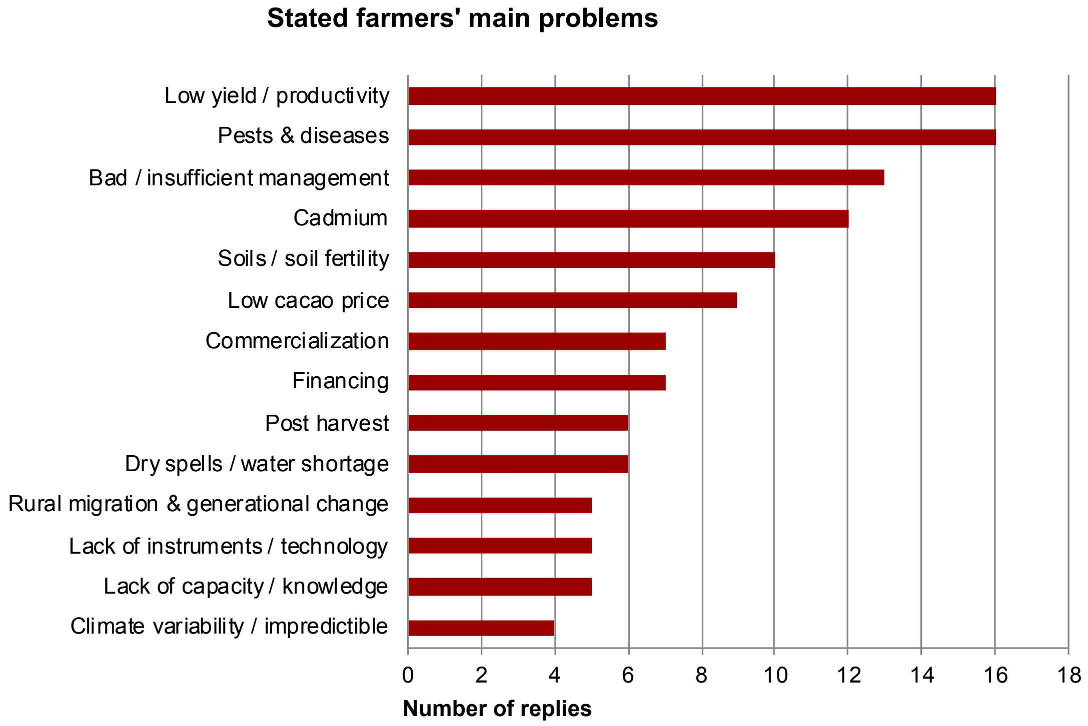

Figure 3. Stated cacao producers' problems and challenges.

The graph shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. Answers were open; only in some cases, a confirmation was asked to see if the keywords "weather", "price" or "diseases" were considered as a problem; this helped to cross check information from previous interviewees. The interviewees' answers were classified afterwards for visualization purposes. Own elaboration from interviews and discussions.

The interviews reveal consensus on both low yield or low productivity and the presence of pests and diseases as the main challenges for cacao production in San Martin and Peru in general. The third challenge is inappropriate agricultural management on farm. These problems are deeply related: low yield can be caused by the presence of pests and diseases; which appear mostly as a consequence of insufficient management. Insufficient management can also directly lead to low yield.

Many factors can lead to low productivity. Insufficient or inadequate use of fertilizers or pruning negatively affect yield. However, yield depends on the cacao variety as well. The stakeholders agree that fine and native cacao varieties yield less than improved varieties. Additionally, agrochemicals affecting the cacao pollinators lead to reduced fructification.

In addition, these factors explain why the majority of San Martin producers only grow one single cacao variety. Over 70 % of cacao production in San Martin accounts for the clone CCN 51[6]. This is an improved hybrid, which produces high yields throughout the year and proves to be more resistant to pests and diseases. Hence, farmers see CCN 51 as a secure source of income.

High humidity –which can be otherwise controlled with pruning– favours the presence of cacao diseases. Most fungi, rather than affecting actual pod production, affect the amount of harvested cacao that has good quality and can be commercialized. Harvests have experienced losses of up to 80 % due to Frosty pod. According to stakeholders, cacao price is less important than pests and diseases, because "*without production, there is nothing to sell*"[7].

Concern also arises regarding cadmium content on soils and cacao derivates due to restrictions for international commercialization (INIA, GORESAM & ICT, 2019). Public and private stakeholders are worried on restrictions to enter European markets, the risk of returned deliveries, paying additional costs for performing laboratory analysis, and having to accept lower prices from non-attractive markets.

Soils may pose difficulties for the following reasons: its cadmium content, low fertility, soil dryness or soils that retain excessive moisture. Low fertility can be managed with agricultural best practices, but farmers cannot invest in fertilizers if their income is already low. While soils that cannot retain moisture become a problem during drought, soils that remain flooded after heavy rainfall events are equally problematic. Flooded soils hinder agricultural management; increase humidity favouring the presence of diseases; and facilitate the erosion of soil nutrients or fertilizers.

Cacao price depends on the international market, cacao quality and its certifications. As a commodity, local stakeholders are not able to influence the price of conventional cacao. In addition, intermediates negotiate cacao price with farmers but may not pay them a fair price. Native, organic or certified cacaos do offer better prices, although their production cost is also higher. Nevertheless, most of the times the price does not compensate farmers' efforts put on cacao production[8] nor allow cacao families a proper income.

Concerns on commercialization are related to regulations for international markets, mainly the European, as mentioned above. Additionally, new concerns have arisen on the consequences of the coronavirus pandemic on global cacao demand and prices[9].

Financing issues included concern on the limited possibilities of farmers to access agricultural credits or loans to invest in their production, for example for buying agrochemicals, fertilizers or certified cacao seedlings. Yet, more frequently, financing problems were related to

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[6] Personal communication, DRASAM, March 2020.

[7] Personal communication, Chacra Pasikiwi, March 2020.

[8] Stakeholders states that "There is a lot of unrecognized effort behind organic cacao grains"; "The price of organic cacao does not reward farmers well (…)."; March 2020.

[9] Foro del cacao y chocolate latinoamericano 2020, & Salón del cacao y chocolate Perú, 2021.

cooperatives and associations. They frequently have to rely on development projects and international cooperation to be able to improve technology for post harvest, provide their members with fertilizers or capacity building, certify their production, among other improvements. Additionally, cooperatives perceived that national customs requirements in order to export were too strict and posed them in disadvantage compared to other enterprises.

Further relevant problems and challenges consisted of the post harvest phase, rural migration and farmers' lack of instruments, capacity or knowledge. These factors directly affect production yield and quality. The post harvest phase is critical since it comprises the extraction of the cacao beans from the pods, the drying and fermentation processes, which can be done on farm or at the cooperatives' centres. Equipment for drying and fermentation is therefore required. These processes must follow a systematic protocol in order to achieve good and homogeneous cacao quality, hence a proper cacao price. Lack of instruments and capacity may refer, additionally, to fertilizing, pruning, planting systems (e.g. shadow), etc.

Regarding weather and climate, there is a consistent agreement that drought or dry spells are critical. Drought or dry spells are problematic when they occur during cacao maturation phase, before harvest, and last two weeks or more. Prolonged dryness reduces pod growth and may also lead to tree death. Changed seasonality, such as longer dry seasons, delayed or shorter rainy seasons, were also revealed as key problems. Stakeholders stated that seasons were unpredictable and this affected farmers' ability to manage cacao, for example not being able to anticipate when to perform pruning or fertilize. Changed seasonality, especially unexpected rainfall, also poses a risk for sun drying cacao beans.

High temperatures were addressed by their effect on evapotranspiration. Higher evapotranspiration leads, on one hand, to higher relative humidity, thus increased risk of diseases; and on the other hand, to increased soil evapotranspiration, soil dryness and hence the need of irrigation.

The stakeholders further indicated the following issues: lacking information services; irrigation; old trees or plantation age; zoning or land tenure; connectivity or logistics; and growing cacao in inappropriate areas[10]. Irrigation can be seen as an adaptation practice in case of drought. In Tocache, large and industrial farmers do irrigate cacao. Yet, for most farmers it is costly and not feasible due to the parcels' topography. Regarding tree age, productivity decreases with trees older than 30 years, depending on the cacao variety[11]. Farmers should replace older trees, which involves high costs, and then need to wait until young trees are productive after 4-5 years. Occasional cacao producers, i.e. not dedicated to cacao as their main activity, typically own older trees.

All in all, the results evidence: i) different perceptions according to stakeholder group; and ii) challenges arise in different phases of the cacao value chain. In the productive phase, i.e. on farm, main challenges are the presence of pests and diseases, management shortcomings, dry seasons or water shortage, changed seasonality and other climatic events. In the post harvest phase, technology and equipment, as well as clear protocols for processing, are critical. For commercialization, important aspects are cacao quality, certifications and awards, as well as relationships with clients and markets. Finally, social issues, particularly rural migration of young generations, was indicated to affect cacao production in the long term.

5.3.1. Yield and income

A brief explanation of problems related to yield and income allows to, first, better understand farmer's perceptions on cacao as an income source, and second, to elaborate recommendations later on. Based on the interviews, a characterization of cacao production systems and average annual yields is shown below (table 5).

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[10] This referred to Huánuco, not San Martin, which was too humid.

[11] Stakeholders pointed at native cacao trees > 50 years in Cusco still under production.

Table 2. Stated yield and production characteristics.

Yield (kg / ha)	Description
> 2000	High technology; improved varieties (CCN51); fertilizers; Tocache producers
1000 - 2000	Conventional production (CCN51); use of agrochemicals
800 - 1000	Organic production; fine varieties; organized producers; low technology
< 800	Inappropriate management; fine and native varieties; non-organized producers

The table shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. The interviewees' answers were classified afterwards for visualization purposes. Own elaboration from interviews and discussions.

This characterization reflects the factors responsible for low productivity, mainly due to agricultural practices and cacao varieties. So, lowest yields occur for non-organized producers with inappropriate management or for native cacao varieties, regardless if in the latter case farmers are associated or sell to gourmet markets. For example, to complement information on small and non-associated producers, who are difficult to contact, the regional cacao producer database provides more information (PIPCACAO project of DRASAM, 2020a, b). The more than 5000 cacao producers in the databse own an average of 2 ha and yield an average of 570 kg / ha (ranging from 200 – 5800 kg / ha).

Systems under organic production, either with fine or conventional varieties, usually yield between 800 – 1000 kg / ha. Higher technology input in monocrop plantations may achieve up to 1500 kg / ha, and there are experiences reaching up to 3000 kg / ha, but stakeholders recognize that this can only be achieved with fertilization and irrigation. Two main systems can be then distinguished: i) an average yield of 800 kg / ha; ii) an average yield of 1500 kg / ha. According to stakeholders, agricultural management and avoiding pests and diseases might make the difference between yielding 800 or 3500 kg / ha. Stakeholders noted that the annual yield average in San Martin is 947, 1000 or 1183 kg / ha. In comparison, the national average is 600 - 700 kg / ha (INIA, 2019).

Different views exist on productivity's implications. There is an agreement that 800 kg / ha is too low. For some stakeholders, cacao is not profitable if yield is lower than 1500 kg / ha; for others, profitability and income generation start at 2500 kg / ha. Additionally, it was observed that 1 ha was not profitable for a farmer and that parcels should be larger than 3 ha to allow earning profit. Finally, a key observation noted that yield should be high enough to allow farmers to still make profit after discounting the losses caused by plagues and diseases.

The relationship between yield, price and farmers' characteristics is not straightforward. Table 6 explains the differentiated prices received on farm for dry cacao beans.

Table 3. Stated price and associated production characteristics.

Price (PEN / dry kg)	Description
15 - 20	Special cacaos; organic, niche and gourmet markets
12 - 15	Fine and aromatic cacaos; organic, niche and gourmet markets
8 - 10	Conventional cacao; fine and aromatic cacaos; organized producers
6.5 - 8	Conventional cacao; commodity price; average yearly price; organized and non-organized producers
< 6.5	Conventional cacao; low price; non-organized producers; dependence on intermediaries

The table shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. The interviewees' answers were classified afterwards for visualization purposes. Own elaboration from interviews and discussions. Note that 1 EUR = 3.8 to 4.2 PEN (Peruvian Nuevos Soles).

Here, a key differentiating factor is cacao variety, which can be a conventional / commercial variety, fine or aromatic cacao, or even special cacao –native-. Niche and gourmet markets refer to special *chocolatiers* in Peru or abroad, as well as cacaos for international competitions and awards. Also, cacao certifications, such as organic, fair trade or carbon neutral, and the ability to negotiate prices with buyers via cooperatives, or with intermediaries, play relevant roles.

Stakeholders noted that conventional cacaos receive the commodity price. This usually ranges from 5.5 - 8 PEN / kg, with an annual average of 6.5 PEN / kg and a maximum of 10 PEN / kg. In contrast, 10 PEN / kg might be seen as a low price for fine and aromatic cacaos. The price difference of organic and conventional production systems is around 1 – 1.5 PEN / kg. When cooperatives negotiate with buyers they might gain 1 PEN / kg, compared to non-organized producers. Intermediaries might negotiate – (0.5 – 1) PEN / kg to non-organized producers. It is important to note that cooperatives have agreements with their members and clients, so that they cannot buy cacao to their members to very low prices; in this sense, they operate as price insurers.

Lastly, some stakeholders pointed at cacaos' low profitability. Dry beans were not profitable. Instead, transforming beans into chocolate proved profitable and revealed a huge gap (> 4 PEN per 50 gr chocolate bar in the national market). Furthermore, if the price difference between organic and conventional cacao is around 1 PEN / kg, but yield difference is 1000 – 2000 kg / ha, organic price should actually be doubled to compensate farmers' effort[12].

5.3.2. Pests and diseases

Cacao pests and diseases appeared as a critical issue (table 7). The majority of stakeholders pointed as fungi, particularly Frosty pod (figure 13), and among insects Carmenta bugs, causing most damage. The replies are in accordance to SENASA's statement on the four key main pests of cacao in Peru: Frosty pod, Witches' broom, Black pod and Carmenta. Occasional pests, which appear certain seasons or years, consist of the cocoa bug and migrant insects, such as locusts. Complementary information on the observations for pests and diseases can be found in annex 12.

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[12] Personal communication, Central Cacao de Aroma, April 2020.

Table 4. Stated cacao pests and diseases damaging production.

Pests and diseases	Fungi		Chromista	Annimalia		
	Frosty pod	Witches' broom	Black pod	Carmenta	Cocoa bug	Locust
Number of replies	14	11	6	12	3	2

The table shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. The interviewees' answers were classified afterwards for visualization purposes. Own elaboration from interviews and discussions.

Briefly, Frosty pod and Black pod fungi infect the cacao pods during their maturation, rotting the inside. Witches' broom deforms cacao trees and fruits; it affects the growth, form and number of branches, pods or flowers (Bailey & Meinhardt, 2016; Murrieta & Palma, 2020a, b, d; CABI Plantwise, 2021). Thus it affects the amount of cacao that can be harvested. Carmenta deposits its larvae inside the cacao pods. These grow inside, eat its content and hence make it impossible to commercialize (Murrieta & Palma, 2020c).

Stakeholders pointed at relationships between climate conditions and diseases. There is agreement that humidity and warmth favour the spread of fungi, especially Frosty pod and Black pod. Some stakeholders indicated Witches' broom was favoured by humidity, while others rather pointed at dryness favouring its spread. It was mentioned that Carmenta increases in dry and warm conditions, and some stakeholders pointed at abrupt changes in seasonality to favour its spread. Locusts were observed to appear in the driest season, but are occasional pests.

Agreement exists that, after climatic conditions, the lack of management and farmers inattention to their crops cause the spread of pests and diseases. Regarding management and control, most farmers already possess the know-how to manage Frosty pod and Black pod. However, Carmenta is seen as a new pest, so that they do not have the knowledge to prevent or control it. Other bugs were seen as controllable. Some observations point at the increased incidence of pests and diseases with time, as well as pests becoming more resistant. Additionally, diseases affect differently each cacao variety. In general, CCN 51 is more resistant, while fine varieties are the most sensitive.

Table 5. Pests or diseases affecting cacao producers in PIPCACAO project in San Martin.

Main pest or disease	%
Frosty pod	44
Carmenta	22
Witches' broom	21
Cocoa bug, other insects	10
Black pod	1
Ants	1
Termites	1

Source: Elaborated based on PIPCACAO database (DRASAM, 2020b).

Figure 4. Cacao pod infested by Moniliasis, Tarapoto, March 2020.

The regional cacao producers database (DRASAM, 2020b) sheds more light on the impact of pests and diseases in San Martin (table 8): 69 % of farmers report the presence of pests and diseases, while only 31% do not. Among those farmers reporting pests and diseases, Frosty pod is the most reported (> 43%), doubling the cases of Carmenta (22%) and Witches' broom (21%).

Not only the extenstion of incidence of pests and diseases is a concern for DRASAM, but also the degree of affectation and implications for yield loss. A disease can, for instance, affect pod quality, number or size, or grain number and quality. Thus, the impact might be a reduction in the harvested yield that can be commercialized. This is the principal impact for farmers, having direct implications on cacao production and their income. Stakeholders tell stories where harvest losses accounted for 20 and 50% of production in case of Carmenta and 25 up to 80% in case of Frosty pod. Due to the severe impacts of pests and diseases in cacao harvest and income for farmers, pests and diseases have been taken into account to analyse the performance thresholds for cacao production in this study.

6. Critical variables for cacao production

This chapter looks into the critical variables for cacao production, putting together insights from the interviews and literature. First, it identifies the critical or trigger situations leading to a performance threshold in cacao. Second, it identifies the critical climate variables and corresponding values according to literature sources and models. Third, it identifies the performance thresholds for cacao production in the study area.

6.1 Trigger situations

The farmers' challenges presented in the previous chapter can be complemented with perceptions about climate in the study area (figure 14). Perceived problems related to weather and climate confirm that drought is indeed the most problematic event for cacao. Perceived changes in seasonality and, especially unpredictable rainfall, are also problematic, because they difficult pruning, harvesting or drying the beans. Note that most problems and perceived changes in climate are related to precipitation, in contrast to temperature.

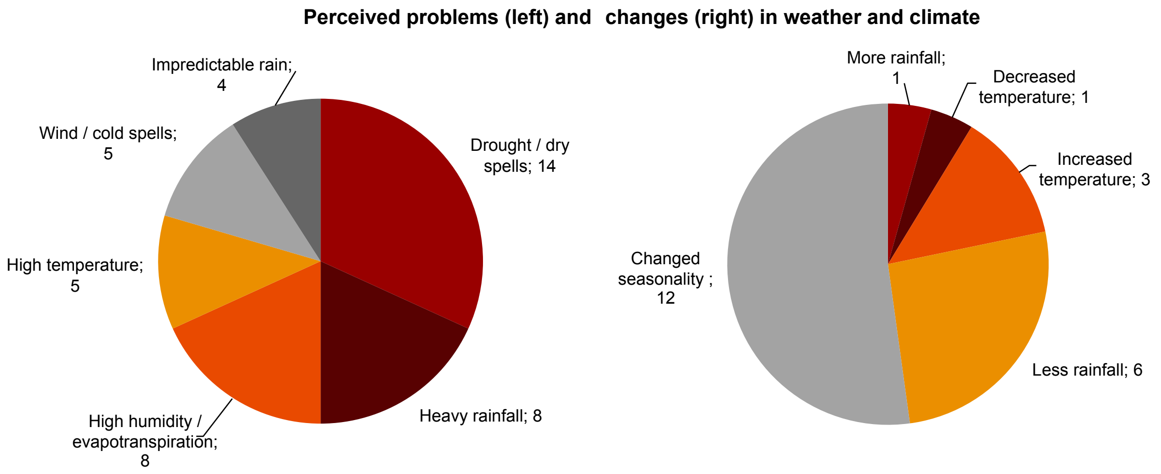

Figure 1. Perceived problems and changes in weather and climate.

The pie charts show perceived problems (left) and changes in weather and climate (right) extracted from interviewees and discussions with local stakeholders regarding weather perceptions in the study area. Values show the number of replies. Note that different perceptions can belong to the same interviewee, or in contrast, refer to varied locations in the study area. Own elaboration from interviews and discussions.

These situations, however, may not necessarily lead to changes in cacao production practices. Therefore, an important question asked to the interviewees consisted in: Which situation, among all the problems discussed, would trigger the farmer to change his or her cacao production, change the main crop, cut down the cacao trees or abandon the parcel (figure 15)? These situations are considered triggers. A follow up question consisted in which strategies the farmer would adopt thereafter (figure 16).

The triggers are economic reasons, drought, and pests and diseases (figure 15). These triggers are in line with the challenges described in the previous chapter. Economic reasons, however, are not further discussed here. Asking about the strategies after a trigger situation confirms that drought, pests and diseases indeed define a performance threshold for cacao production, which the producers do not accept and where the need to adjust practices appears.

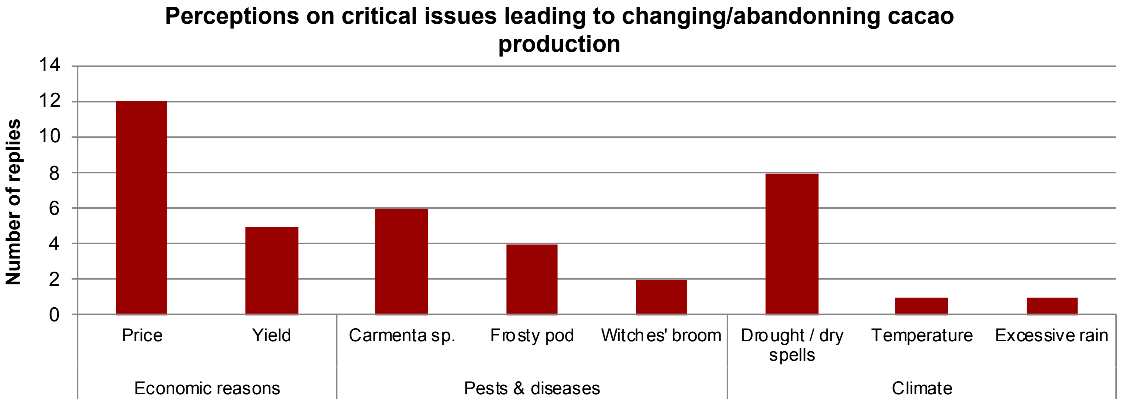

Figure 2. Critical issues or triggers for farmers to change or abandon cacao production.

The bar diagram shows the data extracted from interviewees and discussions with local stakeholders referring to which factor or situation would trigger the farmer to change their cacao production, cut down the cacao trees or abandon the parcel. Values show the number of replies. Note that two or more critical issues can occur simultaneously. Own elaboration from interviews and discussions.

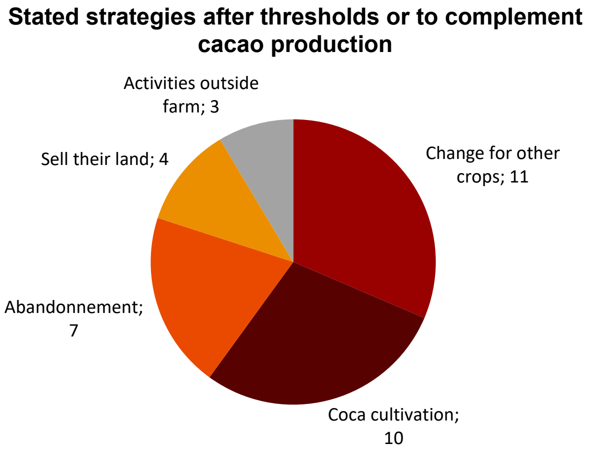

Figure 3. Farmers' strategies after changing or abandoning cacao production.

The pie chart shows the data extracted from interviewees and discussions with local stakeholders indicating which strategies the farmer would take after having deciding to stop or change with cacao production. Values show the number of replies. Note that the strategies can be complementary. Own elaboration from interviews and discussions.

Changing cacao practices is not a casual decision. The decision is taken either after one catastrophic event, or a series of severe events. For example, a farmer may become demotivated after several harvests damaged by pests and diseases, or after several harvests affected by drought, and later decide to change the crop or activity. Stakeholders pointed out that a farmer who begins to lose interest in cacao responds by abandoning the parcel or stopping its management, i.e. by not pruning, fertilizing nor harvesting any more (figure 16). Later, the farmer may decide to change the parcels' main crop or simply add coca cultivation. Similarly, the farmer may choose complementary economic activities outside the parcel.[1]

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[1] Coca cultivation under traditional systems and for local consumption is legal in Peru, because it is a plant with millenary history, medical, nutritional and religious uses. However, when linked to narcotraffic and narco-terrorism, it raises socio-political problems and poses the farmers' families at high risk. Coca is an alternative key cash crop, since it can be planted together with other tree species, has a rapid cycle and guarantees a high income when sold to illegal markets.

It's important to specify what stakeholders consider as a trigger drought. A drought becomes critical when it lasts two weeks or more, is accompanied by high temperatures and occurs during cacao pod maturation and harvest season (May – August). The driest and warmest months comprise July and August, hence drought risk is more severe during these months, where the last harvests also take place. The next section looks further into literature to identify the climatic variables defining the critical drought.

The presence and severe attacks of pests and diseases, especially the latter, is favoured by a high relative humidity (>80%), according to interviewees. However, environmental data on relative humidity were not available for the study area, nor are comprised within the 19 Worldclim bioclimatic variables used here.

6.2 Critical climate variables

Cacao is known to be a drought-senstitive species. Drought affects the flushing cycle, as well as productivity and yield quality (Zuidema et al., 2005; De Almeida & Valle, 2007; Medina & Laliberte, 2017; Gateau-Rey et al., 2018; Lahive et al., 2019). Critical variables for drought are the maximum temperatures during the dry season, the intensity and length of the dry season, i.e. months with rainfall < 100 mm/ month, and the evapotranspiration balance during the driest quarter (Zuidema et al., 2005; De Almeida & Valle, 2007; Schroth et al., 2016). Factor such as wind, radiation intensity and hours of direct sunlight also afftect the intensity of perceived drought by incresing evapotranspiration (De Almeida & Valle, 2007). In addition, drought stress turns the trees more susceptible to the attack of pests and diseases (Gateau-Rey et al., 2018).

The ranges and values for critical variables for cacao are presented in table 9. To summarize:

- An optimal annual mean temperature for cacao is 23 to 25°C, and annual temperatures should not exceed 40°C;
- Optimal annual precipitation is around 1250 - 2500 mm, and should never be < 600 mm, otherwise irrigation is needed (Ceccarelli et al. 2021);
- Optimally, dry months should be zero, but cacao tolerates up to 2 continuous months with <100 mm of precipitation;
- Known temperatures that will lead to tree death are a minimum of 10°C (Eitzinger et al., 2015a) and a maximum of 50°C (CIAT, 2014).

Comparing these values with the interviewees perceptions, it is possible to derive that 1 month with <100 mm of rainfall and maximum temperatures > 32°C already diminishes yield production and affects the harvest. The situation can be exacerbated if dry and hot conditions continue through the dry season, or if the dry season is extended more than 2 months. Therefore, it is also relevant to analyse rainfall and maximum temperatures during the driest quarter.

Ecological models used in the literature also give insights into the bioclimatic variables that are the most explanatory for suitable areas for cacao. There is a large agreement on the following bioclimatic variables as the most critical for cacao (Zuidema et al., 2005; Leguía et al., 2010; Läderach et al., 2013; CIAT, 2014; Eitzinger et al., 2015a, b; Schroth et al., 2016; 2017; Ortega et al., 2017; Ceccarelli et al., 2021):

- Bio 5: Maximum Temperature of Warmest Month
- Bio 7: Temperature Annual Range (Bio 5 - Bio 6)
- Bio 14: Precipitation of Driest Month
- Bio 15: Precipitation Seasonality
- Bio 17: Precipitation of Driest Quarter
- ETP: Potential evapotranspiration

Note that Bio5, Bio14, Bio17 and ETP are helpful indicators of drought conditions. Moreover, Bio5 and Bio14 correspond to the critical temperature and precipitation conditions for the driest month, while Bio17 corresponds to the dry season. The ecological models do capture the drought-sensitivity of cacao, thus are useful to further anlayse performance thresholds accroding to stakeholder concerns.

The following subsection analyses the performance thresholds for cacao production using four selected critical variables precipitation for the driest month (Bio14) and the driest quarter (Bio17), maximum temperature for the warmest month (Bio5) and mean temperature of the driest quarter (Bio9). These four variables reflect stakeholders' concerns, are supported by literature evidence and are available as bioclimatic variables later used for suitability modelling.

Table 1. Critical climate variables for cacao.

Variable	Annual temperature range (ºC)		Annual precipitation (mm)		Number of dry months		Minimum precipitation (mm/ month)		Altitude (m)		Source	Comments
	Optimum	Tolerance	Optimum	Tolerance	Optimum	Tolerance	Optimum	Tolerance	Optimum	Tolerance		
Variable ranges		10 - 40		> 1250		2		40			Zuidema et al., 2005	The study developed and applied the Physiological growth and production model (SUCROS-Cocoa) to several cacao producing countries worldwide.
	23 - 24	9 - 30					>200				De Almeida & Valle, 2007	Review of cacao ecophysiology and environmental requirements worldwide, although mostly with Brazilian examples.
	24 - 28	20 - 40	1200 - 2500	800 - 5000	0	< 2		100	0 - 800	0 -1200	Leguia et al., 2010	Parameters selected for commercial non-intensified cacao production in Aguaytía, Pucallpa, Peru. The study modelled suitability using Maxent.
	22 - 25	17 - 32	1000 - 1200	800 - 2600							CIAT, 2014	Parameters calibrated for Peru for Ecocrop model. The study also analysed Colombia and Ecuador.
	20 - 30 (27)	15 - 43.5 (46)	1250 - 2500	1000 - 2800		< 4					Eitzinger et al., 2015a	Temperatures for hybrid cacao and (Lower Amazon variety). The study applied the Ecocrop model to Trinidad and Tobago and Jamaica.
	(21) 22 -25 (32)	20 -27 (38)	1200 - 3000	900 - 7600	0	1 - 3		100			Schroth et al., 2016	Environmental requirements for cacao based on FAO (2007). In () the mean and maximum recommended annual temperatures. The study modelled suitability in the West African cocoa belt using Maxent.
	20 - 30	15 - 34	1400 - 2000	> 1200					0 - 800		Lahive et al., 2019	Review of cacao ecophysiology and environmental requirements worldwide.
Temperature that will kill the plant	50										CIAT, 2014	
	10										Eitzinger et al., 2015a	

The table above gives important environmental ranges for cacao extracted from literature sources. An optimum and a tolerance range, which together describe the potential niche, are given for key variables: annual temperature; annual precipitation; and number of dry months (length of the dry season). A dry month is defined by receiving <100 mm of rainfall (De Almeida & Valle, 2007). Additionally, altitude is also given. Finally, the sources are specified, as well as the locations and models to which the variables were applied. Tolerance and optimum range for cacao may vary according to the continent and case study.

6.3 Performance thresholds

This section analyses the performance thresholds for cacao production by analysing the projected trends for precipitation for the driest month (Bio15) and the driest quarter (Bio17), maximum temperatures for the warmest month (Bio5) and mean temperature of the driest quarter (Bio9) for the study area.

The values for the bioclimatic variables were analysed for current and future climatic conditions, as modelled by 5 GCM and under RCP 4.5 and RCP 8.5. The corresponding values were interpolated for specific locations across San Martin (table 3 and annex 9).

6.3.1 Precipitation

Cacao tolerates a minimum monthly precipitation of 100 mm (Leguía et al. 2010; Schroth et al. 2016). This threshold has been defined as a performance threshold due to stakeholders' concerns.

Figure 17 shows that, under current conditions, all localities except Tocache, already receive <100 mm rainfall during the driest month; two localities, Picota and Bellavista, receive <50 mm/ month. Low precipitation is projected to exacerbate under RCP 8.5. RCP 8.5 projects a clear decreasing trend for all localities from 2010 to 2070. A minimum rainfall of 36 mm/ month is projected for Bellavista by 2070.

Precipitation projections for the driest month do not show a clear agreement between RCP 4.5 and RCP 8.5. Under RCP 4.5, projections show variability between localities and time periods. While precipitation from Rioja to Lamas remain similar to current conditions, precipitation from Campanilla to Chazuta show slight increases towards 2070. Under RCP 4.5, there is a clear decreasing trend only for Tocache.

Precipitation projections for the driest quarter show a similar distribution across localities. Overall, dry season precipitation for the current conditions are very low. All localities show a dry season of 4 months (driest quarter) with <400 mm, which means that cacao must endure with 4 months at the limit of its tolerance. Moreover, most localities receive <300 mm during the dry season, and the two driest localities, Bellavista and Picota, receive <200 mm. These latter localities, then, receive on average <50 mm/ month during the dry season.

Precipitation projections for the driest quarter also do not show a clear agreement between RCP 4.5 and RCP 8.5. Under RCP 4.5, precipitation is projected to increase for all localities and time periods in comparison to 2010. Yet, even with precipitation increases, three localities remain <300 mm and the two driest localities <190 mm during the driest quarter.

Under RCP 8.5, projections show variability between time periods. Precipitation by 2030 remains close or decreases compared to 2010 values. By 2050, models project precipitation increases close to 2010 values, and by 2070 precipitation decreases below current conditions. Exceptions are Rioja, and in minor way also Campanilla and Tocache, for where also RCP 8.5 projects slight precipitation increases. All in all, only Tocache reaches 400 mm during the driest quarter by 2030 under RCP 4.5, and only Tocache and Campanilla receive >300 mm in all time periods and under both RCPs.

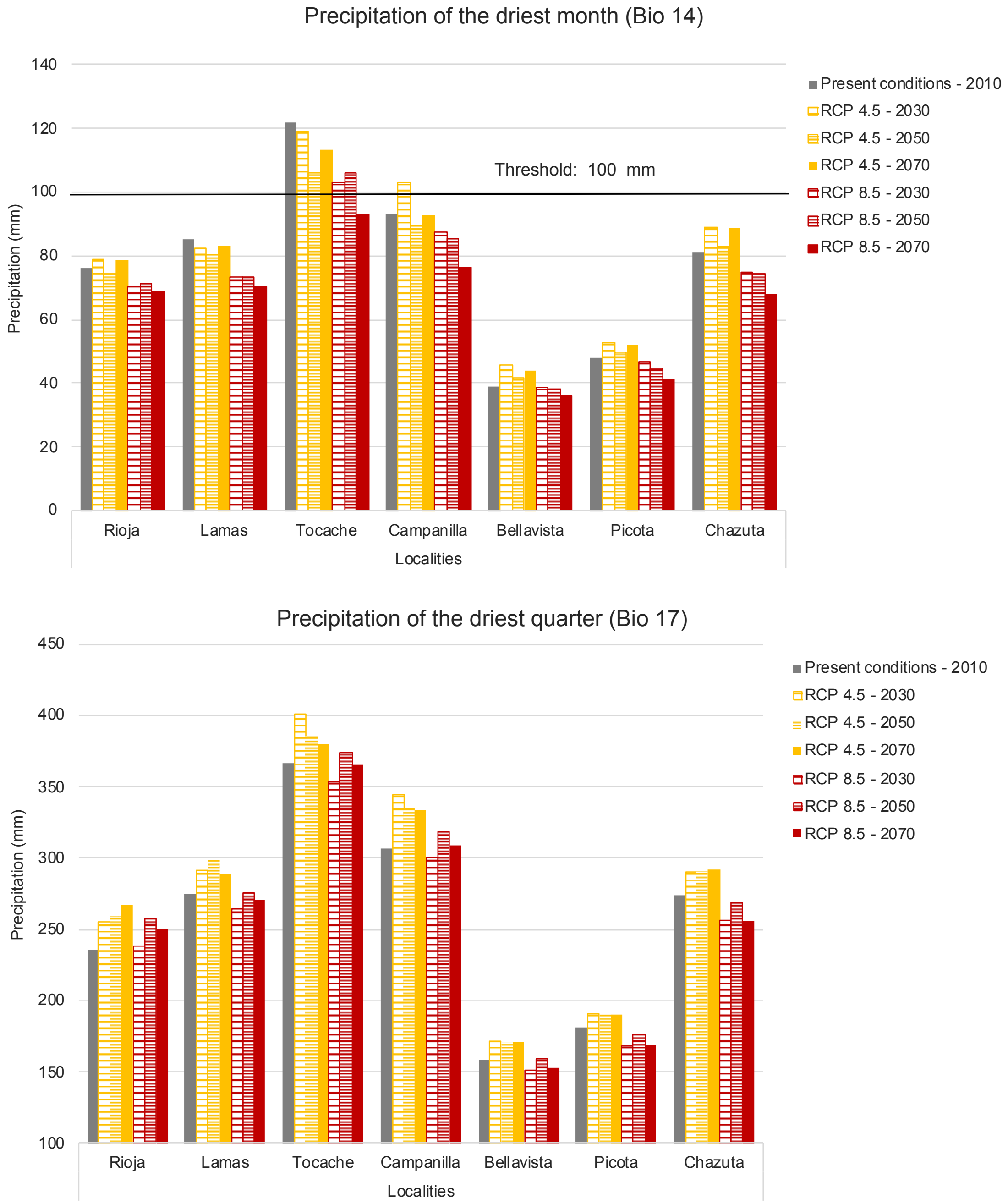

Figure 4. Precipitation of the driest month (top) and quarter (bottom) for locations selected across the study area under present and future scenarios.

The bar diagrams show the ensemble values for Bio14 and Bio17 for selected localities under present and future scenarios. Present conditions (2010) are shown in gray; RCP 4.5 in yellow and RCP 8.5 in dark red. Future periods are represented as 2030 for 2020-2049 (spaced horizontal pattern); 2050 for 2040-2069 (dense horizontal pattern); and 2070 for 2060-2089 (simple fill). The ensembles show the average of 5 GCM: cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr. For details on every GCM please see annex 9.
Precipitation values are given in mm. A threshold for cacao (<100 mm precipitation per month) is shown with a thin black line.
Localities are organized from higher elevation (Rioja, 840 m) to lower elevation (Chazuta, 199 m). The bioclimatic values were extrapolated for the selected localities from the bioclim raster files (spatial resolution of 30 arcsec or about 1 km at the Equator), by superposing the layers on QGIS. The bioclim raster files (Bio1 to Bio19) were obtained from Worldclim and pre-processed by Alliance Bioversity International - CIAT (https://www.worldclim.org/data/bioclim.html).

6.3.2 Maximum temperature

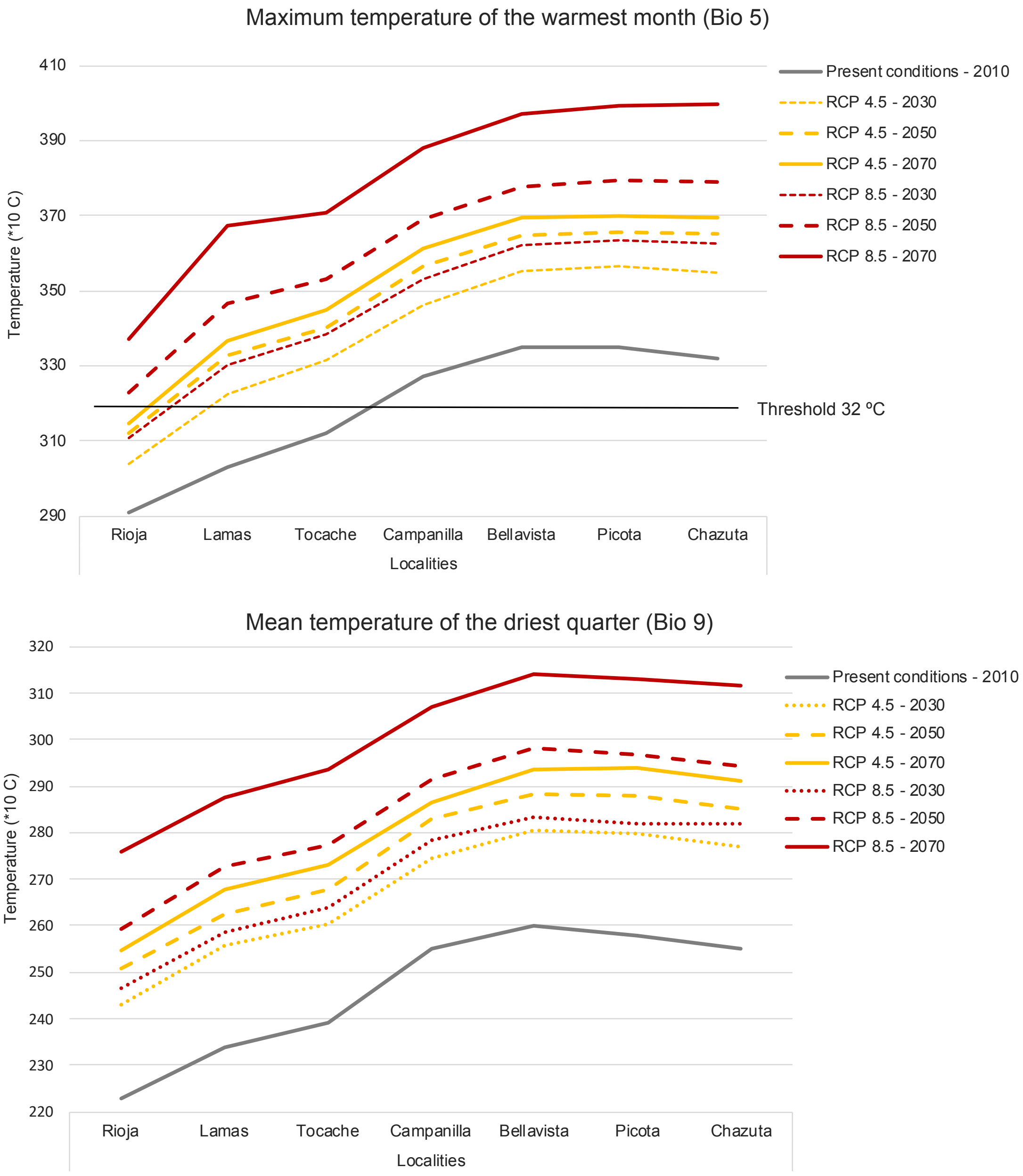

Figure 5. Maximum temperature of the warmest month (top) and mean for the warmest quarter (bottom) for locations selected across the study area under present and future scenarios.

The graphs show the ensemble values for Bio5 and Bio9 for selected localities under present and future scenarios. Present conditions (2010) are shown in gray; RCP 4.5 in yellow and RCP 8.5 in dark red. Future periods are represented as 2030 for 2020-2049 (thin dotted line); 2050 for 2040-2069 (thick dashed line); and 2070 for 2060-2089 (thick continuous line). The ensembles show the average of 5 GCM: cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr. For details on every GCM please see annex 9.
Temperature is given in *10º C to avoid decimals in the calculations. A threshold for cacao (>320 for temperature) is shown with a thin black line.
Localities are organized from higher elevation (Rioja, 840 m) to lower elevation (Chazuta, 199 m). The bioclimatic values were extrapolated for the selected localities from the bioclim raster files (spatial resolution of 30 arcsec or about 1 km at the Equator), by superposing the layers on QGIS. The bioclim raster files (Bio1 to Bio19) were obtained from Worldclim and pre-processed by Alliance Bioversity International - CIAT (https://www.worldclim.org/data/bioclim.html).

Cacao tolerates well a maximum temperature up to 32°C (CIAT, 2014). Here, a threshold of 32°C is considered, because this temperature causes high stress to cacao when coupled to dry conditions.

Figure 18 shows the maximum temperature of the warmest month and the mean temperature of the driest quarter. First, a clear trend in increased temperatures with lower elevation can be identified. This trend is followed in both RCPs and time periods.

Current maximum temperatures reach the 32°C threshold at Campanilla and localities at elevations <300 m. The driest localities, Picota and Bellavista, also reach higher temperatures, with maximum values up to 33.5°C. Future temperature projections show, first, a jump between current and future values, and second, a clear increasing trend with time, where RCP 8.5 projects higher temperatures than RCP 4.5.

According to the projections, Rioja is the only locality where >32°C are projected only under RCP 8.5 after 2050. For Lamas and Tocache, both RCPs project >32°C and >33°C, respectively, already by 2030. Temperatures even >34°C are projected for Campanilla and localities at elevations <300 m as soon as 2030 and under both RCPs. For Picota and Chazuta, maximum temperatures are projected to reach up to 37°C and 39.5°C by 2070 under RCP 4.5 and RCP 8.5, respectively.

The mean temperature of the driest quarter, which comprises both the warmest and driest month in the study area, shows a similar trend with time, per localities and RCPs. Temperature values are higher under all future scenarios compared to current conditions, as well as under RCP 8.5 compared to RCP 4.5. Overall, temperatures are projected to be constantly high. Mean temperatures during the dry season are projected to reach >28°C and >29°C by 2050, and >28.5°C and >30.5°C by 2070 under RCP 4.5 and RCP 8.5, respectively, for Campanilla, Bellavista, Picota and Chazuta. Coupled to a prolonged dry season, these temperatures do put cacao production into stress during the harvest season.

7. Future suitability & adaptation turning points

This chapter presents the ensemble suitability projections for cacao, three diseases and two pests, under RCP 4.5 and RCP 8.5 for 2030, 2050 and 2070. Then, it analyses when and where adaptation turning points for cacao may be reached (table 10). Later, chapter 8 discusses the implications of estimating ATP with suitability projections and performance thresholds.

7.1 Future suitability under climate change scenarios

The figures below show the ensemble suitability projections for each species. Suitability is a measure of how optimal an habitat is for a specific species. Suitability maps are usually interpreted as probability distributions of a species, or where it can be potentially present (Phillips et al., 2006; Philips & Dudik, 2008). As such, suitability maps actually show a continuum range. For clarity, the maps below have been classified to indicate areas where the species will remain suitable compared to the baseline distribution (maps classified at a threshold of 0.75 suitability), areas that will become suitable for the species in the future (>1.0), and areas that will become unsuitable for the species (<0.0).

7.1.1 Theobroma cacao

The modelled suitability for cacao for present conditions reasonably represents the input presence points (figure 19, left). Cacao’s range is along the eastern Andean slopes between 800 m and 1500 m, where it is usually cultivated, although it also grows in the lower Amazon basin. Cacao is also cultivated in the northern coast, however under irrigation (Ceccarelli et al., 2021). The regional and localized changes in projected suitability within Peru seem to follow the complex geographic reality of the Andes mountainous chain. This has implications for (orographic) rainfall distribution and temperature changes along elevational gradients.

The future suitability models show that, in general, cacao’ range will remain similar to the present conditions by 2030. Yet, towards 2050 and 2070, major changes are projected. While both RCP 4.5 and RCP 8.5 project areas that loose and gain suitability for cacao, the projections under RCP 8.5 show larger areas changing and with apparent stronger intensity.

One major change in areas suitable for cacao is elevation. The ensemble suitability model for present conditions roughly indicates areas suitable up to 1300 m in San Martin. In contrast, areas up to 1600 m are modelled as suitable by 2070 under RCP 4.5, and up to 2000 m under RCP 8.5. These gains in suitable areas are mostly towards the western slopes, where natural protected areas are located.

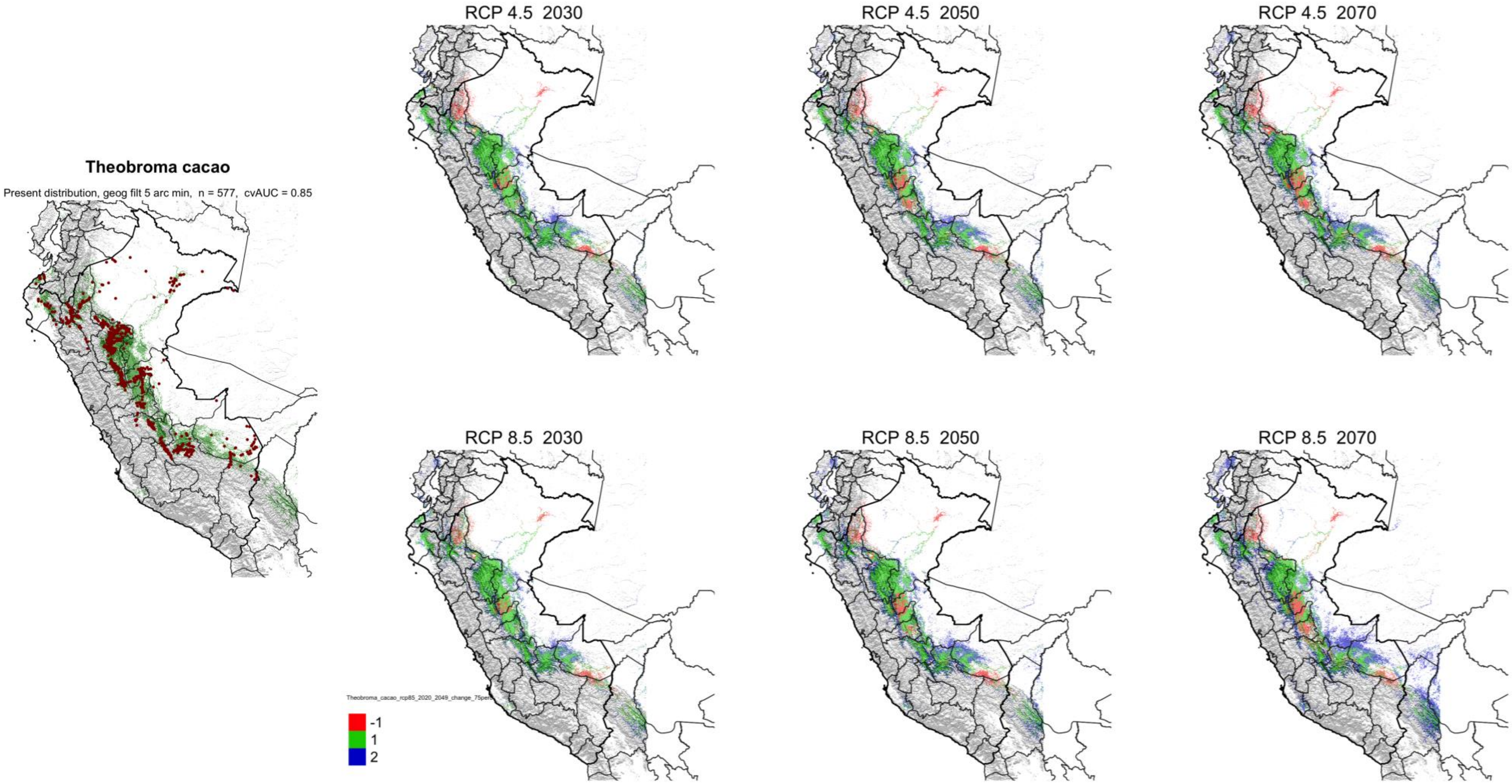

Figure 1. Ensemble suitability models for *Theobroma cacao*.

Modelled suitability por current conditions (2010) is shown in the map to the left. Areas suitable for the species are shaded in light green, while presence points as dark red dots. The input presence points were randomly filtered with a geographic filter at 5 arcmin. The cross-validated Area Under the Curve (cvAUC) is a measure of model performance, where values closer to 1 indicate a good performance. National and regional borders are shown by thin dark gray lines.

Future suitability under RCP 4.5 (top row) and RCP 8.5 (bottom row) show projections for the periods 2030 (2020-2049) at the left; 2050 (2040-2069) at the centre; and 2070 (2060-2089) at the right. The ensemble suitability models were produced using the R script developed by Ceccarelli et al (2021), and jointly adjusted with Alliance Bioversity - CIAT. The maps represent an ensemble averaging the results of 5 GCM (cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr). The maps shows results where > 75 % of the 8 algorithms used for every GCM agree in the direction of change. For clarity, the results have been classified in three categories: the area that loses suitability in the future is shown in red (-1); the area that remains suitable is shown in green (1); and the area that becomes suitable in blue (2).

7.1.2 Diseases

The figures 20-22 show the suitability projections for the fungi causing Witches' broom (*M. perniciosa*), Frosty pod *(M. roreri*) and Black pod (*Phytophthora sp.*) diseases on cacao.

The suitability projections for the three diseases are related to cacao's distribution. Yet, diseases tend to depend more on humidity that cacao. This explains why the northern coast area is shown as unsuitable for the diseases, for example for Witches' broom. The southeastern part of Peru, despite having observation points for the diseases, is not modelled as suitable.

Under RCP 4.5, large areas are projected to become unsuitable for Witches' broom in Peru (figure 20). Suitable areas remain around San Martin and the northern Andes. Projections under RCP 8.5 show a similar trend. Yet, under the latter RCP, the majority of the current suitable areas at the north and centre remain suitable until 2050, and even some areas becoming suitable for Witches' broom are spotted along the Andes. By 2070, under both RCPs, the disease is projected to lose the majority of its suitable range. Rioja is projected to remain unsuitable for this disease by 2070.

Future suitability projections for Frosty pod and Black pod diseases follow a similar trend (figures 21 and 22). Large areas at the eastern Andean slopes and especially at the lower Amazon basin are projected to become unsuitable under both RCPs, particularly after 2050. Suitability loses are more strongly projected for Black pod than for Frosty pod. For example, Rioja will remain unsuitable for Back pod and Tocache will become unsuitable for Back pod by 2070. For Frosty pod, unsuitable areas are projected only for Rioja by 2070 (table 10)[36].

Suitable areas remain for both diseases along the Andes slopes, concentrated in San Martin and the northern Andes. Small and scattered areas than become suitable are projected for Frosty pod in the northern Andes, especially under RCP 8.5 and after 2050. These projected areas are smaller for Black bod and only appear under RCP 8.5 after 2050.

Its worth noting that, in contrast to cacao future projections where large areas remain suitable or become suitable along the Andean slopes and at the Amazon basin, projections for diseases mostly show suitability loses.

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[36] In table 11, Chazuta is shown as unsuitable for Black pod under present and future scenarios. This is because the exact pixel value was analyzed. If the surrounding are taken into account, areas around Chazuta are projected as suitable. These methodological aspect is discussed later.

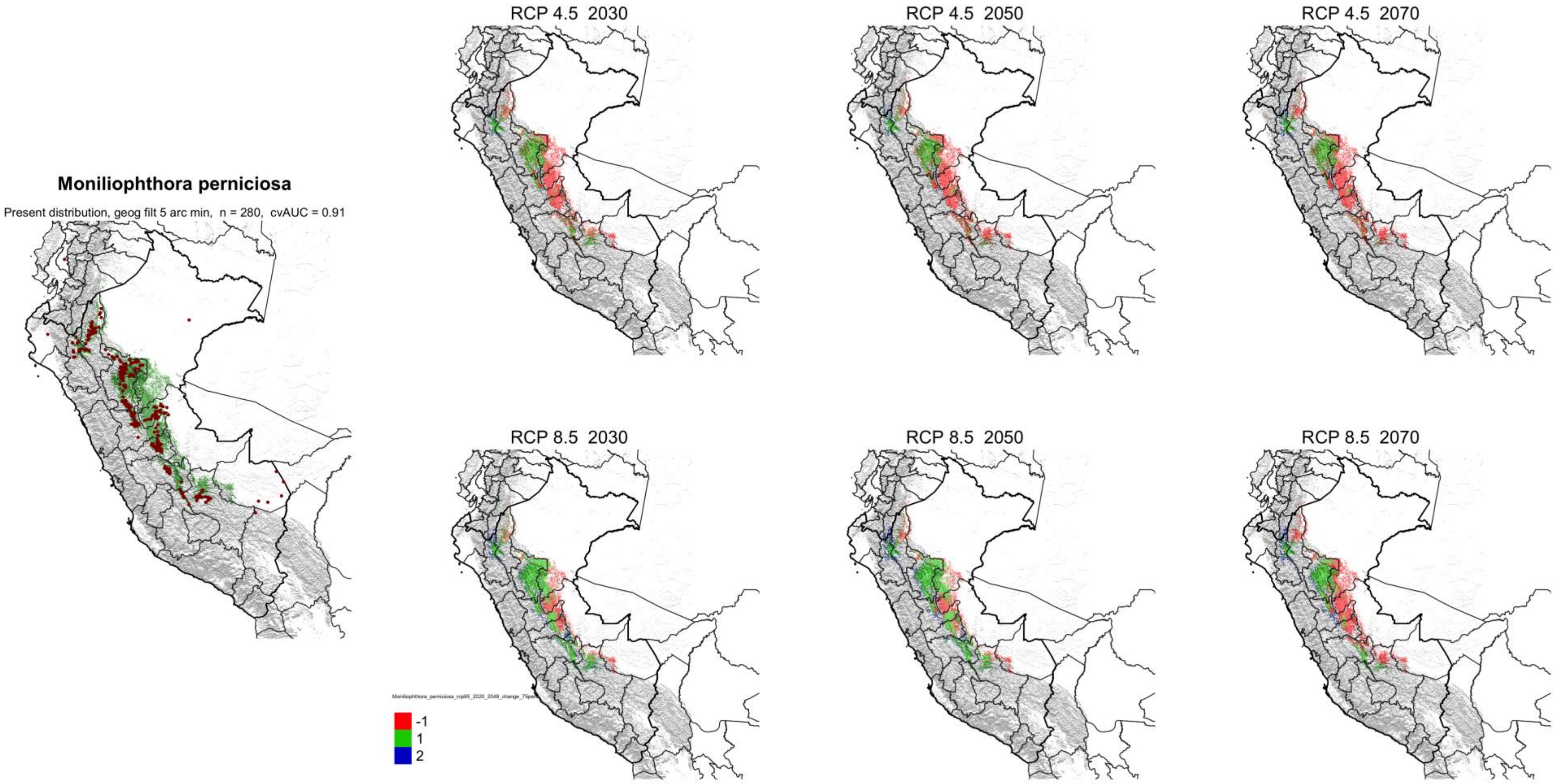

Figure 1. Ensemble suitability models for *Moniliophthora perniciosa*, cause for Witches' broom disease.

Modelled suitability por current conditions (2010) is shown in the map to the left. Areas suitable for the species are shaded in light green, while presence points as dark red dots. The input presence points were randomly filtered with a geographic filter at 5 arcmin. The cross-validated Area Under the Curve (cvAUC) is a measure of model performance, where values closer to 1 indicate a good performance. National and regional borders are shown by thin dark gray lines.

Future suitability under RCP 4.5 (top row) and RCP 8.5 (bottom row) show projections for the periods 2030 (2020-2049) at the left; 2050 (2040-2069) at the centre; and 2070 (2060-2089) at the right. The ensemble suitability models were produced using the R script developed by Ceccarelli et al (2021), and jointly adjusted with Alliance Bioversity - CIAT. The maps represent an ensemble averaging the results of 5 GCM (cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr). The maps shows results where > 75 % of the 8 algorithms used for every GCM agree in the direction of change. For clarity, the results have been classified in three categories: the area that loses suitability in the future is shown in red (-1); the area that remains suitable is shown in green (1); and the area that becomes suitable in blue (2).

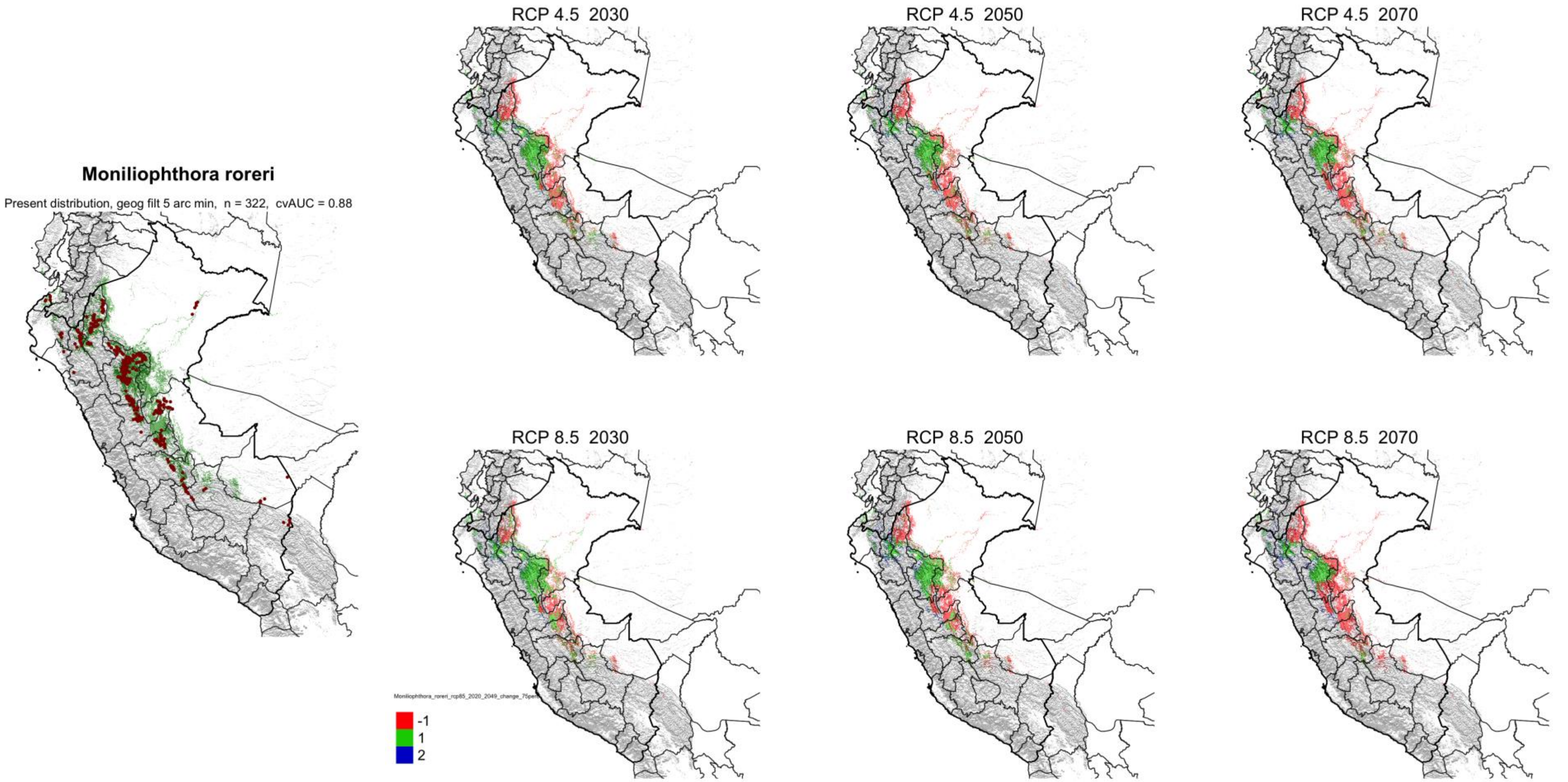

Figure 1. Ensemble suitability models for *Moniliophthora roreri*, cause for Frosty pod disease.

Modelled suitability por current conditions (2010) is shown in the map to the left. Areas suitable for the species are shaded in light green, while presence points as dark red dots. The input presence points were randomly filtered with a geographic filter at 5 arcmin. The cross-validated Area Under the Curve (cvAUC) is a measure of model performance, where values closer to 1 indicate a good performance. National and regional borders are shown by thin dark gray lines.

Future suitability under RCP 4.5 (top row) and RCP 8.5 (bottom row) show projections for the periods 2030 (2020-2049) at the left; 2050 (2040-2069) at the centre; and 2070 (2060-2089) at the right. The ensemble suitability models were produced using the R script developed by Ceccarelli et al (2021), and jointly adjusted with Alliance Bioversity - CIAT. The maps represent an ensemble averaging the results of 5 GCM (cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr). The maps shows results where > 75 % of the 8 algorithms used for every GCM agree in the direction of change. For clarity, the results have been classified in three categories: the area that loses suitability in the future is shown in red (-1); the area that remains suitable is shown in green (1); and the area that becomes suitable in blue (2).

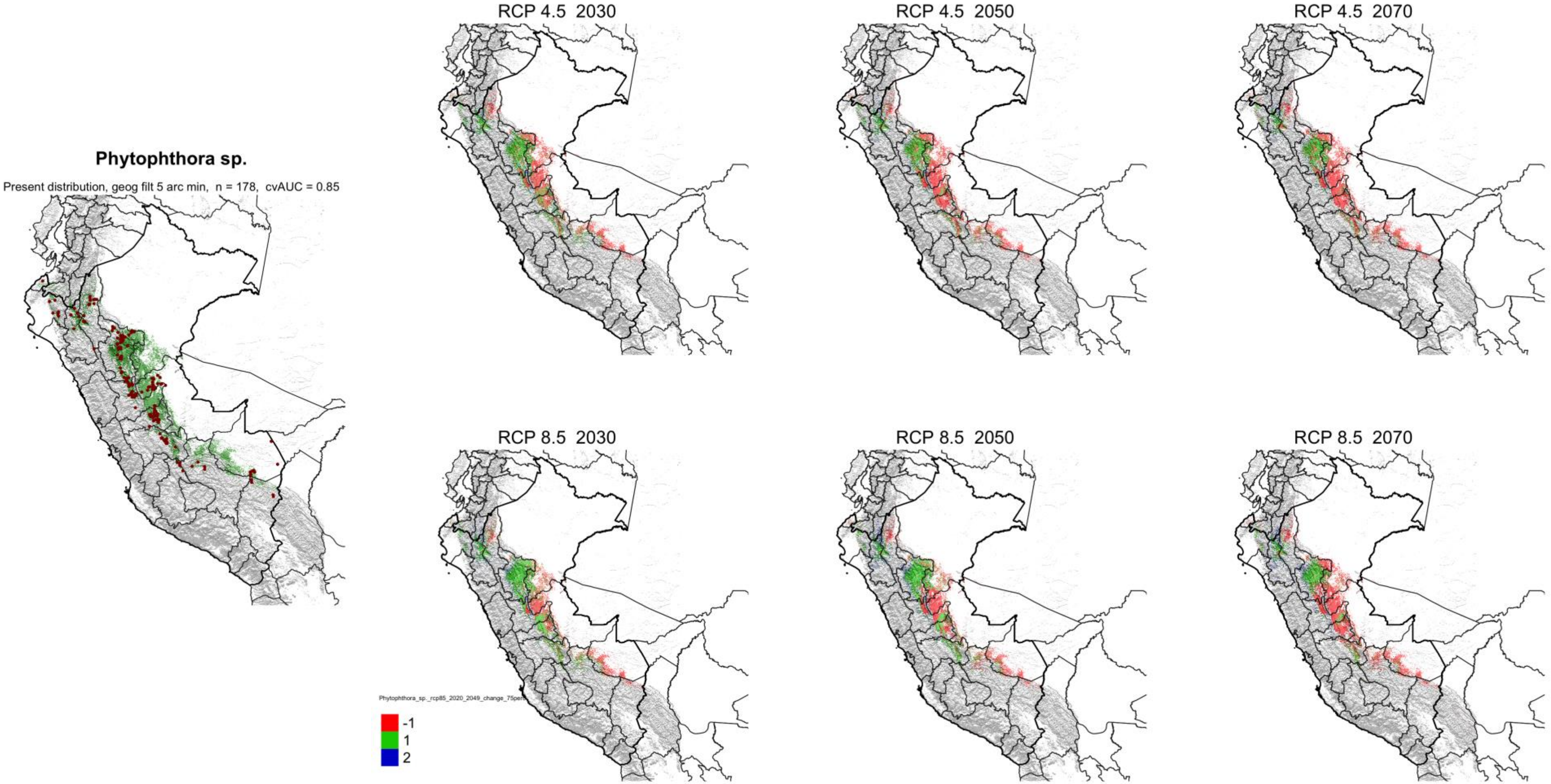

Figure 1. Ensemble suitability models for *Phytophthora sp.*, cause for Black pod disease.

Modelled suitability por current conditions (2010) is shown in the map to the left. Areas suitable for the species are shaded in light green, while presence points as dark red dots. The input presence points were randomly filtered with a geographic filter at 5 arcmin. The cross-validated Area Under the Curve (cvAUC) is a measure of model performance, where values closer to 1 indicate a good performance. National and regional borders are shown by thin dark gray lines.

Future suitability under RCP 4.5 (top row) and RCP 8.5 (bottom row) show projections for the periods 2030 (2020-2049) at the left; 2050 (2040-2069) at the centre; and 2070 (2060-2089) at the right. The ensemble suitability models were produced using the R script developed by Ceccarelli et al (2021), and jointly adjusted with Alliance Bioversity - CIAT. The maps represent an ensemble averaging the results of 5 GCM (cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr). The maps shows results where > 75 % of the 8 algorithms used for every GCM agree in the direction of change. For clarity, the results have been classified in three categories: the area that loses suitability in the future is shown in red (-1); the area that remains suitable is shown in green (1); and the area that becomes suitable in blue (2).

7.1.3 Pests

The figures 23 - 24 show the suitability projections for the lepidoptera *Carmenta sp*. and the cocoa mirid *Monalonion dissimulatum*, both known pests to cacao in Peru.

Presence points for these pests are fewer in comparison to diseases, but are still distributed throughout Peru. The present suitability models show narrower suitable areas. Especially *M. dissimulatum's* suitable area is concentrated in San Martin. As with diseases, the suitability projections for the two pests are related to cacao's distribution.

Future suitability projections for Carmenta differ between RCP 4.5 and RCP 8.5. Under the former, large loses in suitable areas are projected, mostly around the central Andean slopes; few scattered areas remain suitable by 2070. Under RCP 8.5, in contrast, suitability losses are only projected towards the eastern slopes, large areas remain suitable and even some areas become suitable at higher elevations along the Andes by 2030 and 2050. However, in the study area, Rioja and Tocache are projected to become unsuitable for Carmenta by 2070 under both scenarios, and Chazuta only under RCP 8.5 (table 10).

These patterns are slightly similar in the future suitability projections for the cocoa mirid. RCP 4.5 projects large suitability losses; the majority of the cocoa mirid's range is projected to become unsuitable already by 2030. While minor areas remain suitable in San Martin and the northern Andes, very small areas are projected to become suitable along the Andes, mainly at higher elevations at the north by 2050-2070. Under RCP 8.5, the majority of San Martin is projected to remain suitable for the cocoa mirid by 2050, but this area almost disappears by 2070. By 2070, in fact, all analyzed localities are projected to become unsuitable for the cocoa mirid. RCP 8.5 projects larger areas becoming suitable compared to RCP 4.5. These are more notably located at the northern Andes, followed by the central and even southern Andes by 2070.

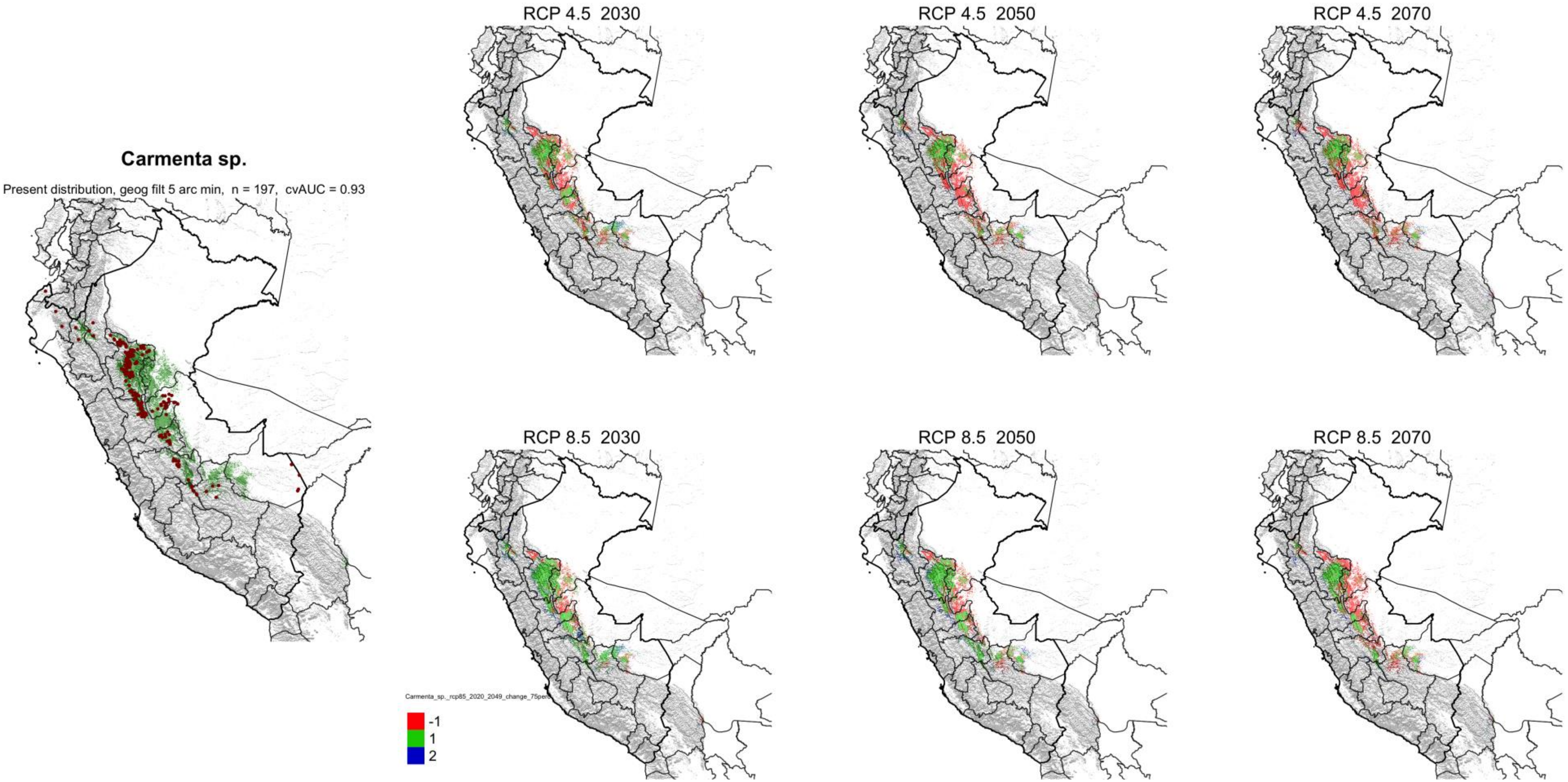

Figure 1. Ensemble suitability models for *Carmenta sp*.

Modelled suitability por current conditions (2010) is shown in the map to the left. Areas suitable for the species are shaded in light green, while presence points as dark red dots. The input presence points were randomly filtered with a geographic filter at 5 arcmin. The cross-validated Area Under the Curve (cvAUC) is a measure of model performance, where values closer to 1 indicate a good performance. National and regional borders are shown by thin dark gray lines.

Future suitability under RCP 4.5 (top row) and RCP 8.5 (bottom row) show projections for the periods 2030 (2020-2049) at the left; 2050 (2040-2069) at the centre; and 2070 (2060-2089) at the right. The ensemble suitability models were produced using the R script developed by Ceccarelli et al (2021), and jointly adjusted with Alliance Bioversity - CIAT. The maps represent an ensemble averaging the results of 5 GCM (cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr). The maps shows results where > 75 % of the 8 algorithms used for every GCM agree in the direction of change. For clarity, the results have been classified in three categories: the area that loses suitability in the future is shown in red (-1); the area that remains suitable is shown in green (1); and the area that becomes suitable in blue (2).

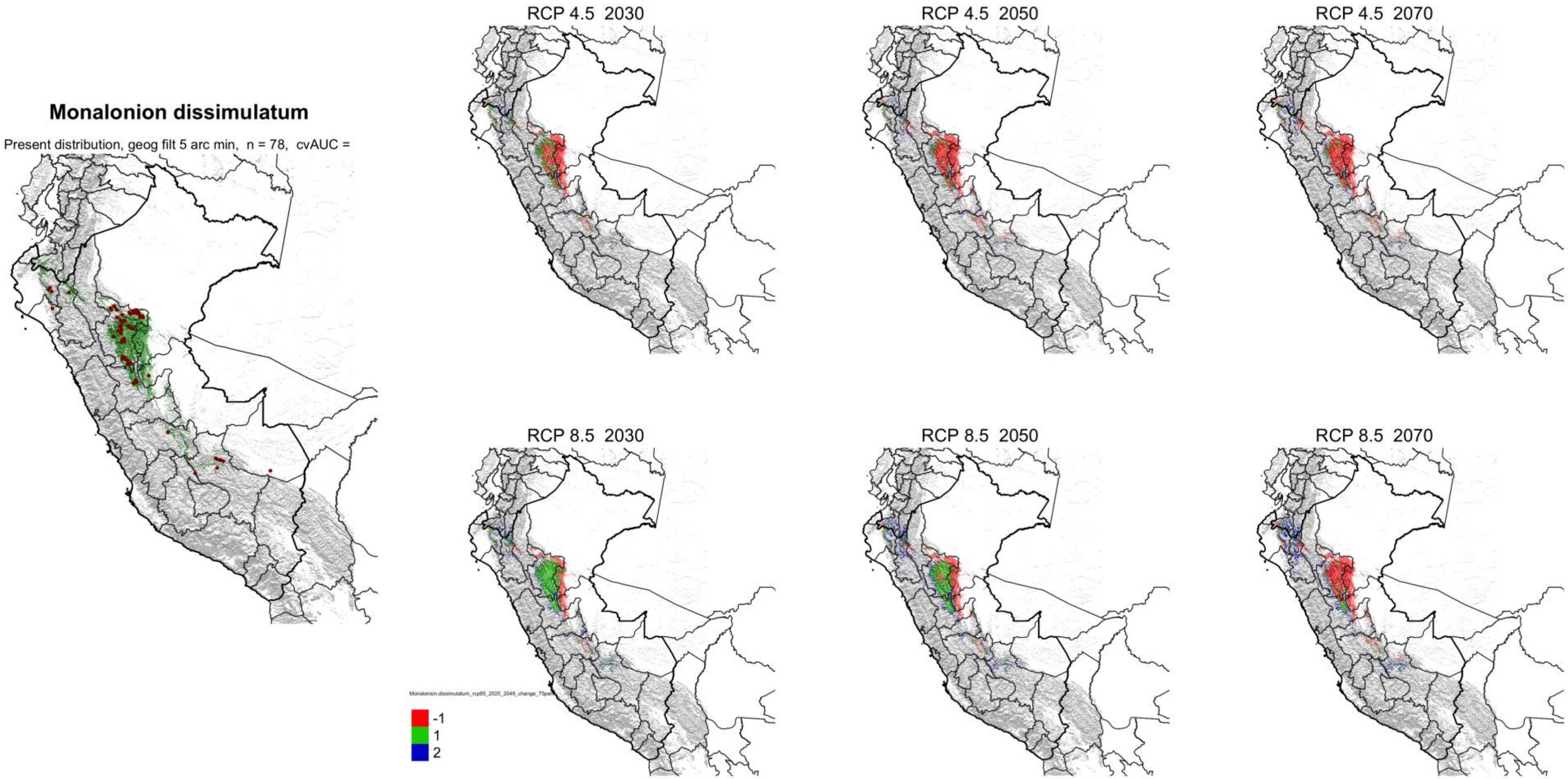

Figure 1. Ensemble suitability models for *Monalonion dissimulatum,* or cocoa bug.

Modelled suitability por current conditions (2010) is shown in the map to the left. Areas suitable for the species are shaded in light green, while presence points as dark red dots. The input presence points were randomly filtered with a geographic filter at 5 arcmin. The cross-validated Area Under the Curve (cvAUC) is a measure of model performance, where values closer to 1 indicate a good performance. National and regional borders are shown by thin dark gray lines.

Future suitability under RCP 4.5 (top row) and RCP 8.5 (bottom row) show projections for the periods 2030 (2020-2049) at the left; 2050 (2040-2069) at the centre; and 2070 (2060-2089) at the right. The ensemble suitability models were produced using the R script developed by Ceccarelli et al (2021), and jointly adjusted with Alliance Bioversity - CIAT. The maps represent an ensemble averaging the results of 5 GCM (cesm1_cam5; gfdl_cm3; miroc_miroc5; mohc_hadgem2_es; and mpi_esm_lr). The maps shows results where > 75 % of the 8 algorithms used for every GCM agree in the direction of change. For clarity, the results have been classified in three categories: the area that loses suitability in the future is shown in red (-1); the area that remains suitable is shown in green (1); and the area that becomes suitable in blue (2).

7.2 Adaptation turning points for cacao

To put it into a nutshell, the study area is projected to largely remain suitable for cacao, and even become suitable at higher elevations. San Martin is projected to mostly remain suitable for diseases and even become more suitable for Black pod at higher elevations. However, there is a trend towards decreases in suitable areas closer to the Amazon basin and in other parts of Peru. Pests, in contrast, are projected to lose suitability across Peru and also in the study area, for examples as soon as 2050 for the cocoa mirid. As a result, it can be expected that pests and diseases may cause less stress on cacao at the eastern Andean slopes and Amazon basin. However, at higher elevations diseases could maintain or increase their pressure on cacao.

On the other hand, maximum temperatures already cause elevated stress on cacao during the warmest month of the year and the dry season. Particularly at central locations and at lower elevations in San Martin, critical temperature thresholds of >32°C are already reached under current conditions, and >34°C may be reached as soon as 2030 under both RCPs. Precipitation during the dry season is already low, with most localities receiving <100 mm in the driest month and <300 mm in the four driest months. Drought stress is more severe at the central locations in San Martin. However, projections show variability in future precipitation between RCPs and time periods.

In other words, performance thresholds for cacao production as have been defined in this study, are already reached under current conditions in localities <300 m elevation, i.e. Campanilla, Bellavista, Picota and Chazuta. In the near future, performance thresholds may be reached in Lamas by 2030, under both RCPs. Nevertheless, these localities are still modelled as ecologically suitable for cacao (table 10).

Rioja and Tocache appear to be better off. The performance thresholds for cacao will not be all reached under the scenarios analysed here, and both localities continue to be modelled as suitable for cacao. Moreover, Rioja is projected to become unsuitable by 2070 for the three diseases and two pests analyzed here.

Tocache is projected to become unsuitable for Carmenta and for Black pod by 2070 under both RCPs. The other localities, in contrast, are still suitable for the majority of diseases and Carmenta. Only Chazuta is projected to become unsuitable for Black pod by 2070 under both RCPs. In all localities, suitability losses are projected for the cocoa mirid. Areas may become unsuitable for this pest by 2050 under RCP 4.5 and by 2070 under RCP 8.5.

Briefly, while suitability models project that the study area will remain suitable for cacao growth under future climate change scenarios, the challenge for cacao producers will be to manage drought and high temperatures during the cacao harvest season, especially at low elevations towards the Amazon basin. Together with drought stress negatively affecting cacao yield, cacao farmers will have to cope with continued presence of pests and diseases.

The following chapter addresses these different outcomes in future suitability for cacao and the performance thresholds, and their implications for defining ATP.

Table 1. Performance and suitability thresholds in San Martin.

Species	Time periods and scenarios		Thresholds per locality																				
			Rioja			Lamas			Tocache			Campanilla			Bellavista			Picota			Chazuta		
			Performance		Suita-bility	Performance		Suita-bility	Performance		Suita-bility	Performance		Suita-bility	Performance		Suita-bility	Performance		Suita-bility	Performance		Suita-bility
			Bio14	Bio5		Bio14	Bio5		Bio14	Bio5		Bio14	Bio5		Bio14	Bio5		Bio14	Bio5		Bio14	Bio5	
Theobroma cacao	2010		X	✓	✓	X	✓	✓	✓	✓	✓	X	X	✓	X	X	✓	X	X	✓	X	X	✓
	2070	RCP 4.5	X	✓	✓	X	X	✓	✓	X	✓	X	X	✓	X	X	✓	X	X	✓	X	X	✓
		RCP 8.5	X	X	✓	X	X	✓	X	X	✓	X	X	✓	X	X	✓	X	X	✓	X	X	✓
Moniliophthora perniciosa	2010				X			✓			✓			✓			✓			✓			✓
	2070	RCP 4.5			X			✓			X			✓			✓			✓			✓
		RCP 8.5			X			✓			✓			✓			✓			✓			X
Moniliophthora roreri	2010				✓			✓			✓			✓			✓			✓			✓
	2070	RCP 4.5			X			✓			✓			✓			✓			✓			✓
		RCP 8.5			X			✓			✓			✓			✓			✓			✓
Phytophthora sp.	2010				X			✓			✓			✓			✓			✓			X
	2070	RCP 4.5			X			✓			X			✓			✓			✓			X
		RCP 8.5			X			✓			X			✓			✓			✓			X
Carmenta sp.	2010				✓			✓			✓			✓			✓			✓			✓
	2070	RCP 4.5			X			✓			X			✓			✓			✓			✓
		RCP 8.5			X			✓			X			✓			✓			✓			X
Monalonion dissimulatum	2010				X			✓			✓			✓			✓			✓			✓
	2070	RCP 4.5			X			X			X			X			X			X			X
		RCP 8.5			X			X			X			X			X			X			X

The table shows when and where performance thresholds and suitability thresholds are met for the different localities in the study area. For clarity, the thresholds are only shown for present conditions and for the period 2060-2089 (shown as 2070) under RCP 4.5 and RCP 8.5. Performance thresholds are only identified for cacao production using Bio14 (precipitation for the driest month) and Bio5 (maximum temperature of the warmest month). For the suitability ensembles, suitability was classified above the quantile 75 per species (i.e. high suitability). The thresholds were extrapolated for the selected localities from the suitability ensembles (spatial resolution of 5 arcmin), by superposing the layers on QGIS. Localities are organized according to elevation (Rioja 840 m to Chazuta 199 m).

A red X indicates that a threshold is met, i.e. the locality is not suitable; whereas a check indicates that the threshold has not been reached, i.e. the locality is suitable.

8. Discussion

The chapter, first, contrasts the findings with the available literature on thresholds and suitability for cacao. Second, it discusses the variables and impacts related to pests and diseases. Third, it discusses the methods and data used, focusing on the inherent uncertainties in them. Fourth, it points at the added value of using performance thresholds and integrated approaches, and discusses conceptual implications. Finally, insights into adaptation strategies and recommendations are given (Box 5).

8.1 Performance thresholds and suitability for cacao

8.1.1 Stakeholders & interviews

This study showed that cacao producers aim at a sustained income and good quality of life. The interviews reflect the findings of the National Agrarian Census (table 11). The main reasons for farmers to plant their crops are economic, such as having an assured market, requiring low investment and the crop’s price (65%). These economic motivations are in line with cacao producers’ goals analysed in this study.

Table 1. Main reasons to plant crops in San Martin.

Assured market	33
Always plants the same crop	28
Crop demand less expenses	20
Crop's price in last campaign	12
Due to advice form technicians	2
Crop has short vegetative periods	2
Other	2
Due to water access	1

Source: Elaborated for San Martin based on the National Agrarian Census[1] (INEI, 2012). Note: the census includes all farmers, not only cacao producers.

According to stakeholders, main challenges are related to economic reasons and reduced yield due to pests and diseases, and drought. These concerns are not limited to Peru. In Bolivia, Jacobi et al. (2013) analysed perceptions of cacao producers in relation to climate change. They found that “Local cocoa producers mention heat waves, droughts, floods and plant diseases as the main impacts affecting plants and working conditions” (2013:1). Similarly, in Trinidad & Tobago, cacao farmers also perceived “drought as their highest threat, followed by floods and pests and diseases" (Eitzinger et al., 2015b: 3). More recently, the price variability of cacao as an international commodity, together with the coronavirus pandemic of 2020-2021, posed further concerns (Huamán & Romero, 2021).

According to stakeholders, main challenges are related to economic reasons and reduced yield due to pests and diseases, and drought. These concerns are not limited to Peru. In Bolivia, Jacobi et al. (2013) analysed perceptions of cacao producers in relation to climate change. They found that “Local cocoa producers mention heat waves, droughts, floods and plant diseases as the main impacts affecting plants and working conditions” (2013:1). Similarly, in Trinidad & Tobago, cacao farmers also perceived “drought as their highest threat, followed by floods and pests and diseases" (Eitzinger et al., 2015b: 3). More recently, the price variability of cacao as an international commodity, together with the coronavirus pandemic of 2020-2021, posed further concerns (Huamán & Romero, 2021).

In addition, local stakeholders perceive needs related to capacity building, for instance in pest management, as well as technological and agricultural inputs such as fertilizers, and market

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[1] Instituto Nacional de Estadística e Informática (INEI) (2012): CENAGRO 2012 (https://www.inei.gob.pe/estadisticas/censos/) Accessed on 24.03.2020.

requirements on cadmium content in cacao derivates (Meter et al., 2019) (annex 6). These goals, challenges and perceived needs are reflected also in agricultural statistics (INEI, 2012, 2017; DRASAM, 2020b), management guidelines and development plans (APPCACAO, 2013; Chavez, 2016; Soto et al., 2017; INIA, 2019; Norandino, 2020), discussions in multi-stakeholder platforms, but also in national and international fora on the cacao value chain[2].

The fact that interview results are supported by statistical, gray and other sources, indicates that these findings are robust. Cacao farmers and different stakeholders in the cacao landscape face very similar key problems, so that they become evident in even a small number of interviews and literature research. In addition, broadening the document search in Spanish helped to identify the key local stakeholders, leading to contacts and interviews of the most knowledgeable experts in their fields. In general, no language nor cultural barrier were experimented in accessing data, discussing with stakeholders or during the field visit, which facilitated access to key details.

8.1.2 Defining the performance thresholds

There is a large body of literature on cacao ecology (De Almeida & Valle, 2007; Medina & Laliberte, 2017; Lahive et al., 2019). As a result, different optimal and tolerance ranges for cacao have been estimated worldwide, both in field as under laboratory conditions. For instance, environmental variables such as maximum temperature, minimum precipitation, flooding (Delgado et al., 2016), shade management (Krauss & Soberanis, 2001), among others, have been assessed.

The temperature and precipitation tolerance ranges for cacao have been estimated for different localities worldwide (table 9). This information was taken into account for estimating the performance thresholds. While literature sources show a large agreement for precipitation, for temperature optimum and tolerance ranges the literature is more varied. For example, there are experiences of cacao tolerating up to 40°C in West Africa, however such extreme heat is only possible with sufficient water provision during the dry season (Schroth et al., 2016). In Peruvian case studies, cacao tolerates well a maximum temperature up to 32°C (CIAT, 2014). In addition, localities across San Martin where cacao is currently grown do show historical maximum temperatures around 32 – 34°C (annex 11). Considering that stakeholders already note that current temperatures pose high stress on cacao when coupled to dry conditions, a performance threshold for maximum temperature of 32°C seems robust for the case study.

Defining the threshold for precipitation also made use of literature sources and interviews. Literature shows a large agreement in the amount of minimum monthly rainfall tolerated by cacao. Regarding the length of the dry season, sources pointed that the optimum number of dry months is 0, but tolerance differed and indicated up to 4 dry months (Eitzinger et al., 2015a). Historical precipitation data in San Martin shows precipitation <100 mm during the dry season: Lamas and Chazuta have 3 months with <100 rainfall, while Campanilla only 2.

According to stakeholders, a critical drought consists of 2 or more weeks without rainfall within the dry season. Two important implications arise here. First, for stakeholders the performance threshold is more related to the time without rainfall that the total amount of received rainfall. Second, analysing climatic data with monthly resolution is not enough to define performance thresholds; on the field, a better time resolution is needed.

Better time resolution is not available for the bioclimatic variables used in this study. One approach to obtain more details is by looking at the historical data on precipitation frequency (annex 11). Monthly precipitation frequency shows that, during the driest months (July and August) Lamas has an average of 9 rainy days, while Chazuta and Campanilla only 7. This low precipitation frequency during the driest months points at a high drought stress on cacao, as well as a relatively high probability that one or more weeks without rainy days occur. No

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[2] Foro del cacao y chocolate latinoamericano, 2020; Salón del Cacao y Chocolate Perú, 2020 (https://salondelcacaoychocolate.pe).

additional information was found on precipitation frequency and its impacts on cacao in the study area.

All in all, comparing the information obtained from the interviews and the literature sources, as well as verifying and supporting those thresholds with historical climate data, allowed to define quite realistic performance thresholds for cacao production in the study area. The proposed performance thresholds, however, can be improved and further defined with climate data with better temporal resolution (weekly or per 15 days), as well as with additional parameters relevant to pests and diseases (relative humidity).

8.1.3 Critical climate variables

In this study, the most relevant variables for cacao production in San Martin were assessed as the minimum precipitation of the driest month and driest quarter, the maximum temperature of the warmest month and the mean temperature of the driest quarter. In the same line, Ceccarelli et al. indicated for Peru that “for cultivated cacao, expansion of suitable range seems to occur in areas that will have higher precipitation of wettest month/quarter and coldest quarter, and similar precipitation of driest month/quarter and warmest quarter compared with current precipitation regimes in currently suitable areas.” (2021:8). Ceccarelli et al. (2021) also identified areas where cacao occurs currently under extreme environmental conditions by applying an outlier analysis. Interestingly, in San Martin cacao already grows in areas with the highest potential evapotranspiration and lowest annual precipitation, but also highest risk of flooding and highest altitude. This shows the striking contrasts in even small study areas and the importance of analyzing climatic conditions at local scales.

Both similarities and differences are found with suitability modelling studies on cacao worldwide (Läderach et al., 2013; Eitzinger et al., 2015a, b; Schroth et al., 2016, 2017; Ortega et al., 2017; Gateau-Rey et al., 2018; de Sousa et al., 2019; Ceccarelli et al., 2019). These differences arise from the study areas, as well as climate scenarios, input variables used as predictors and suitability modelling algorithms used.

For example, the variables found here are similar to those reported for Trinidad & Tobago by Eitzinger et al. (2015b). Eitzinger et al. pointed that reductions in dry season rainfall, an overall reduction in annual rainfall and changes in precipitation patterns were the most likely direct causes of declining crop yield, since temperature increases could be partly mitigated as cacao is grown under shade.

For Peru, in contrast, Bunn et al. (2016) identified the mean temperature of the driest quarter as critical to trigger suitability losses in Peru. Similarly, Ortega et al. (2017) pointed towards more temperature-related variables when modelling the potential distribution of cacao together with *M. roreri* in Central and South America. They found that cacao distribution was mostly driven by precipitation of the warmest quarter, annual temperature range, mean diurnal range, minimum temperature of the coldest month, mean temperature of the coldest quarter and temperature seasonality. This variable selection largely differs from the variables noted here, which could be due to the large extension and heterogeneity of the study area.

More studies have been conducted analysing future suitability for cacao in the West African Cocoa Belt (Läderach et al., 2013; Schroth et al., 2016, 2017). Läderach et al. (2013) noted that shifts in suitability for cacao in Ghana and Côte d’Ivoire were driven by different variables. While PET of the coldest quarter and temperature annual range were critical in areas projected to lose suitability, changes in precipitation seasonality were determinant for areas projected to gain suitability. Läderach et al. argue that decreases in suitability were driven by enhanced evapotranspiration due to increased temperatures which were not offset by increased rainfall. In addition, Schroth et al. (2016, 2017) noted that limiting variables for cacao (and yield production) were related to elevated temperatures during the warm and dry season, the length of the dry season, the intensity of the dry month, as well as potential evapotranspiration, both during the dry season and throughout the year. Further, Schroth et al. (2016) discussed that maximum temperatures could pose limits to adaptation for cacao in West Africa. They argue that projected future maximum temperatures during the dry season could approach the limits of tolerance of cacao (38°C), since today those temperatures are only found at the savannas.

8.1.4 Changes in suitability

The ensemble suitability maps presented here showed that suitable areas for cacao will mostly remain similar to present conditions in the future. Suitability losses are projected for the Andean foothills and lower Amazon, while gains are projected at higher elevations. These results are similar to Ceccarelli et al.'s projections for cultivated cacao. Their projections suggest suitability loses in the northern and central Amazon, while suitability gains are projected towards higher elevations along the Andes. However, balancing areas that gain and lose suitability, this results in a net decrease in suitable areas for cultivated cacao in Peru by 2070 (Ceccarelli et al., 2021). Other studies have suggested slight expansions in suitable areas for cacao towards valleys at higher elevations, for example at the northern Andes in Peru (CIAT, 2014; Bunn et al., 2016).

These potential geographical changes have some implications. Cacao cultivation could theoretically migrate towards higher elevations in Peru and San Martin. Ceccarelli et al. found that the upper elevation limit for cacao might move from 1700 m under present climatic conditions up to 2100 m under future climate scenarios, but it would be very unlikely for cacao to grow at higher elevations due to occasional cold spells (Ceccarelli et al., 2021).

However, areas at higher elevations are currently under other uses, for example coffee cultivation. In Central and South America, as well as in Peru, suitable areas for both coffee and cacao are projected to migrate towards higher elevations (CIAT, 2014; Bunn et al., 2016, 2019; de Sousa et al., 2019). In Central America, upper limits for cacao have been estimated at 1200 m, compared to upper limits for coffee at around 2400 m (de Sousa et al., 2019). Therefore, cacao has been proposed as a strategy to replace areas that become unsuitable for coffee but gain in suitability for cacao (de Sousa et al., 2019). De Sousa et al. indicated that "cocoa could potentially replace 85% of the vulnerable coffee areas under climate change in moist regions at elevations under 400 m a.s.l. and 53% at elevations between 400–700 m a.s.l." (2019:2).

In San Martin, however, several naturally protected areas are located at higher elevations. In protected areas, agriculture production is only allowed under some restrictions, for example under low impact or organic production. The risk of encroachment of cacao cultivation in protected areas has been observed before, both for Peru as in other localities, e.g. Trinidad & Tobago (Eitzinger et al. 2015b; Ceccarelli et al., 2021)

In addition, not only the suitable range of cacao is projected to migrate to higher elevations; this is the case for most fungal diseases and Carmenta as well. As noted by de Sousa et al., cultivating cacao as an alternative to coffee would require addressing the impacts of pest and diseases, as well as costs of technological change, among other challenges (de Sousa et al., 2019).

Areas projected to lose suitability in the lower Amazon basin have also been projected elsewhere (Bunn et al., 2016; Ceccarelli et al., 2021). However, these projections raise some doubts. Cacao is indigenous from the Amazon basin (Motamayor et al., 2002). The highest levels of genetic diversity are observed in the Upper Amazon ranging from southern Peru to Ecuador, as well as the Amazon areas between Colombia, Peru and Brazil (Thomas et al., 2012). In addition, wild cacao genotypes are present in the lower Amazon. When modelling future suitability separately for cultivated and wild cacao in Peru, Ceccarelli et al. found a projected "contraction of suitable area for cultivated cacao while predicting a more positive future for wild cacao in Peru" (2021:1). Therefore, suitability losses in the lower Amazon as projected in this study might partly represent a bias in the input presence points and do not consider the adaptation potential of cacao genotypes.

Trends in suitability changes for cacao are similar in the Americas in the coming decades. In the Caribbean, the majority of analysed areas are projected to remain suitable, as long as wet conditions remain. For instance, according to Ortega et al. (2017), highly suitable areas for cacao under present conditions range from Central America to the Caribbean, northeast Peru and eastern Brazil. By 2080, the authors project that highly suitable areas remain in Central America and Caribbean region, while suitability loses arise in the Brazilian “cerrado” and the Colombian Amazon. For Central America and the Caribbean, suitability loses are projected in lowland areas driven by reduced precipitation (Eitzinger et al 2015a, b; de Sousa et al., 2019). Increases in suitability for cacao are observed at upland areas and surrounding mountain ranges (CIAT, 2014; Eitzinger et al 2015a; de Sousa et al., 2019).

In African case studies, models largely suggest losses in suitable areas for cacao under future scenarios. Climate change projections indicate a reduction in suitable areas in the northern part of the West African Cocoa Belt as these areas shift to the savanna climates (Läderach et al., 2013; Schroth et al., 2016, 2017; Bunn et al., 2019). Areas below 400 m were projected to lose suitability as a result of increases in temperature and evaporation, especially during the coldest quarter and dry season (Läderach et al., 2013).

8.1.5 Mechanisms behind drought stress

Important critique, however, has argued that suitability modelling alone does not explain cacao responses to climate change nor variations in bean yield (Lahive et al., 2019). This is especially true considering the responses of different cacao genotypes and adaptation potential. Therefore, the physiological mechanisms of cacao help to explain the relevance of temperature and precipitation variables for tree survival and yield production during stress conditions.

It is well known that cacao growth and development highly depend on temperature (De Almeida & Valle, 2007; Lahive et al., 2019). Temperatures up to 30°C increase vegetative growth, flowering and fruit development. However, higher temperatures affect final fruit and bean size, and can lead to fruit losses due to cherelle wilt (Daymond & Hadley, 2008). Daymond & Hadley explained that bean number has a positive impact on pod size, while temperature has a negative impact both on pod and bean size. Pod responses to high temperatures are, nevertheless, highly determined by the cacao genotype (Daymond & Hadley, 2008).

Water limitation has been noted as the main cause for yield reduction in cacao, although here, also, significant variation among cacao genotypes exists (Lahive et al., 2019), Zuidema et al. (2005) found that annual radiation and low rainfall during the dry season explained variations up to 70% in bean yield as modelled for 30 locations throughout the tropics. Water limitation alone could explain yield gaps up to 50%. Furthermore, measurements in Brazil during ENSO conditions in 2015-2016 showed that severe and long lasting drought caused high tree mortality up to 15% and decreased yield up to 89% (Gateau-Rey et al., 2018).

During dry periods, flushing is suppressed, leaf loss increases and leaf area is reduced; as a result, light interception, carbon uptake and respiration are compromised (Zuidema et al., 2005; De Almeida & Valle, 2007). Water deficit, then, leads to a decline in carbon uptake, thus limiting sugar transport and resulting in reduced bean size (Lahive et al., 2019).

In sum, these strategies allow the tree to tolerate drought and stress conditions. In turn, flowering and pod production are affected. Hence, climate variables that affect pod production and quality are more relevant for defining the performance thresholds.

8.2 Pests and diseases on cacao

Pests and diseases cause huge losses on cacao worldwide. Frosty Pod and Witches’ broom are the major cacao diseases in South America (Bailey & Meinhardt, 2016). Frosty pod has caused yield losses >80 % and up to 90% (Bailey & Meinhardt, 2016; CABI, 2021). In Peru, *M. roreri* has led to “total loss in some areas and the subsequent abandonment of farms” (Evans et al., 1998, in CABI, 2021[3]). In contrast to these diseases which are restricted to the Americas, Black pod, particularly *P. palmivora,* is found worldwide on cacao farms and has a

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[3] https://www-cabi-org.ezproxy.library.wur.nl/isc/datasheet/34779

wide host range. *P. palmivora* has been attributed to worldwide pod losses up to 30% and an annual tree mortality up to 10% (Acebo-Guerrero et al., 2011; Bailey & Meinhardt, 2016). Phytophthora "causes more damage on cacao than any of the other species" (Bailey & Meinhardt, 2016: 43).

The literature base for cacao pests is very narrow compared to diseases. Fewer examples of quantified losses in cacao yield due to pests are available. In Bolivia, severe attacks of *Monalonion dissimulatum* could lead up to 50% of bean yield loss (Ferrari et al., 2014). Due to the interaction of pests with other species, their direct damage may be more difficult to quantify on field.

Considering these literature statements on severe losses due to pests and diseases, it becomes evident that: i) interview results in Peru did capture the severity of these pests and diseases; and ii) this study gains on salience and relevance by incorporating cacao pests and diseases and thereby addressing stakeholders' concerns on their impacts on cacao.

Modelling studies for pests and diseases are limited. Only one study was found to apply suitability modelling on cacao together with *M. roreri* (Ortega et al., 2017). Ortega et al. modelled suitability for cacao and Frosty pod in Central and South America under present and future conditions. They found that suitable areas for *M. roreri* highly overlay with suitable areas for cacao, both under present and future scenarios. Also, suitable areas for *M. roreri* might increase towards 2080. Lastly, they found that both species were highly influenced by precipitation of the warmest month (Bio18), as well as the the annual temperature range (Bio7) and minimum temperature of the coldest month (Bio6).

Differences and common points can be found with Ortega et al.'s study. Modelled suitable areas for Frosty pod under Ortega et al. show higher suitability in the lower Amazon basin. In contrast, this study pointed at more suitable areas closer to the Amazon foothills. These differences might be due to the input presence points: while Ortega et al. used distribution points from Mexico to Peru, here only points in Peru were considered. The suitability algorithms will always tend to model areas as highly suitable closer to the input presence points. In addition, here an ensemble of suitability modelling algorithms were used, as well as RCP instead of the SRES scenarios. Despite these methodological differences, there is one important common finding: the pathogen distribution tends to overlay with the host distribution, both under present and future scenarios. This underscores the importance of further studies analyzing cacao together with its pests and diseases.

Stakeholders perceive that high relative humidity is associated to increased presence of diseases. These perceptions are supported by the literature. High relative humidity is a key variable for pathogenic fungi such as *M. roreri*, *Colletotrichum gloeosporioides* (Anthracnosis) and *Corticium sp.* (Bailey & Meinhardt, 2016; CABI, 2021). Moreover, a positive correlation has been found between the incidence of Black pod on cacao and relative humidity (Agbeniyi et al., 2017). Agbeniyi et al. found that relative humidity in cacao farms in Nigeria ranged from 70 – 90% and that Black pod incidence increased at higher humidity levels. Similarly, *M. roreri* appears in areas where relative humidity is >80%[4].

In contrast, optimal relative humidity for cacao is 70 – 80%. Pathogenic fungi tolerate environmental conditions that exceed the tolerance of cacao (CABI, 2021). Historical data for San Martin shows that relative humidity ranges from 82 – 87% in Chazuta and 81 – 85% in Lamas (annex 11). Notably, relative humidity is highest during the harvest season, between May to June. These values are then more beneficial for diseases rather than for cacao.

Although relative humidity is a key variable to model suitability for cacao diseases, it was not possible to incorporate it as a predictor layer in the analysis. This data is not available under the bioclimatic variables of WorldClim. An important next step would be to include relative humidity in suitability modelling of cacao' main pests and diseases.

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[4] Personal communication, E. Murrieta, 2021.

Similarly, inundated soils after heavy rainfall events were associated to diseases. Stakeholders in Chazuta pointed that soils that were flooded during several days favoured the presence of *M. perniciosa*. Broadly, the impacts of flooding on cacao turns the trees more vulnerable to diseases. Moreover, Delgado et al., (2016) observed that prolonged flooding can kill cacao seedlings, damages low-lying flower cushions and produces hipoxia and anoxia in the root zone. Younger trees in unshaded cacao plantations are the most affected by flooding, and damage ranges from reduced pod and yield production to tree death (Delgado et al., 2016).

Soil humidity also plays an important role in the spread and survival of fungal diseases. Soil humidity and acidity are important for pathogenic fungi, among them *Phytophthora palmivora,* but also *Fusarium sp., Rhizoctonia sp., Rosellinia sp.* and *Verticilium sp*. (Bailey & Meinhardt, 2016; CABI, 2021)[5]. *Phytophthora sp.*, unlike *M. roreri* and *M. perniciosa*, has a soil-borne phase, can survive longer dry periods in the soil and also affects the roots of cacao trees (Acebo-Guerrero et al., 2011). Soil variables are also important for modelling and understanding root nematodes, prejudicial weeds and parasitic plants to cacao (Willmott et al., 1986a, b; CABI, 2021).

Regarding the pests, there is a striking contrast between what stakeholders perceive as critical on field and the available literature on *Carmenta sp*. There are few studies on Carmenta's ecology and management (Delgado Puchi, 2005; Cabezas et al., 2017; Jorge Panduro, 2018; Luna Quispe, 2019). Since its perceived as a new pest and only present in the Americas, it has not received much attention worldwide. Most related documents comprise guides on integrated management of pests and diseases (Soto et al., 2017; Murrieta & Palma, 2020c; Norandino, 2020). In addition, it seems that technical capacity is not ready to differentiate between the two species *C. theobromae* and *C. foraseminis* on field, so that this specification at species level is not available in the registries.

Different species of the genus Carmenta are present throughout Central and South America and have different plant hosts (Delgado Puchi, 2005). Although being native, Peruvian farmers perceive Carmenta as a relatively new pest[6]. Yet, in certain regions farmers knew that Carmenta was present at higher elevations and therefore would not plant cacao there[7]. With time, observations of Carmenta went from higher (Rioja, 840 m) to lower elevations (300 – 600 m) (annex 12). The question can be raised if cacao production zones expanded or migrated towards higher elevations, or if Carmenta migrated towards lower elevations. The suitability models presented here point at areas becoming suitable for both cacao and Carmenta at higher elevations under future scenarios. Also, a marked loss in suitable areas for Carmenta is projected at lower elevations towards the Amazon under future scenarios. More research is needed to determine if indeed Carmenta has experienced a shift in its geographic range, and if this is due to temperature changes or other reasons.

Different species of the genus Monalonion are also distributed along Central and South America, ranging from 600 - 1800 m of elevation (Gamboa et al., 2020). *M. dissimutaum* has been registered from Guatemala to Bolivia. Yet, 7 different Monalonion species have been associated to cacao plantations in the Neotropics (Gamboa et al., 2020). Moreover, worldwide, there are different mirids affecting cacao, such as *Antiteuchus sp*. in Peru, other species in Africa and Indonesia (CABI Plantwise, 2021). These cacao bugs tend to damage cacao in a similar way, by feeding on the pods and laying their inside them (Valarezco et al., 2012). However, while cacao pods in early development stages are very susceptible to attacks of *M. dissimulatum*, mature pods are highly resistant and yield is only affected when the outside damage is >70% (Ferrari et al., 2014). In general, cocoa bugs and their management are not new to farmers, who are advised to manually revise and pick up affected cacao pods regularly.

The main problem arising from the attacks of mirids, aphids and other pests, is that they leave small perforations on the pods and excrete sugary secretions, which facilitate fungal development (Bailey & Meinhardt, 2016; CABI, 2021). Infections by *Fusarium sp., Capnodium*

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[5] Personal communication, M. ten Hopen, 2021.

[6] Personal communications, SENASA, March 2020; and E. Murrieta, 2021.

[7] Personal communications, E. Murrieta, 2021.

sp. and *Verticillium sp.* have been typically associated to the attacks of mirids and aphids, but also to root nematodes (Willmott 1986a, b). These inter-specific associations are not directly shown in the suitability models. However, it can be inferred that, where pests appear as suitable, is it very likely that associated fungal diseases will also occur. Ecological modelling studies should consider host-pathogen interactions.

The stakeholders' perception of increased attacks and higher damage due to pests and diseases in recent years is considerable. The increased presence of pests and diseases might be an effect of the extension of cacao farms and monocrop plantations, or might be an indicator of the lack of other plant hosts and unhealthy forest ecosystems. Moreover, farmers make use of pesti-, fungi- and herbicides to cope with prejudicial species when they have available resources. The use of these chemical substances is not sufficiently regulated in Peru[8]. Stakeholders are concerned on the effect of these chemical substances on cacao pollinators and beneficial species, which naturally control pests and diseases (annex 6) (Garcia, 2017). The question remains if the increased presence and attacks of pests and diseases is an effect of the use of agrochemicals.

One drawback in this study is that suitability modeling did not consider species density. Analyzing density of pests and diseases could point at areas where attacks are more severe, and research possible explanatory causes. This would also be a first step to compare areas with high density of pest and diseases with areas where agrochemicals are used or, in contrast, with areas under organic production. Further research could analyze the incidence of pests and diseases and the magnitude of their attacks by comparing organic and non-organic farming systems, as well as comparing agroforestry systems and monocrop plantations. In addition, studies are needed to further differentiate the taxonomy, as well as to understand the characteristics and ecology of the species of Carmenta and Monalonion within their genera (Delgado Puchi, 2005; Gamboa et al., 2020). Increased capacity and knowledge would help to create more detailed registries, which in turn could be used to improve modelling studies.

8.3 Uncertainties in methods and data

Different sources of uncertainties should be critically analyzed for this study.

A first source of uncertainties arises from the species distribution data. When possible, geographic registries for all species were corrected regarding both spatial coordinates and species names and genus. Yet, the possibility remains that some records in the data sources were registered with unprecise or equivocal coordinates. In addition, few species presence data was found on cacao pests and diseases in global databases such as GBIF or GlobalFungi. Therefore, the great majority of geographic registries was obtained from the stakeholders' internal databases on cacao, its pests and diseases. This implies that almost all presence points for pests and diseases were taken on cacao parcels in Peru. On the one hand, this denotes a clear association between cacao as host and its pests and diseases. On the other hand, this might have generated a bias in the suitability models, since presence points of pests and diseases are on the same locations and environmental conditions as for cacao. Presence points for pests and diseases outside cacao parcels would have been an asset. However, this data is not available.

To reduce some of these uncertainties, several measures were taken. First, the sources for species data were diversified, including publications. Second, when feasible, the modelling was done at species or at genus levels. For example, since the identification of *M. roreri* and *M. perniciosa* fungi is straightforward, these were modelled at species level. In contrast, Carmenta modelling grouped *C. foraseminis, C. theobromae* and *Carmenta sp.* in general due to the lack of more detailed registries. Third, the suitability modelling script contemplated filtering species presence data to specifically reduce geographic bias.

A second source of uncertainties arises from the climatic variables used as input for the suitability modelling, as well as for identifying the performance thresholds. A comparison of

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[8] Personal communications, INIA, 2020; and E. Murrieta, 2021.

historical climate data (1989 - 2019) for the study area (annex 11) and bioclimatic variables for present conditions (2010) (annex 9) gives insights into the quality and representativeness of the predictor variables used.

When comparing the maximum temperature for the warmest month, Bio5 shows between 32 – 34°C for Lamas, Chazuta and Campanilla. Historical data indicates 29 – 34°C. For the mean temperature of the driest quarter, Bio9 shows 23 – 25.5°C, while historical data 23 – 26.5°C. For the mean temperature of the coldest month, Bio6 shows 17 – 19°C, and historical data 19 – 22°C. The bioclimatic values for 2010 are fairly close to the historical data, but there are some temperature degrees of difference and bioclimatic values for minimum and maximum temperatures are more extreme in the models than in historical data. Important here is that the models do represent the geographical variations between the localities, e.g. Lamas is cooler compared to Chazuta and Campanilla. In addition, the temperature annual range is also fairly close, although bioclimatic variables show a larger amplitude.

Looking at the precipitation for the driest month, Bio14 shows broadly between 80 – 90 mm rainfall for Lamas, Chazuta and Campanilla. Historical data shows between 60 – 90 mm. For the driest quarter, Bio17 shows 270 – 310 mm, while historical data 280 – 415 mm. For precipitation, historical data shows notably larger variability between the locations, including lower minimum precipitation for the driest month. The geographical variations between the localities are well reproduced, e.g. Campanilla receives more rainfall than Lamas and Chazuta. As a result, bioclimatic variables used in this study are able to reproduce annual variability and trends in temperature and precipitation, as well as relative differences in the study area.

This ability of models to reproduce variability and seasonality is key, especially in mountain areas. Modelling requires finer spatial resolution when applied to areas of topographic complexity or where environmental variables vary largely across small distances (CIAT, 2014: Navarro-Racines et al., 2020). In the case of the Andes, its advised to use models that reproduce well rainfall seasonality[9], which proved to be the case in this study.

Here, bioclimatic variables showed more extreme values for temperature compared to historical data. As a result, it's likely that models will also project a more pronounced seasonality for temperature under future conditions. Notably, precipitation projections showed higher variability and uncertainty than temperature. The latter showed clear trends with time, RCP and elevation. However, precipitation projections did not show clear trends neither in time nor between RCPs. Studies analyzing future scenarios for cacao in Ghana found that most GCM pointed towards a more pronounced seasonality of precipitation in the future (Bunn et al., 2019). Since Bunn et al. use 19 GCM, differences in projected seasonality likely arise due to the ensemble models and the different topographies between the study areas.

Third, climate models and scenarios have inherent uncertainties (Knutti et al., 2013; Medina & Laliberte, 2017; Navarro-Racines et al., 2020). Therefore, ensemble models are a good approach to address inherent uncertainties in both future climate and GCMs (Knutti et al., 2013; Bunn et al., 2019; de Sousa et al., 2019). Two RCPs, the more realistic RCP 4.5 and the higher end RCP 8.5, were used to compare a wider range of future scenarios.

The 5 GCM used have a good performance, show a plausible range of different responses and equally possible futures (Knutti et al., 2013; Bunn et al., 2019). The CMIP5 generation of models also performs better than previous generations and reproduces values closer to observations (Knutti et al., 2013) This study did find differences between the individual outputs of the 5 GCM for the critical bioclimatic variables and suitability maps (annex 9). The ensemble values for the bioclimatic variables and suitability maps indeed seemed representative of the GCM range and of the statistical mode, although the ensembles are an average of the GCM's outputs and may hide extremes.

In general, suitability algorithms that use presence only data to generate pseudo absences, among them Maxent, have a good predictive accuracy and are reliable (Phillips & Dudik,

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[9] Personal communication, C. Bunn, 2020.

2008; Mateo et al., 2010). Nevertheless, suitability algorithms have inherent uncertainties, which may arise from the statistical calculations and parameters of the algorithms, and might still reproduce biases or generate errors in the pseudo absences, especially when they are generated randomly (Mateo et al., 2010). Algorithms and filtering methods should be tailored to the available species data and modelling objectives, as then evaluated carefully (Ceccarelli et al., 2021). Here, some algorithms did not perform well with categorical variables. Therefore, several trial runs were conducted and only 8 of over 20 available modelling algorithms were chosen for the ensemble suitability modelling (Ceccarelli et al., 2020).

Suitability models for future scenarios should also be interpreted with caution. It has been noted that suitability algorithms have difficulties when projecting novel climates in a study area, for which they have no historical analogues (Bunn et al., 2019). Moreover, the resolution of spatial filtering of presence points has been found to have a strong impact on the output suitability maps (Ceccarelli et al., 2021) (annex 10).

Finally, for the performance threshold approach used here, the temporal resolution of bioclimatic variables used might have been too broad. The bioclimatic variables were available at a detail of 1 month for key temperature and precipitation variables. However, as discussed with stakeholders, farmers already perceive undesirable drought outcomes at 2 weeks, and the life cycle of pests and diseases takes only around days to weeks. Further, for precipitation in the driest month (Bio14), it matters how that precipitation is distributed within that month, i.e. if it rains evenly all weeks, or if 3 weeks are dry and the last week receives heavy rainfall. It has been acknowledged before that finer variables such as the frequency and intensity of drought, hot spells, or extreme precipitation events, are needed for modelling crops and biodiversity, but that GCM may not adequately simulate these events (Navarro-Racines et al., 2020).

Lessons learnt considering these uncertainties comprise triangulating data sources, using model ensembles, as well as different algorithms. When possible, these measures were applied in this study. All in all, models are still representations of reality and projections based on mathematical algorithms, not predictions, and should be interpreted within a given context. As a conclusion, the data, methods and results of this study are reasonably good given the resources available.

8.4 Added value of integrated approaches

This study combined two different methods to estimate the ATP for cacao in the Peruvian Amazon and, in doing so, helped to address the research gaps identified in section 1.2.

The performance thresholds comprise a consultative process, where stakeholders' perspectives are investigated as a starting point to identify ATP. In this way, the method allows to investigate and incorporate stakeholders' preferences and priorities, in this case ”what matters on farm”, into scientific research. This is of special importance in cacao, as critique has observed that:

> “Despite all these research initiatives, when compared to other economically important crops, the extent of investigations and published material in relation to cacao physiology and responses to drought, temperature, or increased CO_2 stresses, there is limited information. The available literature does not reflect cacao's market value, or its importance to the livelihoods of millions of farmers.“ (Medina & Laliberte, 2017:34)

The strength of this study is therefore to pay attention to the most striking stakeholders' concerns on field, bring them into research and work towards results that are relevant and salient for the case study and involved stakeholders. Besides, by bringing in stakeholders' perspectives, performance thresholds complement climate and ecological modelling approaches.

Suitability modelling, on the other hand, brings several advantages from a scientific and methodological point of view. The method provides a quantitative and precise result, which can be replicated, statistically evaluated, and compared to a growing volume of literature and resources on modelling algorithms, climate scenarios, available environmental variables, species distribution data, etc. Suitability modelling, hence, provides a robust base to identify ATP – from an ecological point of view. A further advantage of modelling is that it allows to explore possible scenarios and situations. Information over other territories or in future time periods helps to complement stakeholders' own knowledge about their locations and brings in key insights for planning.

Estimating performance thresholds and adaptation turning points were innovative research methods for cacao and San Martin. One previous study analyzed ATP for potato production systems in southern Peru (Gómez Álvarez, 2019). However, the study area, stakeholders involved, and agricultural system are very different from the one studied here. This research adds to the literature on ATP, especially in Latin American case studies. To date, only three studies have applied the ATP approach in Latin America (Smolenaars, 2018; Arce Romero, 2019; Gómez Álvarez, 2019). Furthermore, this study innovates by using suitability models to estimate the ATP, as this has not been done before.

Finally, note that stakeholder-defined thresholds can differ from ecological thresholds as estimated by suitability models. Climatic variables, time periods and spatial scales where ATP appear will be different if estimated by different methods or if thresholds are determined according to different stakeholders. Therefore, defining the threshold and selecting the methods are decisive steps in an ATP study. A recommendation for future research analyzing ATP consists in defining well the specific threshold of concern –either as socio-political thresholds, tipping points, ecological niches, etc.–, especially when applying different methodologies or conceptual backgrounds.

8.5 Conceptual implications

Limits to adaptation and performance thresholds, as have been analyzed here, are different concepts. Differences between adaptation limits and performance thresholds arise from their practical implementations.

Adaptation limits for cacao refer to the conditions where its growth is not possible (Schroth et al., 2016). According to Schroth et al. (2016), adaptation measures would not be sufficient if maximum temperatures during the dry season reach the tolerance limits of cacao. In contrast, performance thresholds in this study refer to the conditions where yield is (un)acceptable for a famer, in order to obtain a sustained income and an acceptable quality of life. Cacao yield involves the conditions where the number and size of pods per tree, and the number and quality of beans per pod, are optimal or at least acceptable. In this sense, performance thresholds are closer to the optimal ecological niche for cacao, while adaptation limits refer to the outer boundaries of its tolerance.

This also helps to explain the outcomes of this study related to the suitability models for cacao. While a close analysis of performance thresholds indicates that maximum temperature during the warmest and driest months, as well as precipitation during the driest month, are already reached under present conditions and might be exacerbated under future scenarios in San Martin, the suitability models for cacao still indicate that the study area will remain suitable under climate change scenarios. Briefly, suitability models project the potential ecological niche, while producers are interested in yield. The latter is affected by short-term variability and extremes. Hence, during drought, or due to severe attacks of pests and diseases, cacao trees may survive –within their tolerance range–, but harvest is affected. As a result, the potential commercial value decreases for the farmer. It has been stressed before that "suitability is not necessarily correlated with yield quantity or quality" (Ramirez-Villegas et al., 2013, in Ceccarelli et al., 2021).

Similitudes can be also found between adaptation limits and performance thresholds. A first similitude is that, beyond both concepts, adaptation to climate change is theoretically still possible. Adaptation limits can change with time and across space (Adger, 2009). Hard adaptation limits can be overcome with technological change, while soft limits may change according to social values. Also, a performance threshold does not imply that adaptation is not possible (Kwadijk et al., 2010). Rather, it leads to defining an adaptation turning point, i.e.

a moment in time when additional actions or a different strategy are needed. A second similitude between both concepts is that both are socially constructed (Adger, 2009; Werners et al., 2018a). Both are defined by stakeholder's considerations on what is acceptable in a specific moment in time and for a specific place. To the author's knowledge, neither performance thresholds nor turning points have been assessed before for cacao.

8.6 Cacao & adaptation to climate change

Cacao production in Peru in the context of climate change can be seen from two perspectives: i) cacao cultivation as an adaptation strategy itself; or ii) strategies to adapt cacao to the present and future challenges. Both perspectives are related, and strategies to adapt cacao can also make cacao production more resilient compared to other strategies. Adaptation alternatives for the agricultural sector in Peru have been analyzed elsewhere (MINAGRI, 2012, 2013; CIAT, 2014; GTM-NDC, 2018).

The importance of discussing adaptation measures is two-fold. On one hand, cacao has a high social and economic value for local stakeholders. As mentioned lines above, performance thresholds tell the story about the farmers' challenges. On the other hand, cacao is important for Peruvian agriculture, and therefore is included in both the agricultural sectoral planning and the climate change political framework. The inclusion of cacao in adaptation planning is described in Box 4, and further background on national adaptation is given in annex 4. It is not the aim of this study to determine adaptation strategies, but some insights into best practices and innovative options to increase the resilience of cacao production are given below.

A first example of an adaptation measure to target drought comprises guaranteeing a sufficient water supply during the dry season. Irrigation not only allows cacao trees to tolerate higher temperatures, but also increases yield (Schroth et al., 2016; Lahive et al., 2019). In Ghana, irrigation increased pod production by 40% during a severe dry season and reduced the incidence of cherelle wilt (Hutcheon et al., 1973, cited in Lahive et al., 2019). Different irrigation methods do increase bean yield, but drip irrigation has proven to deliver larger increases as compared to sprinkler irrigation (Lahive et al., 2019). The effectiveness of irrigation, however, can be reduced if evapotranspiration and water demand are high, for example due to associated trees in mixed or agroforestry systems (Lahive et al., 2019).

Despite evident benefits, irrigation is not widely adopted, mainly because it is expensive. In addition, there are practical limitations or local barriers, such as such as topography or the absence of close water sources (Lahive et al., 2019; stakeholders communications, 2020). Some examples of implemented irrigation in Peru comprise large cacao plantations in Tocache, because cooperatives are well organized, have resources and access to technology. In the northern Peruvian coast, since annual rainfall is below cacao's tolerance range, cacao must be irrigated (Ceccarelli et al., 2021).

A second adaptation measure to regulate heat and drought stress on cacao is shade management. Shade can reduce temperatures at the tree canopy trees by up to 4°C (De Almeida & Valle, 2007). Shade management also reduces evapotranspiration as well as soil dryness. This is especially important during drought. For instance, soil dryness directly caused by severe drought was responsible to reduce the cacao pod production and kill up to 15% of the trees in Brazil (Gateau-Rey et al., 2018). Agroforestry can also reduce the incidence of diseases (Krauss & Soberanis, 2001; De Almeida & Valle, 2007). Krauss & Soberanis tested the effectiveness of biocontrol and shading for the rehabilitation of abandoned and diseased cacao fields in Peru. They found that Frosty pod and Witches' broom incidence were higher in unshaded fields. Shade had no effect on Black pod incidence. Shading should be complemented with adequate ventilation to reduce fungal diseases (Schroth et al., 2016).

Shade trees in agroforestry systems provide additional social and economic benefits (Cerda et al., 2014; Somarriba et al., 2014; Schroth et al., 2016; Vaast et al., 2016; Medina & Laliberte, 2017; Maas et al., 2020). Agroforestry systems allow farmers to diversity their farm income with timber and non-timber products (Cerda et al., 2014; Schroth et al., 2016).

Typically, agroforestry systems comprise species for the provision of fruit, timber, firewood, shade only, medicinal or construction materials (Cerda et al., 2014). In their study in five Central American countries, Cerda et al. (2014) found that fruit and timber products in traditional cocoa agroforestry systems generated modest cash incomes, but contributed largely to family savings and food security. In addition, in denser and intensified agroforestry systems, the contribution of all non-cacao products to family benefits was similar or higher than those of cacao (Cerda et al., 2014). Moreover, timber species contribute to farmers' annual income either in the form of timber sold or directly used, or as family savings in the form of standing and harvestable trees (Somarriba et al., 2014).

In addition, agroforestry allows for varied ecosystem services, among them increased pollination of cocoa trees, as well as soil, water and biodiversity conservation and carbon storage (Schroth et al., 2016; Maas et al., 2020). Incorporating N-fixing species in the agroforestry system is important as well (Vaast et al., 2016; de Sousa et al., 2019). These services are indispensable for long-term and sustainable crop systems (Maas et al., 2020). Agroforestry systems are both more resilient to diseases, disturbances, extreme weather events and climate change, as well as to price volatility of agricultural products (Vaast et al., 2016; Maas et al., 2020). Finally, incorporating native crop varieties, diverse producers' perspectives and even traditional cultivation methods can enhance both biodiversity and well-being of smallholders (Maas et al., 2020). Facing increased uncertainties due to climate change, diversification can reduce the dependency of farmers on one crop as their principal income source, or even be a step in the progressive replacement of cacao to more heat and drought adapted crops and trees (Schroth et al., 2016).

Nevertheless, there are some drawbacks to agroforestry systems. Agroforestry species can compete with cacao for water, nutrients and light (Schroth et al., 2016). Experts also advise that shade proportion should be adjusted according to the tree ages, and should not exceed 30% for mature trees. Heavy shading has been proven to cause yield reduction (Zuidema et al., 2005). Although cacao plantations under full sun yield higher in the short term, this reduces the productive life of cacao trees, deteriorates the soil and increases trees' vulnerability to diseases and disturbances (Zuidema et al., 2005; Maas et al., 2020).

The diversification of cacao genetic varieties on farm is equally important. Cacao varieties not only differ in bean yield and quality, but also have different tolerances to temperature, weather disturbances, soils, pests and diseases (Daymond & Hadley, 2008; Adu-Acheampong et al., 2012; Läderach et al., 2013; Medina & Laliberte, 2017; Lahive et al., 2019; Ceccarelli et al., 2021). Therefore, managing different varieties can function as an insurance strategy at farm level. Ongoing research focuses on analyzing and identifying the most resilient and productive varieties (Arévalo et al., 2017; Ceccarelli et al., 2021). Meanwhile, it remains a challenge to implement cacao-diversified approaches in practice, because markets put pressure for specific and homogeneous cacao characteristics and higher yields (Maas et al., 2020).

In flood-prone areas, further adaptation measures should address flooding and heavy rainfall events. Historically, cacao was cultivated in more fertile floodplains in the Amazon basin and, although this is less common nowadays, climate change could lead to occasional flooding in some areas (Delgado et al., 2016). Although there is limited research on flooding on cacao, it is suggested that some genotypes are more resistant to inundated conditions and that agroforestry can help to reduce the impacts of floods (Delgado et al., 2016). Besides, cacao is known to require well-drained soils and a good drainage system (De Almeida & Valle, 2007). Therefore, potential measures could point at improving drainage systems on farm, enhancing soil texture or managing an understorey to absorb more water or regulate soil humidity.

Further important measures comprise integrated pest management to limit losses caused by pests and diseases. Best practices consist in combining biological, cultural and chemical management, and complement them with supplying a proper amount of fertilizer (Soto et al., 2017; Murrieta & Palma, 2018). There is a wide diversity of fungus and bacteria used to combat pests and diseases on cacao (Avelino et al., 2011; Tirado-Gallego et al., 2016). Antagonic fungi work by competing with pathogenic fungi for space and nutrients. The best known belong to the genus *Trichoderma sp.,* which is applied to control Frosty pod, Witches' broom and Black pod (Tirado-Gallego et al., 2016; Murrieta & Palma 2020a; Norandino, 2020). Research has shown that *Trichoderma sp*. reduces Black pod disease caused by *Phytophthora palmivora* in field sites (Acebo-Guerrero et al., 2011). Moreover, *Trichoderma sp., Bauveria sp*. and other entomopathogens are available as natural controllers for Carmenta (Murrieta & Palma, 2018; Jorge Panduro, 2018; Luna Quispe, 2019; Murrieta & Palma, 2020c). In general, there is great diversity of beneficial insects that can control pests such as mirids and aphids.

To summarize, measures can be implemented to protect cacao trees from drought stress, from the attack of pests and diseases, or to achieve social, ecological and economic co-benefits. In theory, these measures could be able to modify the identified performance threshold for cacao production. Further opportunities are given in the recommendations (Box 5).

Box 4. Cacao in the agricultural and adaptation planning frameworks

Due to its importance for Peruvian national agriculture, cacao is included in both the agricultural sectoral planning and the climate change framework. Cacao institutions and platforms already exist at national and regional levels, as well as several development projects promoted by the government and other organizations (see annex 5).

Regarding sectoral plans, the Sectoral Strategic Multianual Plan 2015-2021 (PESEM) defines the functions for the Ministry of Agricultural Development and Irrigation, as well as agricultural business and development goals (MINAGRI, 2015). The PESEM has two specific objectives: the first refers to natural resources and biodiversity management; the second aims to increase competitivity and market participation, especially of small farmers. In each objective, cacao's importance stands out in the indicators. For the first objective, an indicator measures the agricultural surface with certified organic crops, such as coffee and cacao. A goal is to increase the organic certified cacao surface from 22% in 2014 to 35% by 2021. For the second objective, an indicator measures the organic exports. The goal is to increase the organic cacao exports from 21% in 2014 to 33% by 2021 (MINAGRI, 2015: 54).

Additionally, the PESEM addresses the conversion of illegal coca crops to coffee, cacao and tropical fruits in the Amazon basin (MINAGRI, 2015). Concerns on coca crops have driven multiple public and private efforts to promote cacao crops as an alternative since 1980. It's interesting to note that, according to PESEM, adaptation to climate change is a criterion for selecting the alternative crop. For the rest, coca is seen as a socio-environmental problem (MINAGRI, 2018a).

The National Strategy on Forests and Climate Change (ENBCC) is aligned to the Nationally Determined Contributions (NDC) and therefore addresses both mitigation and adaptation (MINAM, 2015a). It's main objective is to reduce forest loss and degradation, hence GHG emissions, and to increase landscapes' and people's resilience. Deforestation occurs due to the clearance of forests to create agricultural surface and pastures and is the main cause for GHG emissions. In 2012, cacao was the third crop causing deforestation in the Amazon basin (MINAM, 2015a). Proposed measures include the recovery of abandoned parcels, as well as agroforestry systems. The ENBCC emphasizes reducing vulnerability for indigenous people, farmers and vulnerable groups.

Recently, Peru has been developing and strengthening a legal framework on climate change including adaptation, although adaptation was also prioritized in earlier sectoral policies. The main documents are: the Risk Management and Climate Change Adaptation Plan in the Agricultural Sector; the National Climate Change Strategy (MINAM, 2015b); the Framework Law on Climate Change (Peruvian Government, 2018) and its legal guidelines (Peruvian Government, 2019); the NDC and the National Adaptation Plan (NAP). See annex 4 for a complete overview on policies.

Agriculture is among the prioritized areas for adaptation in the NDC and the NAP. The MIDAGRI classifies adaptation measures for production systems and for value chains. Under the latter approach, vulnerability, adaptive capacity and measures are analysed for each agricultural product along the value chain. To enhance farmers' adaptive capacity, adaptation measures comprise agroclimatic information services, adaptive technological innovation services, entrepreneurial strategies which incorporate managing climatic risk and opportunities, and promote aggregated value for products in vulnerable areas. Cacao is also viewed under the value chain approach[10].

Cacao is, nevertheless, included in the agricultural mitigation measures (MINAGRI-DGAAA, 2018). A measure on sustainable management of permanent crops in the Amazon for reducing GHG emissions refers explicitly to cacao and coffee. It seeks to intervene 25 000 ha of cacao crops in the northern Amazon region (including San Martin) with options such as enhanced technology, soil and waste management in the production and post-harvest phases. Despite possibilities for cacao agroforestry or deforestation caused to extend cacao plantations (MINAM, 2015a), the NAP does not mention cacao in mitigation measures for forestry nor land use change.

It is worth noting that, under MIDAGRI's perspective, considerations of adaptation in cacao must go along with mitigation; both approaches must incorporate co-benefits[11].

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[10] Personal communication, DGAAA, March 2020.

[11] Personal communication, DGAAA, March 2020.

Box 5. Recommendations

Stakeholder collaboration, policies & development projects

- Stakeholders in Peru are in close contact and are mostly aware of other organizations' work. Yet, stakeholder collaboration can be enhanced. Public institutions could take the lead to call for enhanced cooperation in, for example, sharing information or just communicating progress.
- Discussion platforms and events related to the cacao and chocolate value chain take place regularly. These discussions, from the local to the international level, are more than best practices. They bring together varied stakeholders and communicate the state of the art in the cacao and chocolate value chain. These efforts should continue, and possibilities to replicate them at smaller scales or for other products in Peru could be explored. Sharing lessons learnt from these discussion platforms and collaborative experiences would be very welcome.
- Development projects –on cacao, adaptation to climate change or risk reduction in the agricultural sector– could make more explicit the link between the project and the existing political framework on agricultural development planning and adaptation to climate change (e.g. PLANGRACC-A in MINAGRI, 2012). Public policies in Peru do contain objectives and indicators aiming to promote organic cacao agriculture, increase the exportation of organic cacao (PESEM), or mitigating GHG in agroforestry systems (NDCs), just to name a few. Strengthening and providing more evidence on the link between projects and policies could help to leverage important funding, communicate the project's relevance, and forge collaborations with key stakeholders.
- In addition, conducting targeted capacity needs assessments to implement specific policies or increase adaptive capacity would be very useful. Taking the PESEM as an example, if a goal is to increase the exports of organic cacao, a capacity needs assessment would help to identify what needs to be improved and how to address it, for example if cacao cooperatives and associations require capacity building and technical assistance on the topic, or if their members require to access loans and credits to first invest in their production.
- Stakeholders would benefit if the political framework on adaptation to climate change and risk reduction in the agricultural sector in Peru was updated. If doing so, it would be an asset to increase the detail of adaptation goals and indicators, for instance, to target specific value chains or geographic regions and, perhaps more importantly, groups of agricultural producers according to their characteristics and realities.

Adaptation & risk management strategies

- Some adaptation strategies were discussed in section 8.6. Shade management, agroforestry systems, integrated pest control or irrigation technologies could be implemented depending on the locality and available resources.
- General adaptation strategies can comprise:
    - capacity building and information services regarding the impacts and management of drought, heat or pests and diseases –at farm level, association or for larger organizations–;
    - diversify products on farm, including cash crops, products for self-consumption and ecosystem services;
    - diversify cacao genetic variety on farm, aiming to complement the climatic tolerances, cadmium uptake and other characteristics of genotypes;
    - diversify on farm income by developing services, such as tourism and educational uses;
    - increased access to agricultural credits and agricultural insurance schemes; and
    - strengthen collaboration networks at multiple levels.
- Together with capacity building, information services are important particularly for risk management. Currently, SENAMHI issues regularly an agrometeorological bulletin and communicates agroclimatic risk alerts for specific products, among them cacao. It would be interesting to complement these communications by incorporating agroclimatic conditions and risks for key pests and diseases for main crops. A monitoring system for agricultural risks could incorporate measures targeted to different farmer groups according to their characteristics.
- Market-based strategies to increase the added value of cacao consist of organic and origin certifications, CO2 neutral or GHG mitigation labels, fair trade, and traceable cacao, among others. Although they seem similar at a first glance, these certifications have different implications. Only fair-trade certifications, for example, do guarantee a basic

income or price continuity for cacao farmers, which can become increasingly important when considering failed harvests due to climate change impacts or price oscillations in the cacao commodity market.

- In the same line of fair-trade products, it would be innovative to develop a market for climate-resilient and socially-responsible products. Although this exists in one way or another, no certification exists for cacao derivates made explicitly from a blend of different cacao genotypes, aiming to incentivize cacao genetic diversification on farm, conserve native germplasm, and also promote more resilient farming practices.
- Converting cacao parcels to organic, agroforestry systems or beginning to trace beans or track GHG mitigation is costly both in time and economic resources. Farmers, associations and cooperatives will benefit from varied support in the transition to these more sustainable schemes.
- Also related to market possibilities, this study showed that performance thresholds for cacao production bring stakeholders perspectives and stories to scientific research. These stories have the power to communicate and visualize the goals and challenges of local stakeholders, and could help to build powerful marketing strategies aiming to help farmers adapt to climate change and improve their living conditions.

Future research

- Ongoing research to identify tolerant and resilient cacao varieties should be enhanced. Specific attention could be given to identify genotypes tolerant to abiotic stresses, like weekly and monthly droughts, high temperatures, flood and different soil types, but also to biotic stresses, like fungal diseases, pests and even to potential competition for resources with tree agroforestry species.
- A key delivery could be to find out and recommend cacao genotypes that can be planted together in order to complement each other's tolerance ranges or maximize co-benefits (e.g. guarantee a sustained income for farmers during critical weather events).
- Future research could benefit from incorporating a more integrated ecological approach, like host-pathogen or symbiotic interactions at farm level. Ideally, this approach allows to incorporate the main crop, e.g. cacao, together with pathogens, parasitic plants, competing species, but also pollinators and beneficial insects.
- There remains an important gap in researching the impacts of climate change on the main pollinators of cacao, specifically *Forcipomyia sp.* and *Parajalysus andinus.* Similarly, the impacts of climate change on other species providing ecosystem services, such as shade, timber, medical plants or natural enemies of pests, could also be studied.
- In the same line, it's worth studying the impacts of commonly used agrochemicals, e.g. fungi-, herbi- and pesticides, on these species.
- In addition, better temporal resolution is needed in the available data and bioclimatic variables to properly analyze the risk of severe and short-term drought, or conditions that favour the spread of pests and diseases.
- As has been highlighted in this report, integrated methods –such as combining stakeholder- and modelling-approaches– allow a more complete overview of the problematic. Further integrated methods and approaches should be explored.

9. Conclusions

This research aimed at approaching adaptation turning points for cacao production in the Peruvian Amazon by identifying performance thresholds and applying suitability modelling. Brief answers to the research questions are given below.

In the cacao stakeholders' landscape, diverse stakeholders interact constantly and exchange knowledge and resources. With cacao production, farmers aim at an economic activity that delivers sustained income and allows them to achieve an acceptable quality of life. Their main challenges comprise drought and attacks of diseases and pests. Also, low international prices negatively affect the cacao economy.

For farmers, droughts of two weeks during the harvest season are critical, because they reduce the yield that could be harvested and commercialized. This time is shorter than drought periods (up to 4 months) that cacao may tolerate according to literature sources. Precipitation of the driest month and driest quarter, as well as the maximum temperature of the warmest month and driest quarter, are also critical variables.

The suitability models show that the distribution range of cacao is mostly projected to remain suitable, both under RCP 4.5 and RCP 8.5 scenarios. Areas that may become suitable are located along a narrow NNW - SSE stripe along the Andes at higher elevations. In contrast, areas that may become unsuitable are projected along the Andean foothills and lower Amazon basin, especially towards 2070. These potential shifts in areas suitable for cacao have been also described in the literature.

The range of diseases is projected to remain suitable and follows a similar geographic trend as cacao. However, for some diseases the loss of suitable areas is prominent along large areas at the eastern Andean slopes and towards the lower Amazon. The insects show varied responses under future scenarios. *Carmenta sp*. maintains large suitable areas in San Martin and *Monalonion sp*. gains in suitable areas under RCP 8.5. However, large losses are modelled for most of the species ranges. The continuity of pests and diseases under future scenarios, as well as their tendency to accompany shifts in cacao's range, should be a main reason for concern in the study area.

In San Martin, cacao production will face critical high temperatures under both RCP 4.5 and RCP 8.5 scenarios. Most of the study area already reaches the performance threshold of 32°C during the warmest month under current conditions. This situation will further exacerbate, as up to 36°C are projected for 2050 under RCP 4.5 and up to 40°C by 2070 under RCP 8.5. High temperatures exacerbate stress generated by low precipitation during the driest season. Most localities in San Martin already experience precipitation below the performance threshold of 100 mm/ month, which is even lower in central localities (<50 mm/ month). While there is no clear precipitation trend under RCP 4.5, RCP 8.5 projects a reduction in rainfall compared to current conditions. Under RCP 8.5, all analyzed localities would experience precipitation under the performance threshold during the driest month by 2070.

However, even though these performance thresholds are reached in the study area under present and future conditions, the ensemble suitability models still show the study area as ecologically suitable for cacao, even under RCP 8.5 by 2070. This work discussed that, while suitability maps point at cacao's potential niche or ecological tolerance, performance thresholds are closer to the optimal ecological niche, where yield production is acceptable under stakeholders' perceptions.

At first sight, it is good news that cacao remains suitable under future climate conditions. However, challenges are related to managing the performance thresholds identified for cacao, as well as the continued presence of pests and diseases in the study area. To maintain acceptable yield levels in the future, the implementation of adaptation measures should be evaluated. Adaptation is particularly advised to target the increasing risk of drought stress during the dry season, diversify cacao varieties as well as agroforestry species, conduct integrated pest and diseases management and, if possible, explore new market opportunities and certification schemes.

Considering the data and methods applied, as well as contrasting the results with the existing scientific literature for climatic variables and suitability modelling applied to cacao, this study achieved fairly robust results. Furthermore, to the author’s knowledge, this work is the first to model cacao together with varied cacao pests and diseases in a single modelling exercise.

In addition, by applying performance thresholds and ATP, this study was innovative for cacao case studies and for Peru. The strength of this study consisted in incorporating the most striking stakeholders’ concerns on field into research and work towards results that are relevant and salient for the local stakeholders. Besides, by bringing in stakeholders’ perspectives, performance thresholds complement climate and ecological modelling approaches.

Finally, some general recommendations comprise: strengthening stakeholder collaboration and knowledge exchange; building on the existing risk management and adaptation policy frameworks to develop adaptation in the cacao sector; implementing or improving adaptation strategies such as agroforestry, climate and agrometeorological information services, and certification schemes. Future research on climate change impacts on cacao should incorporate cacao’s ecology and broaden its scope, looking also at pests, diseases and pollinators, as well as on ecosystem services. Similarly, future research should address combinations of cacao genotypes and agroforestry products to complement their tolerance ranges and maximize social, economic and environmental co-benefits.

Stakeholders, from the small farmer to the national government, look forward to research and practical information on climate change impacts on cacao and its pests and diseases. In addition, there is a momentum to share this knowledge via local discussion platforms and to incorporate it into national cacao plans.

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Annexes

1. List of interviews

Stakeholder		Stakeholder characteristics							Interview			
		Type / group					Perspective					
Nr.	Organization	Public	Private	Academia	NGO / coop.	Research	Individual	Collective	Group meeting	In person	Call / virtual	Date
1	MIDAGRI, SENASA, INIA, ANA, MINAM, IICA, PNUD, PUM	1	1		1			1	1			19.02.2020
2	INIA	1						1	1			19.02.2020
3	INIA	1				1	1			1		03.03.2020
4	MINAGRI-DGA	1					1				1	26.03.2020
5	MINAGRI-DGAAA	1					1			1		05.03.2020
6	SENASA	1						1		1		19.02.2020
7	CAMCAFÉ		1				1				1	24.03.2020
8	Proyecto Cacao, DRASAM	1					1			1		11.03.2020
9	INIA	1				1	1			1		12.03.2020
10	IIAP	1				1	1			1		14.03.2020
11	ICT				1	1	1			1	1	14.03.2020
12	Cooperative Agraria Oro Verde LTDA		1					1		1		13.03.2020
13	Chacra Pasikiwi		1				1			1		13.03.2020
14	Asociación de Mujeres Cacaoteras Mishky Cacao		1					1		1		13.03.2020
15	Central Cacao de Aroma		1					1			1	02.04.2020
16	ACOPAGRO		1					1			1	03.04.2020
17	Allima Cacao		1					1			1	04.04.2020
18	Pachincao		1				1				1	18.03.2020
19	Alianza Cacao				1		1			1		04.03.2020
20	Proyecto Paisajes Productivos Sostenibles, PNUD				1		1				1	06.03.2020
21	ICT				1	1	1				1	04.03.2020
22	UIQ			1		1	1				1	03.03.2020
23	UNAS	1		1		1	1				1	18.03.2020
24	BI-CIAT				1	1	1				1	05.03.2020
25	CIRAD				1	1	1				1	20.02.2020
26	CIAT				1	1	1				1	14.04.2020
27	GIZ				1		1				1	17.03.2020
28	WUR			1		1	1			1		10.02.2020
29	WUR			1		1	1				1	07.02.2020
	TOTAL	**8**	**8**	**4**	**8**	**12**	**21**	**8**	**2**	**12**	**16**	

2. Coordination meeting with stakeholders: agenda

Reunión de coordinación
Investigación sobre cacao y cambio climático

Fecha: Miércoles 19 de febrero, 2020

Lugar: INIA, Sala de Cambio Climático, en Av. La Molina 1981, La Molina.

Horario: 09:00 – 11:00 am

Objetivos:

- Coordinar prioridades y necesidades de investigación en temas de cacao y cambio climático.
- Presentar la propuesta de investigación sobre puntos críticos para la adaptación al cambio climático en la producción de cacao en el Perú.
- Orientar la investigación propuesta, ajustar expectativas y alinearla con los instrumentos de gestión nacionales y sectoriales.

Agenda:

Hora	Tema	Responsable
09:00 – 09.15	Bienvenida	Carlos Arbizu, INIA / Carmen Rosa Chávez, MINAGRI
09:15 – 09:30	Ronda de presentación	Todos los participantes
09.30 – 09.50	Prioridades y necesidades de investigación en cambio climático: perspectivas por institución	Representantes de instituciones
09:50 – 10:10	Propuesta de investigación: puntos críticos para la adaptación en la producción de cacao en el Perú.	Stefanie Korswagen, WUR
10:10 – 10:30	Ronda de preguntas y discusión	Todos los participantes
10:30 --10:50	Próximos pasos y recomendaciones	Todos los participantes
10:50 – 11:00	Cierre	Carlos Arbizu, INIA

3. Coordination meeting with stakeholders: key results

Prioridades y necesidades de investigación en cambio climático

- Desde la perspectiva de cada institución pública y privada:

¿Cuáles son sus prioridades y qué necesidades identifican para la investigación en cacao en contexto de cambio climático?

Prioridades y necesidades de investigación en cambio climático

Modelos climáticos y predicciones

Impactos sobre la producción de cacao

Sistemas de monitoreo, control y alerta temprana

Buenas prácticas agrícolas y conocimiento local

Información oportuna y articulación entre actores

Variabilidad genética del cacao y variedades resistentes

Efectos de plagas y enfermedades

Relación con otras problemáticas: cadmio, deforestación

Conservación y servicios ecosistémicos

Ronda de preguntas y discusión

- Los participantes expresaron su interés y preocupación en varios aspectos, entre ellos:
  - las variables climáticas y no climáticas (eg. suelos) que impactarán en la producción de cacao en un futuro
  - los impactos reales en la producción de cacao, eg. rendimiento futuro
  - los efectos de plagas y enfermedades
  - la necesidad de información oportuna, sistemas de monitoreo y alerta temprana para la toma de decisiones
  - la disponibilidad de y acceso a data climática y modelos, así como su calidad y precisión
  - la necesidad de sistematizar conocimientos existentes y buenas prácticas para ponerla a disposición de las organizaciones públicas y privadas, en especial actores clave en la toma de decisiones

Próximos pasos y recomendaciones

- Desde la perspectiva de cada institución pública y privada:
  - ¿Cuáles son sus recomendaciones y sugerencias para el desarrollo de la investigación?
  - ¿Cuáles son sus expectativas y necesidades para la devolución de resultados?

Próximos pasos y recomendaciones (1)

- **Relacionar puntos críticos con pérdida productiva**: floración (Tmax, Tmin); poda (tiempo de sequía); plagas (T)
- Incorporar la variable de **evapotranspiración** puesto que esta variable depende mucho de la temperatura, y que influiría en gran medida en el **requerimiento de agua** por el cacao
- En el caso de **sequías se sugiere utilizar el SPJ** como indicador, resultaría interesante ver cómo va a variar este indicador en un contexto de cambio climático
- Incorporación de información de **conocimiento ancestral** en la producción
- Considerar qué **riesgo** representarían **cultivos ilícitos** como la coca y cuál sería el impacto en el desarrollo de cacao como programa de desarrollo alternativo

Próximos pasos y recomendaciones (2)

- Sistematizar el **estado del arte del conocimiento sobre cambio climático y sus impactos en el cacao** y ponerlo a disposición de las organizaciones y tomadores de decisión
- Recoger **buenas prácticas existentes en mitigación y adaptación** al cambio climático, así como en manejo de plagas y enfermedades; sistematizarlas, compartirlas y vincularlas con cambio climático
- Aprovechar la **plataforma de colaboración** en el marco del Plan de Acción para compartir información

4. Adaptation policy in Peru

Adaptation in Peru is linked to disaster risk management and vulnerability reduction, which influence the latter policies. In 2011 the National Disaster Risk Management System and later the National Plan on Disaster Risk Reduction 2014-2021 incorporated adaptation into the political framework. The link between adaptation, vulnerability and risk management was also included in sectoral policies. Specifically, there is a Risk Management and Climate Change Adaptation Plan in the Agricultural Sector (PLANGRACC-A) (MINAGRI, 2012).

The PLANGRACC-A has the objective of reducing climate risks, vulnerabilities and negative effects on the agricultural sector through strategies, policies and actions that are aligned with the regional governments (MINAGRI, 2012). It considers adaptation as a national agricultural priority, which should be embedded in planning documents. Among its policies, the PLANGRACC-A comprises research, technology, information, capacity building, raising local awareness and enhancing public investment for risk management and adaptation.

The National Climate Change Strategy (ENCC) has two strategic objectives; the former refers to adaptation and the latter to mitigation. The former states: “The population, economic agents and the State increase consciousness and adaptive capacity for action against adverse effects and opportunities deriving form climate change” (MINAM, 2015b: 45). Two indicators aim to measure: i) the increase in the proportion of people prepared for, and ii) the increase in the production of scientific research and technological development as a base and guideline for disaster risk management in a context of climate change and for adapting to climate change.

The Framework Law on Climate Change (LMCC) establishes principles, approaches and guidelines related to public policies for managing climate change adaptation and mitigation in order to reduce the country’s vulnerability, seize the opportunities of low carbon development and accomplish international commitments under the UNFCCC (Peruvian Government, 2018). Additionally, the LMCC’s guidelines indicate, among others, the following instruments to manage climate change: sectoral, regional and local planning instruments incorporating climate change, the NDC and the ENCC (Peruvian Government, 2019). The guidelines also define adaptation measures.

Peru submitted its NDC in 2016 to the UNFCCC. The NDC include mitigation, adaptation and transversal issues. The NDC prioritize five thematic areas for adaptation –among them agriculture-aiming to reduce vulnerability and risks associated to climate change, as well as seize opportunities (High-level Multisectoral Working Group for the Nationally Determined Contributions (GTM-NDC), 2018; MINAGRI-DGAAA, 2018). The National Adaptation Plan (NAP) and responsible authorities continue to work on the adaptation goals, measures and indicators identified in the NDC (GTM-NDC, 2018).

5. Stakeholder landscape: Cacao projects in San Martin

As stated before, cacao is a nationally prioritized product. Cacao is among the prioritized agricultural products in the plans of 10 out of 24 Peruvian regions (MINAGRI, 2018), and the second prioritized crop and value chain after coffee in San Martin (INIA, GORESAM & ICT, 2019).

Given this context, the number of projects and stakeholders working around it is large. Summarizing, cacao projects aim to increase productivity and competitivity. This can be achieved through improved cacao varieties, applying agricultural best practices on farm, improved pest management and control, enhanced use of technology along the value chain, stronger organizations, and strategies such as accessing certifications and differentiated markets, among many other. Research plays a pivotal role to improve cacao productivity and competitivity.

At national level, several technical guidelines exist on how to cultivate cacao (MINAG, 2004); improve best practices (Murrieta & Palma, 2018), particularly pest management and control (Soto et al., 2017; Murrieta & Palma, 2020a,b,c,d); improve cacao quality[12]; mitigate cadmium presence in cacao products (INIA, GORESAM & ICT, 2019); among others. Since European Union's regulations on maximum cadmium contents affect Peruvian cacao exports, several organizations have set up research projects on cadmium (Da Silva, 2019; INIA, GORESAM & ICT, 2019; DRASAM, 2020a). In addition, SENASA implements projects on integrated pest management in San Martin, offering capacity building and technical assistance to cacao producers (Soto et al., 2017; INIA, 2019).

Since 2019, public and private stakeholders are working on a National Action Plan on cacao[13]. Both the elaboration process and the plan seek to improve collaboration between stakeholders, address knowledge gaps and improve the cacao and chocolate value chain, especially regarding quality and market opportunities. Current progress includes consultancy studies, such as diagnostics of the cacao value chain, and an important on-going participatory management platform[14]. According to the stakeholders, climate change should be considered in the plan.

The National Action Plan process is deeply related to the Regional Technical Discussion Table on cacao in San Martin. A Regional Technical Discussion Table is a public and private discussion space which seeks to enhance the competitivity of a value chain (GORESAM, 2018). In San Martin, the regional government coordinates a very active Discussion Table on cacao and chocolate, which is a pivotal space for stakeholder coordination and collaboration.

In San Martin, the public sector support several initiatives on cacao. An on-going project, "PIPCACAO"[15], operates to extend and improve support services for cacao producers in the region (DRASAM, 2020a). It works with more than 2000 organized cacao producers on capacity building and enhanced associativity, as well as on the elaboration of technical guidelines, studies on plague control, cadmium mitigation and improved cacao genetic varieties. A second on-going project, "PROCACAO"[16], works to improve support services for the cacao transformation value chain in selected localities (GORESAM, 2020). It aims to reach over 1600 producers and enhance capacities and equipment for cacao manufacture, together with associativity and entrepreneurial capacities.

There is an agenda for innovation in the cacao and chocolate value chain in San Martin for 2020-2030 (INIA, GORESAM & ICT, 2019). The regional agenda prioritizes research, innovation and development needs in order to contribute to cacao and chocolate competitivity and their positioning in sustainable markets. The agenda includes six priority issues that range from cacao germoplasm conservation to diversified export portfolios based on cacao properties~~.~~

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[12] A National Quality Institute operates under the Ministry of Production, whose task is to elaborate technical norms to which enterprises can adhere in a voluntary basis. Currently, a normalization comittee is working to standarize processes along the cacao and chocolate value chain in order to improve quality. Personal communication of C.R. Chávez, MINAGRI (April, 2020).

[13] Personal communication of C.R. Chávez and other stakeholders in multiple interviews between February and April, 2020.

[14] The platform and the National Action Plan are supported by the IICA (http://gestionparticipativa.pe.iica.int/Procesos.aspx).

[15] Public Investment Project on Cacao (PIPCACAO) for the "Ampliación y mejoramiento de los servicios de apoyo al desarrollo productivo de la cadena del cacao a los productores de la región San Martín" (DRASAM, 2020a).

[16] PROCACAO, GORESAM, 2020: "Mejoramiento del servicio de apoyo a la cadena productiva de transformación del cacao en las localidades de Bambamarca, Saposoa, Santa Cruz y Chazuta, Provincias de Tocache, El Dorado, Huallaga y San Martin – Región San Martin" Código Invierte.Pe 2335797.

The National Institute for Agrarian Innovation also highlights that San Martin holds the highest number of cacao projects financed by them[17] (INIA, 2019). In line with the regional priorities, research has recently focused on how to mitigate cadmium absorption; agroforestry systems' co-benefits on soils and carbon storage, as well as for productive diversification; technology transfer; and biological pest control possibilities for *Carmenta* sp. and *M. roreri* (INIA, 2019; INIA, GORESAM & ICT, 2019). However, resilience to climate change is explicitly stated in the pending agenda at all levels (INIA, 2019: 56).

Therefore, a proposal for the National Plan on Agrarian Innovation (PLANIA) contemplates a Transversal Programme on Agrarian Innovation for Climate Change (Consorcio APOYO Consultoría S.A.C. & AC Pública S.A.C., 2019). This proposal responds to the agricultural sectors' vulnerability to climate change and also seeks to mitigate GHG emissions. The methodology proposes analysing vulnerabilities, climatic risks, mitigation and adaptation measures per prioritized crop. Next, it proposes identifying innovation needs, as well as current capacities and resources on climate change, to elaborate a strategy to address agrarian innovation gaps on climate change. Finally, it contemplates the programme's monitoring and evaluation. The programme, however, is broadly proposed for prioritized crops at national level.

In contrast to the lack of studies on adaptation and resilience, there have been previous efforts on mitigating GHG emissions on cacao. A Nationally Appropriate Mitigation Action (NAMA) for cacao was presented in 2014[18], but did not become official. The regional government approved a plan for low-carbon development addressing, among others, goals, procedures and governance arrangements (GORESAM, 2018). There is an on-going study on cacao impacts on deforestation, emission reductions and climate change (Encomenderos, 2020). The study will explore opportunities for reducing cacao farmer's vulnerability and improve sustainability of the cacao value chain. Last, progress has been achieved in quantifying cacao carbon footprints; for instance, ten cooperatives in San Martin measure their carbon footprints.

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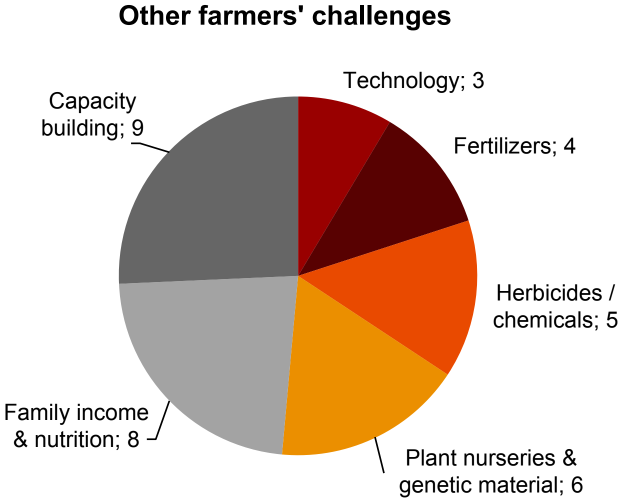
[17] The National Plan on Agrarian Innovation (Plan Nacional de Innovación Agraria, PLANIA) aims to consolidate the National Agrarian Innovation System (SNIA). It provides financing for research projects, publications, capacity building and further improvements, not only on cacao (Consorcio APOYO Consultoría S.A.C. & AC Pública S.A.C., 2018; INIA, 2019).

[18] Personal communication of O. Deheuvels (February, 2020) and C.R. Chávez (April, 2020).

6. Other problems and needs

Secondary problems for cacao production were further revealed during the interviews or derived from stakeholders' improvement needs or recommendations.



The pie chart shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. The interviewees' answers were classified afterwards for visualization purposes. Own elaboration from interviews and discussions.

To detail capacity building needs, key results from the agrarian census are presented in the table below. Although general and not very recent, the trends persist. The vast majority of farmers do not receive capacity building frequently. In case of assistance, crops are the main topic of capacitation. Less frequent capacitation topics reflect areas needed to improve farmers' income and resilience, as well as add value to their produce. Technology issues are linked to capacity building and refer to inappropriate equipment for the post harvest phase.

Details on received capacity building.

Census question	Replies (%) per agricultural surface size (ha)				
	Answer	< 0.5	0.5 - 5	> 5	Mean
Has received capacity building?	No	97	91	83	87
	Yes	3	9	17	13
In case yes, in which topics?					
Crops		53	71	64	63
Management, conservation, processing		27	19	17	21
Livestock		7	3	11	7
Business and commercialization		10	2	3	5
Associativity for production, commercialization		3	4	5	4

Source: Elaborated for San Martin based on the National Agrarian Census (INEI, 2012). Note: the replies refer to capacity building received in the last 6 months prior the census.

Family income and nutrition appeared as concerns in the interviews since cacao produces insufficient income for farmers' families. It was indicated that cacao contributed approximately to 30 % of families' income, thus not covering a minimum wage. Yet, it was positively observed that cacao took many families out of extreme poverty and illegal crops. Farmers plant additional crops to compensate basic needs.

Farmers acquire cacao seedlings from local plant nurseries, sometimes managed by the municipalities, or sometimes directly from development projects. According to interviewees, plant nurseries are risky, because not all have certified plant material. Thus they may either have low yield varieties or contain fungi spores, which will later affect farmers' whole production. In addition, concerns arose on cacao plantations with a single variety. Monocrop systems were feared to be more sensitive to diseases, for example.

Different views arise on agrochemicals. On the one hand, it is perceived that farmers do not apply (or not enough) herbi- or insecticides or fertilizers (either chemical or organic). This affects the spread of diseases, reduces yield, among other impacts. On the other hand, chemical inputs are perceived negatively. Abuse of chemicals may kill the cacao pollinator or affect neighbour parcels under organic schemes. In addition, governmental regulation is not strict enough to limit chemicals that also pose dangers for human health. So, problems of chemical traces and cross contamination arise, affecting cacao commercialization in later phases.

The importance of plant nurseries, agrochemicals and fertilizers is reflected on the interviews as well as on the agrarian census. The table below shows the access of farmers to and use of agricultural inputs. In sum, > 75 % of farmers in San Martin do not use or have access to certified plant material, insecticides, fungicides or fertilizers.

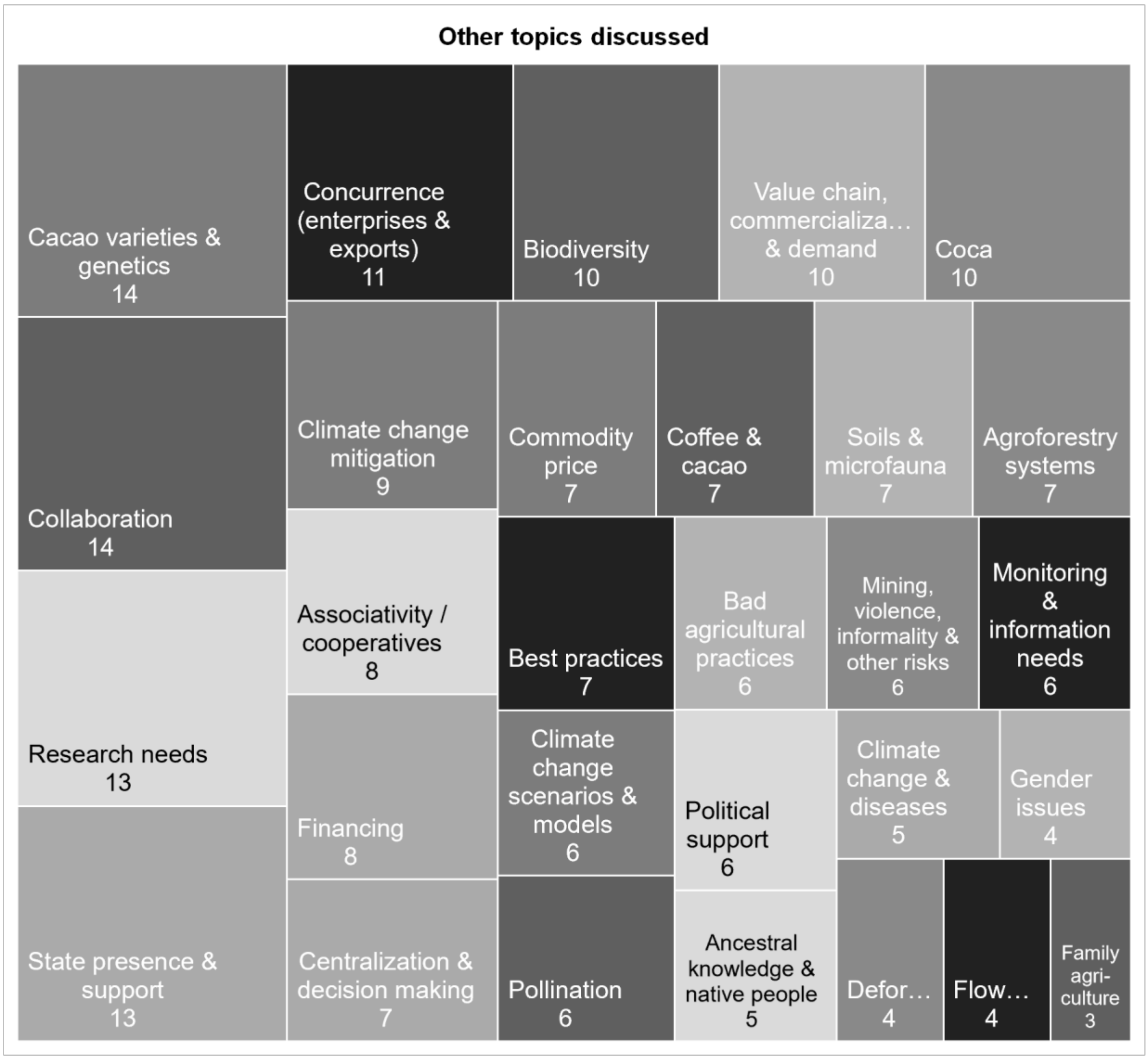
Details on farmers access to and use of agricultural inputs.

Census question	Replies (%)	
	Yes	No
Nurseries and genetic material		
Certified seeds / seedlings	19	81
Organic certified crops	3	94
Agrochemicals		
Herbicides	48	52
Chemical insecticides	24	76
Fungicides	21	79
Biological pest control	6	94
Non-chemical / biological insecticides	3	97
Fertilizers		
Chemical fertilizers	25	75
Guano, manure or organic fertilizer	19	81

Source: Elaborated for San Martin based on the National Agrarian Census (INEI, 2012).

Finally, many topics were discussed in the interviews, which emerged as perceived bottlenecks, as research needs or as recommendations (figure below). For instance, among academia and researchers, the lack of collaboration and state support was highlighted; whereas public sectors emphasized the need of information (on climate change, resilient varieties, best practices) and monitoring systems. The private sector highlighted concurrence in the international market or with intermediaries, management issues, certifications and differentiated market opportunities. In addition, perceived problems refer also to a certain deficiency in cooperatives' management and the lack of standardized protocols for cacao processing.

Attention was paid to financing issues from varied angles. Researchers and academia claim for research funds. And, while private stakeholders refer to the lack of a financial culture and lacking investments on farm, it is also noted that access to credits should be facilitated for small farmers and cooperatives.

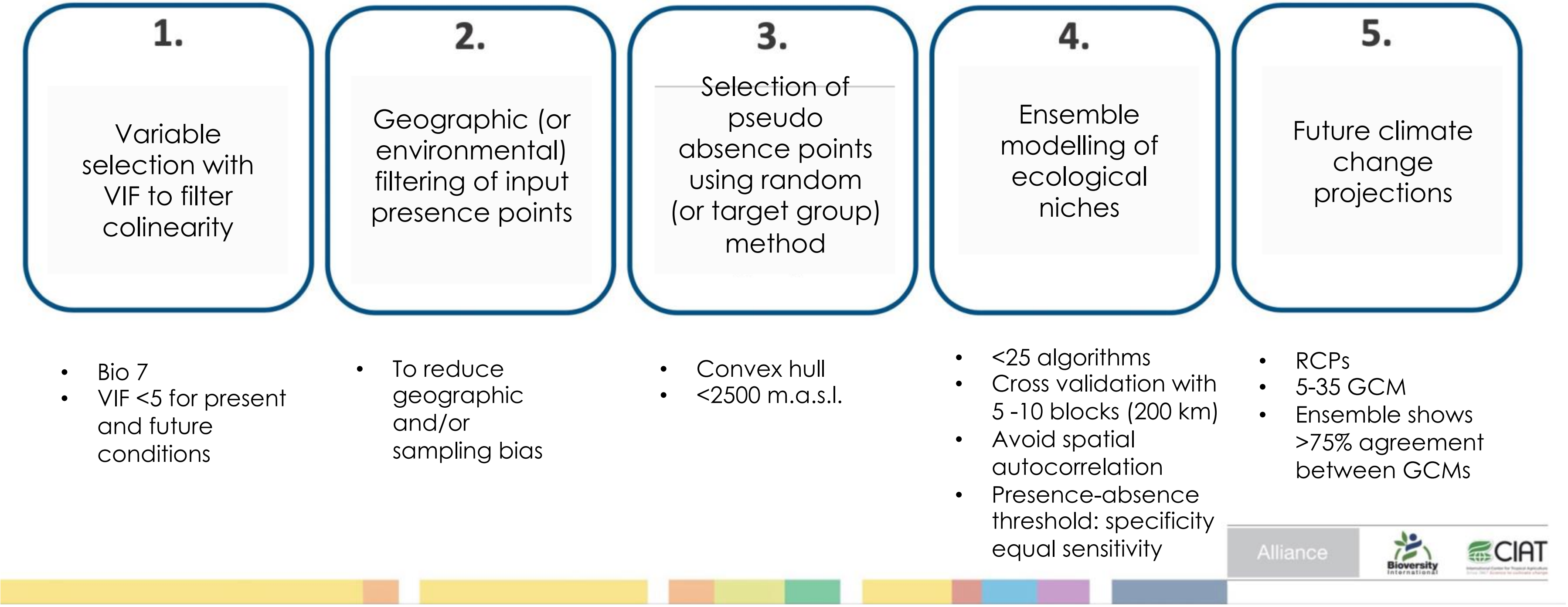


The figure shows the data extracted from interviewees and discussions with stakeholders in Lima and San Martin. The interviewees' answers were classified afterwards for visualization purposes. The numbers indicate the times the topic came up during an interview or conversation with stakeholders. Own elaboration from interviews and discussions.

For researchers, an urgent need was to develop and select resistant varieties, namely varieties resistant to diseases, with low cadmium absorption and resistant to climate change. Stakeholders recognize climate change as a problem, but affirm that it is not the only one. It was stated that the cacao stakeholders should adapt not only to climate, but also to market demands. Additionally, mitigation was considered as important as adaptation.

Biodiversity was highlighted due to Peruvian unique cacao varieties, the country's role as a centre of origin of cacao, susceptible varieties, as well as how to enhance biodiversity with multiclonal parcels and different forestry species. Concerns on cacao pollinators also were mentioned. Coca was frequently discussed. Although cacao has been used to replace coca plantations, farmers are tempted to go back to satisfy income needs.

7. Suitability modelling method under present and future scenarios



1.

Variable selection with VIF to filter colinearity

- Bio 7
- VIF <5 for present and future conditions

2.

Geographic (or environmental) filtering of input presence points

- To reduce geographic and/or sampling bias

3.

Selection of pseudo absence points using random (or target group) method

- Convex hull
- <2500 m.a.s.l.

4.

Ensemble modelling of ecological niches

- <25 algorithms
- Cross validation with 5 -10 blocks (200 km)
- Avoid spatial autocorrelation
- Presence-absence threshold: specificity equal sensitivity

5.

Future climate change projections

- RCPs
- 5-35 GCM
- Ensemble shows >75% agreement between GCMs

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Source: Viviana Ceccarelli, Gabriela Wiederkehr Guerra, Tobias Fremout, Fredy Yovera Espinoza, Evert Thomas: Suitability and climate change modelling course. Dec.16-18, 2020

8. Suitability modelling algorithms

Algorithm	Name	References	Links and sources
MAXENT	Maximum Entropy	Phillips, S.J. M. Dudík, R. E. Schapire. [Internet] Maxent software for modeling species niches and distributions Steven J. Phillips, Robert P. Anderson, Robert E. Schapire, 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling 190:231-259.	http://biodiversityinformatics.amnh.org/open_source/maxent. https://www.rdocumentation.org/packages/dismo/versions/1.3-3/topics/maxent
GBM	Generalized Boosted Regression Models	G. Ridgeway (1999). “The state of boosting,” Computing Science and Statistics 31:172-181. The package implements extensions to Freund and Schapire’s AdaBoost algorithm and J. Fried- man’s gradient boosting machine.	https://cran.r-project.org/web/packages/gbm/vignettes/gbm.pdf https://cran.r-project.org/web/packages/gbm/gbm.pdf
GBMSTEP	Generalized Boosted Regression Models STEP	Hastie, T., R. Tibshirani, and J.H. Friedman, 2001. The Elements of Statistical Learning: Data Mining, Inference, and Prediction. Springer-Verlag, New York Elith, J., J.R. Leathwick and T. Hastie, 2009. A working guide to boosted regression trees. Journal of Animal Ecology 77: 802-81	https://search.r-project.org/CRAN/refmans/dismo/html/gbm.step.html https://cran.microsoft.com/snapshot/2016-01-20/web/packages/dismo/vignettes/brt.pdf
RF	Ranfom Forest	Breiman, L. Random Forests. Machine Learning 45, 5–32 (2001). https://doi-org.ezproxy.library.wur.nl/10.1023/A:1010933404324	https://cran.r-project.org/web/packages/randomForest/randomForest.pdf https://link-springer-com.ezproxy.library.wur.nl/article/10.1023/A:1010933404324
GLM	Generalized Linear Model	R Core Team (1995-2016)	https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/glm https://stat.ethz.ch/R-manual/R-patched/library/stats/html/glm.html
GLMSTEP	Generalized Linear Model STEP	Hastie, T. J. and Pregibon, D. (1992) Generalized linear models. Chapter 6 of Statistical Models in S eds J. M. Chambers and T. J. Hastie, Wadsworth & Brooks/Cole. Venables, W. N. and Ripley, B. D. (2002) Modern Applied Statistics with S. New York: Springer (4th ed).	https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/step
RPART	Recursive Partitioning and Regression Trees	Terry Therneau [aut], Beth Atkinson [aut, cre], Brian Ripley [trl] (producer of the initial R port, maintainer 1999-2017) Breiman L., Friedman J. H., Olshen R. A., and Stone, C. J. (1984) *Classification and Regression Trees.* Wadsworth.	https://cran.r-project.org/web/packages/rpart/index.html https://www.rdocumentation.org/packages/rpart/versions/4.1-15/topics/rpart Breiman L., Friedman J. H., Olshen R. A., and Stone, C. J. (1984) *Classification and Regression Trees.* Wadsworth.
NNET	Feed-Forward Neural Networks and Multinomial Log-Linear Models	Brian Ripley [aut, cre, cph], William Venables [cph] Venables, W. N. and Ripley, B. D. (2002) *Modern Applied Statistics with S.* Fourth edition. Springer.	https://cran.r-project.org/web/packages/nnet/nnet.pdf https://cran.r-project.org/web/packages/nnet/index.html

9. Values for critical bioclimatic variables for selected locations under present and future scenarios

Scenarios & models			Bio 14 (Precip driest month, in mm)							Bio 5 (Max temp warmest month, in *10 C)							Bio 7 (Temp annual range, in *10 C)						
			Localities							Localities							Localities						
			Rioja	Lamas	Tocache	Campanilla	Bellavista	Picota	Chazuta	Rioja	Lamas	Tocache	Campanilla	Bellavista	Picota	Chazuta	Rioja	Lamas	Tocache	Campanilla	Bellavista	Picota	Chazuta
Present conditions	**2010**	**Ensemble**	**76**	**85**	**122**	**93**	**39**	**48**	**81**	**291**	**303**	**312**	**327**	**335**	**335**	**332**	**124**	**134**	**138**	**141**	**142**	**148**	**149**
RCP 4.5	**2020 - 2049**	**Ensemble**	**78,8**	**82,4**	**119**	**103,2**	**45,6**	**52,6**	**89**	**304**	**322,6**	**331,6**	**346**	**355,4**	**356,6**	**355**	**116,4**	**133,4**	**140,2**	**140,4**	**144,4**	**149,6**	**151,6**
		cesm1_cam5	89	87	134	117	48	58	97	305	319	333	344	352	354	353	122	133	142	140	142	148	149
		gfdl_cm3	52	55	67	52	22	27	49	318	354	353	370	381	387	388	119	158	161	163	169	179	182
		miroc_miroc5	103	93	127	134	62	63	110	308	319	333	347	356	355	352	120	129	140	140	144	147	149
		mohc_hadgem2_es	76	85	146	111	44	52	86	306	321	330	345	354	354	352	123	134	141	142	146	149	151
		mpi_esm_lr	74	92	121	102	52	63	103	283	300	309	324	334	333	330	98	113	117	117	121	125	127
	2040 - 2069	**Ensemble**	**74,6**	**80,4**	**106**	**89,6**	**41,6**	**49,8**	**83**	**312**	**332,6**	**340**	**356,4**	**364,8**	**365,6**	**365**	**116,8**	**136,2**	**140,6**	**141,6**	**145,6**	**151,2**	**154,2**
		cesm1_cam5	93	81	140	111	46	55	90	314	327	339	353	359	362	362	122	133	141	138	140	147	149
		gfdl_cm3	45	52	50	40	18	24	44	337	376	373	390	402	407	409	128	170	168	170	178	187	192
		miroc_miroc5	99	109	139	140	60	70	117	308	323	334	351	358	356	355	117	131	135	137	140	144	148
		mohc_hadgem2_es	74	83	95	68	31	41	75	312	330	339	357	364	363	361	121	135	143	146	148	152	154
		mpi_esm_lr	62	77	106	89	53	59	89	289	307	315	331	341	340	338	96	112	116	117	122	126	128
	2060 - 2089	**Ensemble**	**78,4**	**83,2**	**113,2**	**92,6**	**44**	**51,8**	**88,6**	**314,6**	**336,6**	**345**	**361,4**	**369,4**	**370**	**369,4**	**115,2**	**135,8**	**141,2**	**142,2**	**145,6**	**151**	**154,4**
		cesm1_cam5	90	82	143	115	48	59	100	317	332	344	358	364	366	366	122	134	140	138	138	145	149
		gfdl_cm3	38	36	51	42	19	25	39	340	377	377	393	404	409	411	127	169	169	170	177	187	191
		miroc_miroc5	109	113	136	133	57	69	119	307	328	340	357	364	363	362	110	129	139	141	143	147	151
		mohc_hadgem2_es	75	85	108	64	30	39	75	318	337	346	365	372	370	368	121	136	143	146	151	153	155
		mpi_esm_lr	80	100	128	109	66	67	110	291	309	318	334	343	342	340	96	111	115	116	119	123	126
RCP 8.5	**2020 - 2049**	**Ensemble**	**70,6**	**73,2**	**102,8**	**87,4**	**38,8**	**47**	**75**	**310,6**	**330,2**	**338,2**	**353**	**362**	**363,4**	**362,4**	**120,2**	**138**	**144,2**	**144,8**	**148,6**	**154**	**156,8**
		cesm1_cam5	87	88	122	105	44	53	89	307	322	334	347	355	356	355	119	131	139	138	140	145	148
		gfdl_cm3	35	35	49	38	17	22	38	319	353	355	371	380	386	387	116	154	158	160	164	174	178
		miroc_miroc5	101	99	149	141	59	72	105	308	323	334	348	358	357	356	120	132	141	140	145	148	151
		mohc_hadgem2_es	65	72	118	78	33	41	73	308	325	333	350	359	358	356	122	135	139	142	146	149	151
		mpi_esm_lr	65	72	76	75	41	47	70	311	328	335	349	358	360	358	124	138	144	144	148	154	156
	2040 - 2069	**Ensemble**	**71,2**	**73,6**	**105,8**	**85,6**	**38,2**	**44,8**	**74,4**	**322,8**	**346,8**	**353,2**	**369**	**377,6**	**379,4**	**379**	**120,4**	**142,6**	**147**	**147,2**	**150,8**	**157,4**	**160,8**
		cesm1_cam5	89	82	134	111	46	56	92	320	338	348	362	369	371	371	121	136	142	139	140	147	150
		gfdl_cm3	37	39	46	33	15	19	37	344	382	383	398	409	414	416	127	169	170	171	178	188	193
		miroc_miroc5	115	117	154	155	66	74	118	310	334	343	360	366	368	367	113	134	141	142	143	150	153
		mohc_hadgem2_es	74	81	124	72	30	38	69	319	338	345	362	371	370	369	120	134	140	144	147	150	153
		mpi_esm_lr	41	49	71	57	34	37	56	321	342	347	363	373	374	372	121	140	142	140	146	152	155
	2060 - 2089	**Ensemble**	**68,8**	**70,2**	**93,2**	**76,6**	**36,2**	**41**	**67,8**	**337,2**	**367,4**	**370,8**	**388,2**	**397**	**399,2**	**399,6**	**120,8**	**149,4**	**150,6**	**152,2**	**156,6**	**163,4**	**167,4**
		cesm1_cam5	86	76	116	95	40	47	78	335	361	365	378	387	390	392	123	146	147	144	147	155	160
		gfdl_cm3	26	18	25	20	11	10	14	370	410	408	425	437	443	445	141	187	184	186	195	204	210
		miroc_miroc5	113	118	142	150	69	74	118	317	342	352	370	377	376	375	109	131	139	141	143	147	150
		mohc_hadgem2_es	84	95	111	61	29	40	79	331	359	364	384	391	390	390	114	137	141	146	149	153	156
		mpi_esm_lr	35	44	72	57	32	34	50	333	365	365	384	393	397	396	117	146	142	144	149	158	161

Annex

Scenarios & models			Bio 17 (Precip driest quarter, in mm)							Bio 9 (Mean temp warmest quarter, in *10 C)							Bio 6 (Min temp coldest month, in *10 C)						
			Localities							Localities							Localities						
			Rioja	Lamas	Tocache	Campanilla	Bellavista	Picota	Chazuta	Rioja	Lamas	Tocache	Campanilla	Bellavista	Picota	Chazuta	Rioja	Lamas	Tocache	Campanilla	Bellavista	Picota	Chazuta
Present conditions	**2010**	**Ensemble**	**236**	**275**	**366**	**307**	**159**	**181**	**274**	**223**	**234**	**239**	**255**	**260**	**258**	**255**	**166**	**169**	**173**	**188**	**192**	**188**	**184**
RCP 4.5	**2020 - 2049**	**Ensemble**	**255**	**291,6**	**400,4**	**344,4**	**171,8**	**190,6**	**290,8**	**243**	**255,6**	**260,4**	**274,6**	**280,6**	**279,8**	**276,8**	**187,6**	**189,2**	**192,2**	**205,4**	**211**	**207**	**203,4**
		cesm1_cam5	282	304	430	363	185	203	306	241	258	258	271	277	276	273	183	186	191	204	210	206	204
		gfdl_cm3	165	181	229	193	102	109	164	252	263	273	288	296	296	295	199	196	192	206	212	208	206
		miroc_miroc5	324	349	441	431	204	231	374	247	259	259	272	278	277	273	188	190	193	207	212	208	203
		mohc_hadgem2_es	249	294	468	366	178	195	287	241	252	261	276	279	277	274	183	187	189	203	208	205	201
		mpi_esm_lr	255	330	434	369	190	215	323	234	246	251	266	273	273	269	185	187	196	207	213	208	203
	2040 - 2069	**Ensemble**	**259**	**298,2**	**385,4**	**335,2**	**171**	**190,8**	**290,8**	**250,8**	**262,4**	**267,8**	**282,8**	**288,4**	**288**	**285,2**	**194,4**	**196,4**	**199,2**	**215**	**218,4**	**214,4**	**210,6**
		cesm1_cam5	299	298	417	356	183	202	301	250	264	265	281	286	284	281	192	194	198	215	218	215	212
		gfdl_cm3	155	171	202	180	98	105	155	265	276	285	302	302	309	308	207	206	204	220	223	220	217
		miroc_miroc5	323	389	460	443	212	245	394	250	259	263	277	282	279	274	190	192	199	214	217	212	207
		mohc_hadgem2_es	247	285	425	321	169	186	276	249	260	269	283	291	289	287	191	195	196	211	215	211	207
		mpi_esm_lr	271	348	423	376	193	216	328	240	253	257	271	281	279	276	192	195	199	215	219	214	210
	2060 - 2089	**Ensemble**	**267,4**	**288**	**380,2**	**334**	**170,6**	**190,4**	**292,4**	**254,6**	**267,8**	**273**	**286,6**	**293,6**	**293,8**	**291**	**198,6**	**201**	**203,6**	**219**	**223,2**	**219**	**215**
		cesm1_cam5	310	289	434	366	190	209	312	252	268	270	286	294	292	290	193	197	204	219	225	221	217
		gfdl_cm3	135	152	171	147	78	88	135	269	289	290	299	306	314	313	212	210	207	223	226	222	220
		miroc_miroc5	340	392	448	442	212	242	392	254	259	269	281	287	285	280	196	199	201	215	220	216	211
		mohc_hadgem2_es	245	279	411	302	159	177	269	255	266	275	290	297	296	293	197	201	203	218	221	217	213
		mpi_esm_lr	307	328	437	413	214	236	354	243	257	261	277	284	282	279	195	198	203	220	224	219	214
RCP 8.5	**2020 - 2049**	**Ensemble**	**238**	**264,6**	**353,8**	**300,8**	**151,4**	**168,8**	**256**	**246,6**	**258,4**	**263,8**	**278,4**	**283,2**	**281,8**	**282**	**190,4**	**192,2**	**194**	**208,2**	**213,4**	**209,4**	**205,6**
		cesm1_cam5	277	293	377	327	169	187	283	245	255	261	275	282	281	277	188	191	195	209	215	211	207
		gfdl_cm3	129	146	169	150	80	89	139	254	266	275	290	290	289	297	203	199	197	211	216	212	209
		miroc_miroc5	318	356	453	430	209	230	339	244	260	260	276	280	279	282	188	191	193	208	213	209	205
		mohc_hadgem2_es	239	271	430	316	158	175	261	246	257	262	277	283	281	278	186	190	194	208	213	209	205
		mpi_esm_lr	227	257	340	281	141	163	258	244	254	261	274	281	279	276	187	190	191	205	210	206	202
	2040 - 2069	**Ensemble**	**257**	**275,6**	**373,6**	**318,8**	**159,8**	**176,6**	**269**	**259,2**	**272,8**	**277,2**	**291,6**	**298**	**296,8**	**294,2**	**201,6**	**204,2**	**205,8**	**221**	**226**	**222**	**218,2**
		cesm1_cam5	303	287	412	352	185	203	300	256	274	277	290	297	293	290	198	202	206	223	228	224	221
		gfdl_cm3	117	133	142	126	70	76	119	271	290	290	306	315	315	314	216	213	211	225	230	226	223
		miroc_miroc5	363	377	491	475	221	239	370	256	265	269	283	289	287	284	196	200	202	217	222	218	214
		mohc_hadgem2_es	246	285	452	324	166	182	268	257	269	276	292	296	298	295	199	204	205	219	224	220	216
		mpi_esm_lr	256	296	371	317	157	183	288	256	266	274	287	293	291	288	199	202	205	221	226	222	217
	2060 - 2089	**Ensemble**	**250,6**	**271**	**365**	**309,4**	**153,4**	**168,8**	**255,6**	**276**	**287,6**	**293,4**	**307**	**314,2**	**313**	**311,4**	**215,8**	**217,8**	**220**	**235**	**239,8**	**235,8**	**232,2**
		cesm1_cam5	285	263	374	322	168	181	268	270	284	291	304	312	312	311	211	214	217	234	239	235	232
		gfdl_cm3	96	90	90	82	45	47	79	295	311	310	326	336	336	335	228	223	223	237	242	239	235
		miroc_miroc5	373	393	508	493	225	243	368	267	271	280	293	299	297	293	207	211	214	228	233	229	225
		mohc_hadgem2_es	259	298	469	315	163	181	282	275	286	295	308	314	312	309	217	222	223	237	241	237	234
		mpi_esm_lr	240	311	384	335	166	192	281	273	286	291	304	310	308	309	216	219	223	239	244	239	235

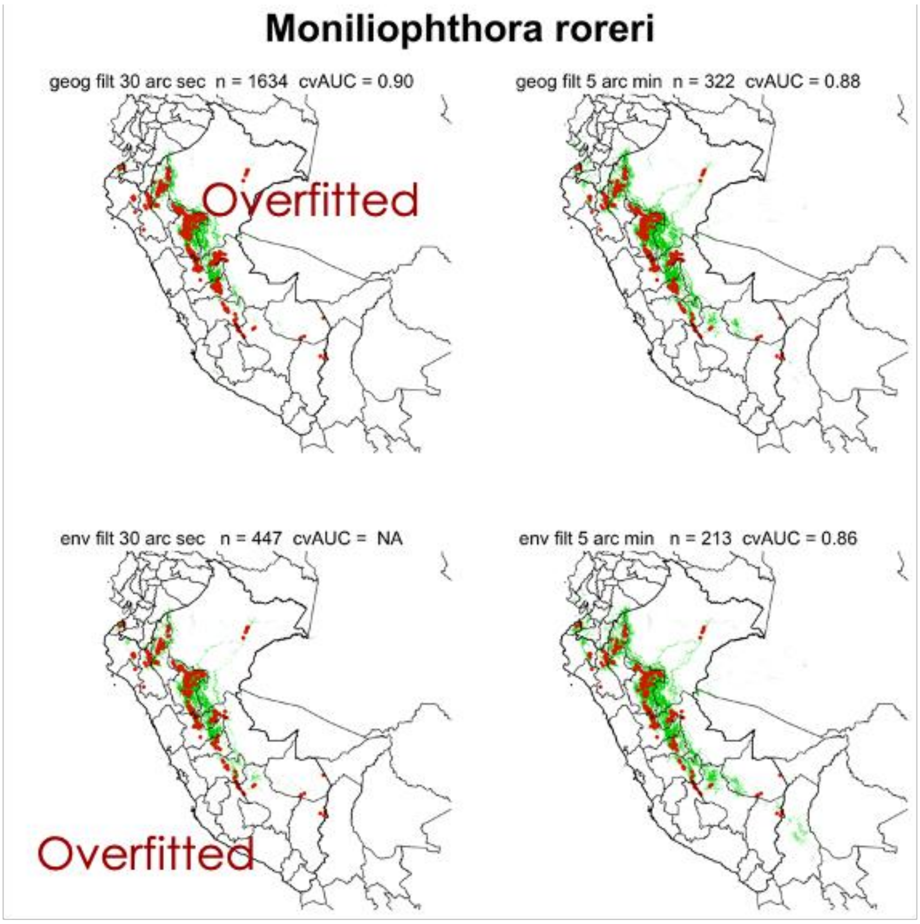
The table shows the values for the bioclimatic variables under: i) present conditions, i.e. 2010, generated by a model ensemble); ii) future conditions under RCP 4.5, for the periods 2020-2049, 2040-2069 and 2060-2089, under 5 different GCM and an emsemble; and iii) future conditions under RCP 8.5, for the periods 2020-2049, 2040-2069 and 2060-2089, under 5 different GCM and an emsemble. The values were extrapolated for the selected localities from the bioclim raster files (which have a spatial resolution of 30 arcsec or about 1 km at the Equator), by superposing the layers on QGIS. Localities are organized according to elevation (Rioja 840 m to Chazuta 199 m). Precipitation is given in mm; temperature variables are given in *10ºC to avoid decimals in the calculations. The ensemble values are noted in bold and with grey background. Bioclim variables (Bio 1 to Bio 19) were obtained from Worldclim (https://www.worldclim.org/data/bioclim.html)

10. Evaluation of parameters and models

Evaluating model performance comprised a series of steps. First, the filtering method and spatial resolution had to be decided. Therefore, models for all species were produced, under current conditions, for different filtering methods and spatial resolutions:

- Geographic filtering
    - 10 arcmin
    - 5 arcmin
    - 30 arcsec
- Environmental filtering
    - 10 arcmin
    - 5 arcmin
    - 30 arcsec

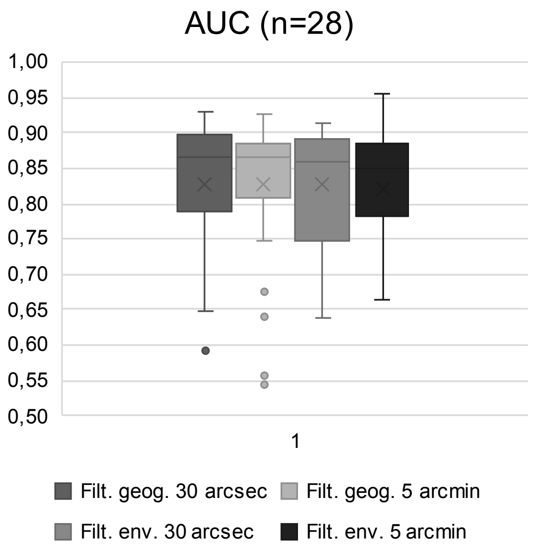
For all of this maps, model performance was evaluated by, first, comparing the actual presence points and the modelled present suitability (see example below).

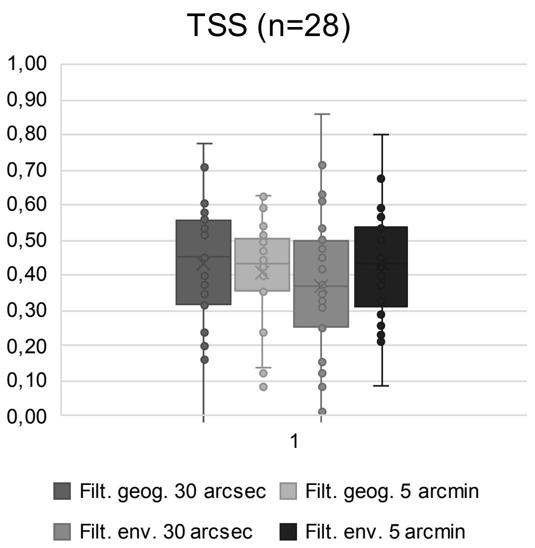


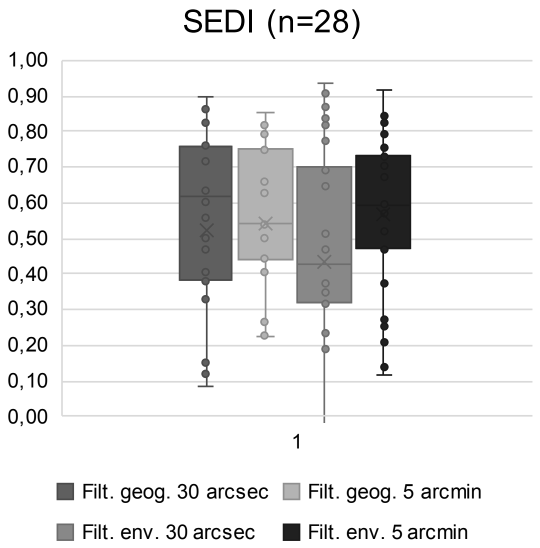
Second, four indexes to evaluate model performance were analysed to identify the best performing filtering method and resolution:

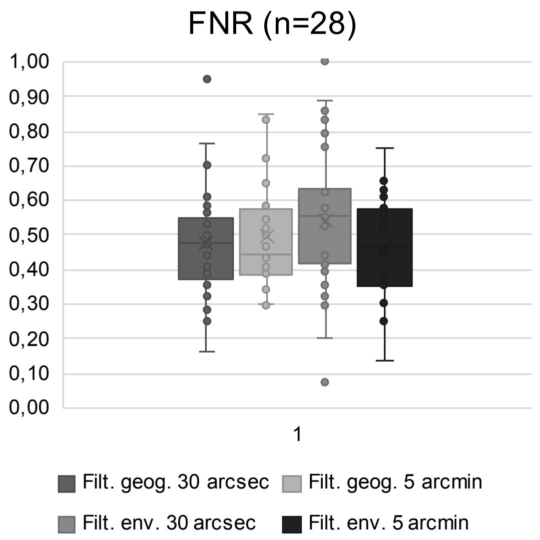
- AUC: Area Under the Curve
- TSS: True Skill Statistic
- SEDI: Symmetric Extremal Dependence Index
- FNR: False Negative Ratio

The indexes showed varying responses. Therefore, a simple graphical box plot visualization proved insufficient. A simple approach consisted in counting the number of times where each resolution performed the best for each species, comparing the four indexes. Comparing model performance on the maps, as well as the indexes, the geographic filter at 5 arcmin was selected as the best option (in red).







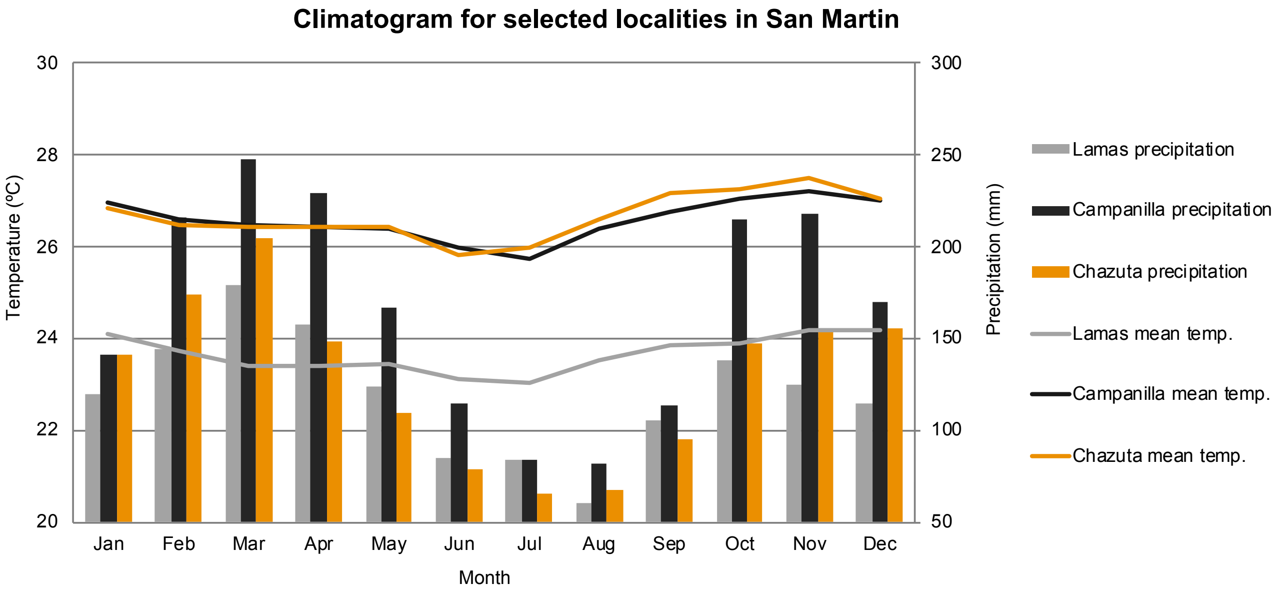


Number of times the filter performs best (species n = 28)

Filter	Spatial resolution	Indicator				Count
		AUC	TSS	SEDI	FNR	
Geographic	30 arcsec	9	7	9	9	34
	5 arcmin	8	11	9	9	**37**
Environ-mental	30 arcsec	5	4	5	2	16
	5 arcmin	6	6	5	8	25

11. Historical climate data for the study area

The following graphs represent historical climate data for three selected localities in San Martin. The data was directly obtained from SENAMHI[19]. The meteorological stations were selected together with the meteorological specialist in Tarapoto to represent geographical distribution across San Martin. Different time series were available depending on the station and parameters (see table below). Some months in the data series had to be filled with the series average. Based on the obtained monthly data, mean, maximum and minimum temperatures were derived, as well as averages for monthly total rainfall, relative humidity and rainfall frequency.



Station	Latitude	Longitude	Altitude (m)	Temperature series	Precipitation series	Rel. hum. Series
Lamas	06° 16' S	76° 42' W	920	1989- 2019	1989- 2019	1989- 2019
Campanilla	07° 26' 25 S	76ª 41' 40 W	390	2000- 2018	1989- 2019	2000- 2019
Chazuta	06° 35' S	76° 11' W	200	2013- 2018	1989- 2018	2013- 2018

Source: SENAMHI, 2020

Mean annual temperature remains quite constant through the year. The average is around 25.5 - 27.5ºC in Campanilla and Chazuta, and 23 – 24ºC in Lamas. Lamas is relatively cool compared to other stations, which can be due to its higher altitude.

Separate climatograms for each station show how temperature values (mean, maximum, minimum and also temperature amplitude) slightly increase after the dry season. Moreover, climatograms do show that maximum temperatures reach >32ºC in Campanilla and Chazuta. Thus, historical data also indicates that performance thresholds for cacao production arise in these localities under present conditions.

These historical temperature values are well represented by the bioclimatic variables. First, the bioclimatic variables represent the differences in temperature and precipitation between the localities; e.g. Campanilla and Chazuta are warmer, while Lamas is cooler; and Campanilla receives more rainfall that the other two stations (figures 17 and 18). Second, values for monthly maximum temperature (Bio5), monthly minimum temperature (Bio6) and mean temperature for the driest month (Bio9) for present conditions are fairly similar to the observed values in these three stations (see annex 9 for

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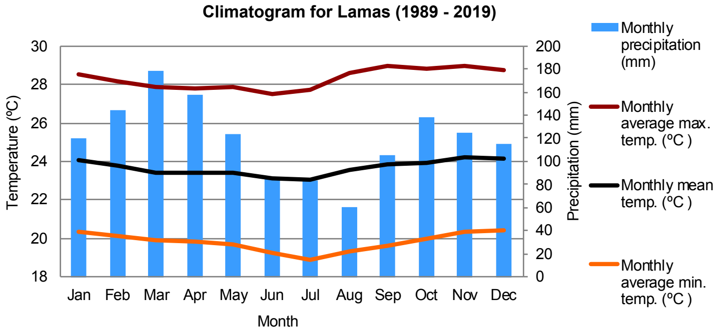
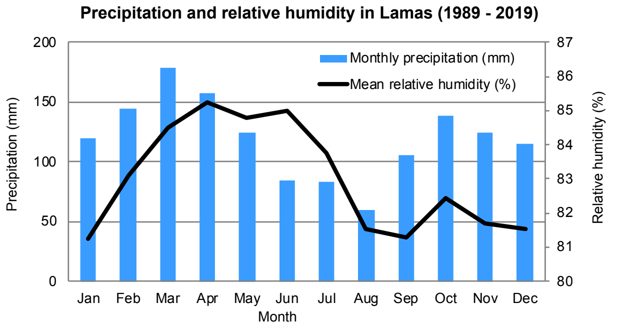
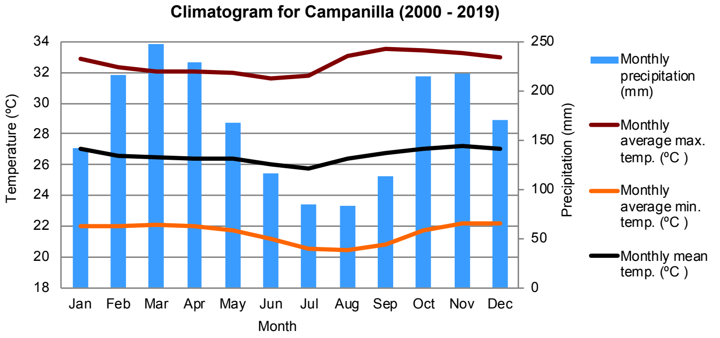
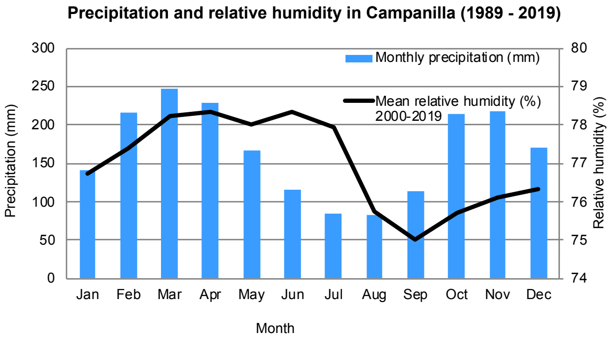
[19] University students in Peru may request free access to a limited amount of climatological data from SENAMHI stations. Therefore, a commitment has to be signed and the student compromises to give back the thesis report.

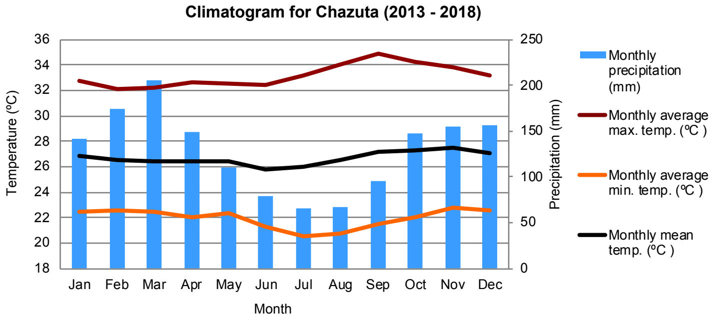
bioclimatic values). Third, time series for temperature (not shown here) do show a slight increase in mean and maximum temperature in the study area. This increasing trend is also observed in the bioclimatic variables (Bio5).

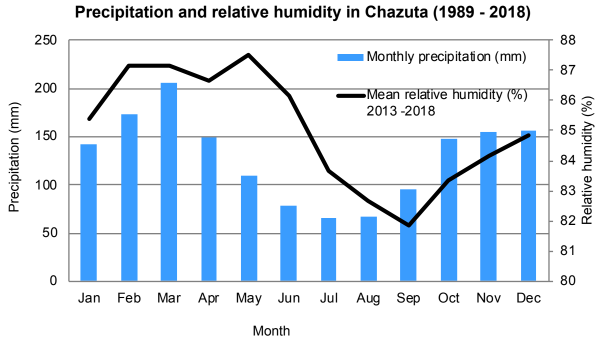

Climatogram for Lamas (1989 - 2019)


Precipitation and relative humidity in Lamas (1989 - 2019)


Climatogram for Campanilla (2000 - 2019)


Precipitation and relative humidity in Campanilla (1989 - 2019)


Climatogram for Chazuta (2013 - 2018)

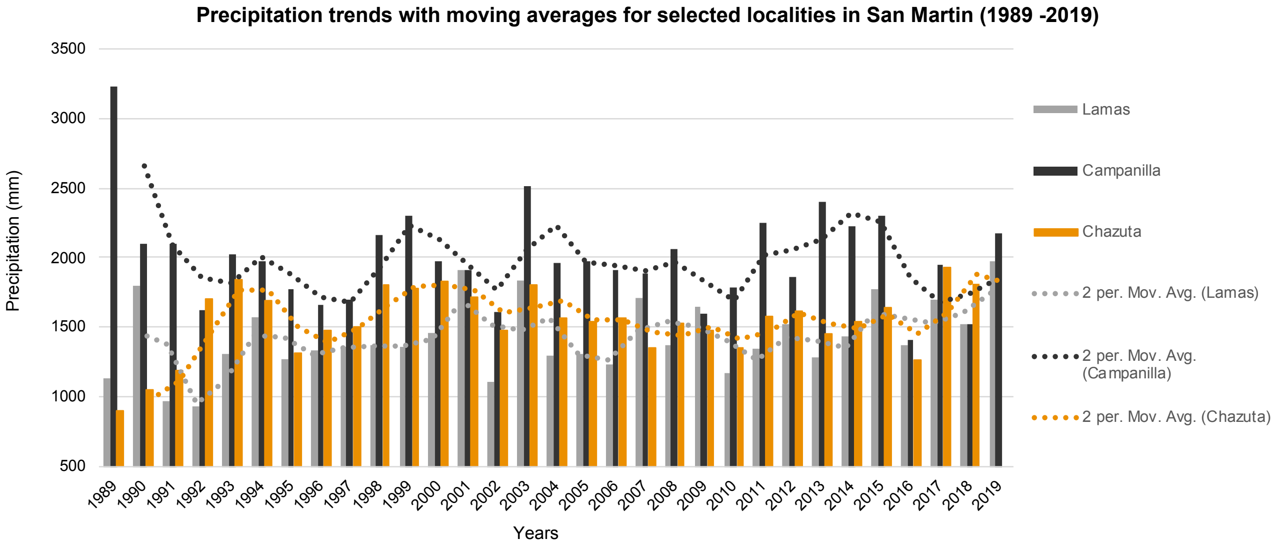

Precipitation and relative humidity in Chazuta (1989 - 2018)

For the three localities, precipitation shows a clear bimodal distribution, which determines seasonality in the study area. Rainfall seasonality was described by interviewed stakeholders. The climatograms for the historical data do support stakeholders' observations for the driest months being June to August. Seasonality is also in line with the existence of two cacao harvests in the study area.

Although the stations receive different amounts of precipitation, both per month and annually, and the second rainy peak between October and December has different intensities, the main trends in precipitation are similar. Most importantly, the driest quarter is the same across the localities (June - September), as well as the two driest months, June and August.

Historical data also shows how Lamas, Campanilla and Chazuta receive <100 mm during the driest month, i.e. that the performance threshold for cacao production is met under present conditions. These features, as well as the marked precipitation seasonality are, again, well represented by the bioclimatic variables.

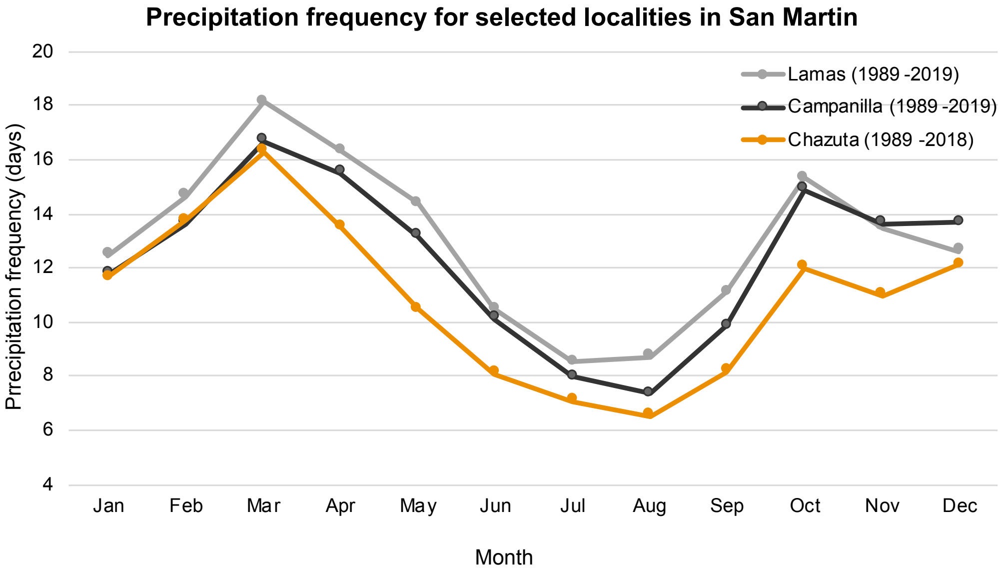
Relative humidity was available for the historical data. Lamas and Chazuta are very humid (81-85% and 81-88%) compared to Campanilla (75-79%). The climatograms also show a time lag between rainfall and relative humidity; i.e. humidity peaks after the wettest months, and is the lowest at the end of the dry season. This lag and high relative humidty levels during the main harvest (April - June) have implications for the incidence of pests and diseases. As mentioned by stakeholders, relative humidity >80% is prejudicial for cacao and increases the incidence of diseases, which is particularly critical during cacao pod development.



Another important observation regarding precipitation is the interannual variability. Interannual variability is large and drought cycles are known to be influenced by both El Niño Southern Oscillation and the North Atlantic Oscillation (Marengo et al., 2008; Zou et al., 2016; Jimenez et al., 2018). Considering interannual and decadal variability, no clear increasing nor decreasing trend in precipitation can be confirmed for the observed time series.

As has been noted in this study, future climate projections for precipitation in the study area do not show a clear trend, neither between RCPs nor in time. Models' difficulty in projecting rainfall can be traced back to the high variability showed here and the complexities behind modelling ocean-atmosphere interactions.

A final observation for precipitation addresses precipitation frequency, i.e. the number of rainy days per month. Precipitation frequency sheds light on how rainfall is distributed within one month. As shown in the graph below, the driest months, July and August, have an average of 9 rainy days in Lamas and around 7 in Chazuta and Campanilla. No further data was available to see if these were consecutive rain days or not. This low precipitation frequency during the driest months points at a high drought stress on cacao, as well as a relatively high probability that 1 or more weeks without rainy days occur.

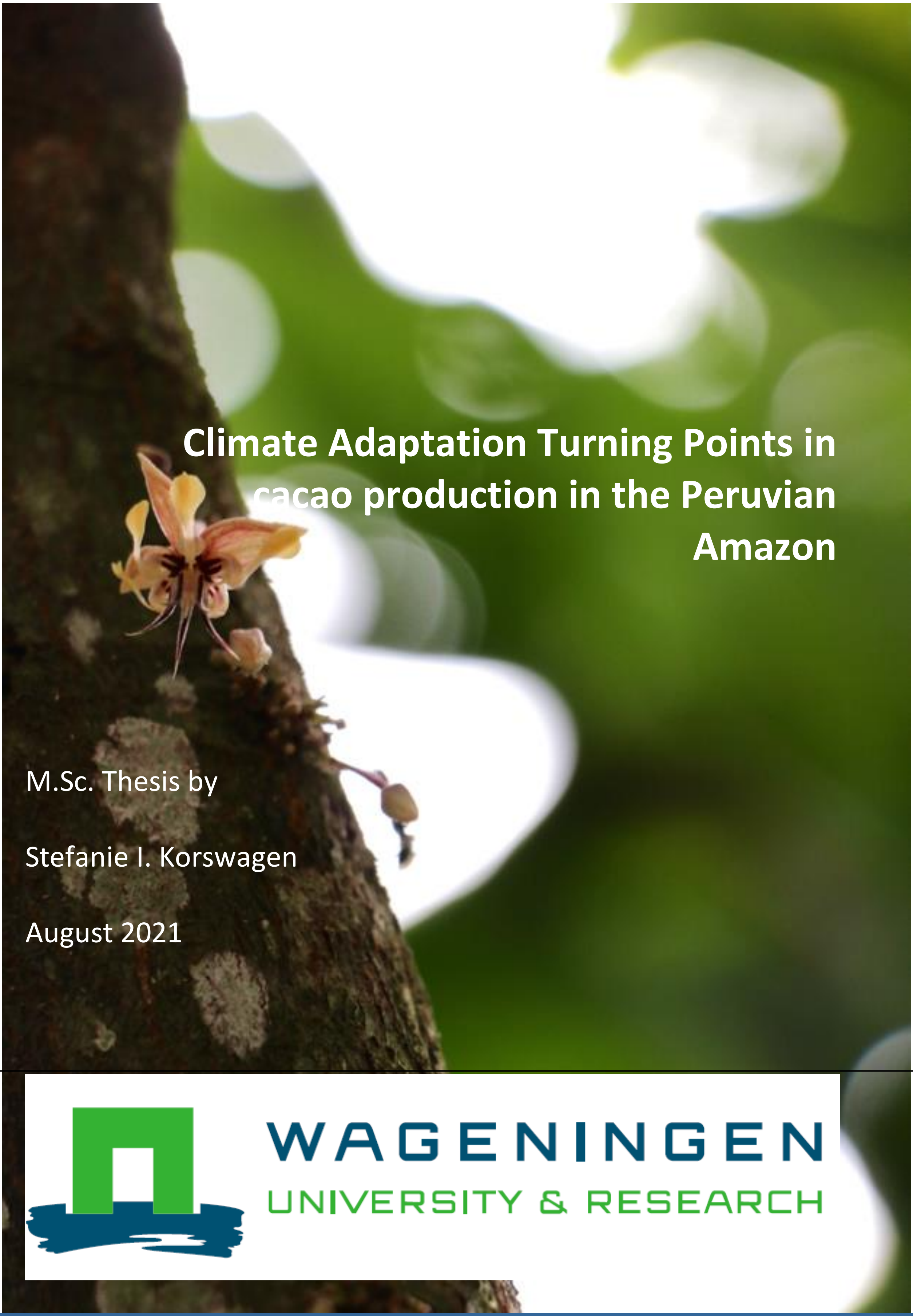


12. Complementary observations on cacao pests and diseases

Species			Georreferenced presence points			Part of the plant that is affected						Do experts judge the species as a priority?	Is it a pollinator or natural enemy?	Is soil in the species' lifecycle involved?	Registries in Peru			Key variables and observations on the species' distribution
Type	Group	Species	Clean and filtered points	Total clean points	Explanations for records, grouping and assumptions made	All plant	Leaf	Stem/ branch	Pod	Flower	Root				Native or introduced	Earliest registries	Source	
Disease	**Moniliophthora perniciosa**		1951	**1951**	1 point added from neighbour countries. 4 points registered as *Crinipellis perniciosa* (synonym).	**X**	X	X	**X**	X		**Yes**	No	N.D.	Native	1995	Publications	Dry climate/ season limits Witches' broom, it needs warm and humid climate to reproduce. Witches' broom is not present in Tumbes due to the dry climate. Yet, it's absence in northern coast might also be due to native cacao types (criollo). Together with Black pod, Witches' broom is one of th emost perjudicial cacao diseases in the Americas (Bailey & Meinhardt, 2016).
	Moniliophthora roreri		2705	**2705**					**X**			**Yes**	No	N.D.	Native	1995	Publications	Relative humidty is key: Monilia appears where relative humidity is >80%. In San Martin, humidity ranging from 85-90% has been recorded. Monilia is very tolerant to excessive heat, while cacao is not. Drought limits the distribution of M. roreri. "Thus, the climatic limitation of distribution for M. roreri is likely to be defined by the limits for its cultivated host, cocoa, as the pathogen has tolerated experimental conditions that exceeded the tolerance limits for cocoa." (CABI, 2021). M. roreri was detected in the Amazon basin of Ecuador and Peru in the late 1980s and since then has expanded in the Americas (CABI, 2021). Monilia is more severe in San Martin than in other regions of Peru (might be due to humidity or CCN51). Economic impacts of Monilia reach up to harvest losses between 20 and 90% and it has been noted that crop failures render cocoa production economically unfeasible (Bailey & Meinhardt, 2016; CABI, 2021).
	Phytoph- thora sp.	*Phytophthora capsici*	1	**713**	Discard 1 point from P. capsici. Group *P. palmivora* and *P sp.* due to lack of differentiation between the species in data sources.				**X**			**Yes**	No	Yes	Native	1995	Publications	The pseudo fungus has a phase on soil, so that soil humidity might allow its survival on drier climates. Black pod is favoured by free water in soil and on foliage (M. ten Hopen). In Peru, Black pod is not yet present in Loreto, Cusco nor in the coast. It's important to differentiate between Phtytophthora species: while *P. palmivora* attacks the pod, other species attack the stem. In addition, different species have been recorded worlwide. For example, *P. megakarya* is only present in Africa (Bailey & Meinhardt, 2016). Worldwide, "the most important black pod pathogen is P. palmivora (...) [whihc] was first reported on cacao in 1909 and currently causes more damage on cacao than any of the other species." (Bailey & Meinhardt, 2016).
		Phytophthora palmivora	65						**X**						Worldwide	1995	Publications	
		Phytophthora sp.	648				X	X	**X**	X	X					2018	BI-CIAT	
Pest	**Carmenta sp.**	*Carmenta foraseminis*	7	**1371**	Group all *Carmenta sp.* due to lack of differentiation between species in data sources.				**X**			**Yes**	No	No	Native; recently seen as pest	2015	SENASA	Relative humidity, altitude and the dry season are important for the species. In Peru, first observations of Carmenta as a pest were in the central Amazon (VRAE). While Carmenta occurs naturally, the description as a pest is recent. Until some years ago, farmers knew that Carmenta occured at higher elevations, for which they would not plant cacao at higher elevantion (Moyobamba and Rioja). Later, Carmenta began to lower its altitudinal range in San Martin. There is less Carmenta in the lower Amazon, Ucayali or Pasco. In the VRAE, *C. foraseminis* was observed at 600 -800 m (2006), but now it appears at 300-600 m. In Tumbes (coast), *C. theobromae* was registered in 2004. It's likely that the pest expanded due to inappropriate agricultural practices. It appears next to the forests, where it finds a natural host (*Gustavia sp*).
		Carmenta sp.	1364													2009	SENASA	
		Carmenta theobromae	0					X								2020	SENASA	
	Monalonion dissimulatum		322	**322**	Assume records for *Monalonion sp.* belong to *M. dissimulatum, since it's the most* common cocoa bug named as such.		**X**		**X**			**Yes**	No	No	Native	2009	Publications	Important variables are shadow, temperature, humidity and rainfall seasonality. Lower rainfall is associated to higher Monalonion populations, as well as defficient shadow (Valarezco et al., 2012). *M. dissimulatum* was first recorded in Palcazu in Peru as a pest. It's present in the northern coast, but it's rare/ low abundance (C. Ocampo). Varied Monalonion sp. are found throughout the Americas. As with aphids, the use of pesticides against mirids also eliminates natural enemies, so that the pest can expand. Both nynphs and adults feed mostly on pods of all ages and colours (Valarezco et al., 2012). When feeding, insects eyect toxins that eventually cause the pod to die.

The table summarizes aspects on main cacao pests and diseases discussed with experts. These discussions helped to prioritize which species to model and consider key variables for modelling their distribution. Here, only the selected 5 species are shown. The original databse comprised >50 species, comprising fungi, insects, nematodes and weeds. The table incorporates inputs and observations from M. Dita (Senior Scientist at BI-CIAT, Bogota), Carolina Ocampo (BI-CIAT), E. Murrieta (Agrobusiness Specialist at Peru Cacao Alliance, Lima), L. Bagny Beilhe (Researcher on pest management in Perennial Crops at CIRAD, Montpellier) and colleagues from their organizations.

Annex



Climate Adaptation Turning Points in cacao production in the Peruvian Amazon

M.Sc. Thesis by

Stefanie I. Korswagen

August 2021