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Climate Dynamics and Agricultural Adaptability in the Brazilian Amazon

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requirements for the degree Doctor of Philosophy

in Geography

by

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ABSTRACT

Climate Dynamics and Agricultural Adaptability in the Brazilian Amazon

by

Corrie L. Monteverde

Recent climatic shifts and deforestation in the Brazilian Amazon have likely ushered the region into a new ecological and climatic regime with profound implications for biodiversity, ecosystem services, and local communities. This dissertation employs a comprehensive approach to address Brazil's National Adaptation Plan goals by integrating climate modeling and evaluation, field interviews, and risk mapping methodologies across three interrelated studies.

The first paper evaluates the performance of thirteen Coupled Model Intercomparison Project phase 6 (CMIP6) models in simulating precipitation within the Amazon River Basin. The study assesses model efficacy in capturing precipitation variability using spatial pattern mapping, Taylor diagram analysis, and empirical orthogonal function analysis. It provides insights crucial for agricultural and hydrological planning.

The second study delves into the adaptation strategies of small-scale farmers in Rondônia, highlighting the transformation in agricultural practices due to changing climate conditions. Through qualitative interviews, it explores how increased temperatures and altered precipitation patterns drive shifts from traditional crops to cattle ranching and milk

production. It emphasizes the need for policy interventions that support sustainable farming and climate resilience.

Lastly, the third paper investigates the climatic impacts of deforestation in unprotected areas of the Amazon. Advanced climate-land surface modeling quantifies temperature, precipitation, and evapotranspiration changes, mapping out the risks to agricultural productivity. This risk mapping integrates climatic, agricultural, demographic, and socioeconomic data to identify heightened-risk municipalities, advocating for more robust conservation measures.

These studies contribute a deeper understanding of the Brazilian Amazon's relationships between climate change and human-environmental systems. The findings underline the importance of integrating scientific research with policymaking to mitigate climate change's impacts and support local communities' sustainability.

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Chapter 1. Introduction

The Brazilian Amazon, a region encompassing roughly 4 million km^2 and home to about 10% of the world's biodiversity, is experiencing unprecedented shifts due to climatic changes and ongoing deforestation. These shifts have potentially transitioned the region into a new ecological and climatic regime, posing significant risks to biodiversity, ecosystem services, and the livelihoods of local communities. Understanding and adapting to these changes is crucial for sustaining and improving the livelihoods of the region's vulnerable populations and is central to Brazil's National Adaptation Plan (NAP) (https://unfccc.int/sites/default/files/resource/Brazil-NAP-English.pdf). Brazil has outlined three main goals, among others, to promote reducing and managing climate-related risk in response to climate change. Their initiatives will prepare natural, human, productive, and infrastructure systems to adapt to a changing climate. A subset of their goals is listed below (**Table 1**) with the corresponding dissertation paper, which could aid in the development and success of that goal.

Table 1 Brazil's National Adaptation Plan selected goals, initiatives, and corresponding dissertation paper.

Goal	Initiative	Paper
Expansion and dissemination of scientific, technical, and traditional knowledge: production, management, and dissemination of climate-risk information	• Enhance the quality of climate projections as inputs for public policy for adaptation • Support for development of tools and generation of knowledge as inputs for climate-change mitigation and adaptation strategies • Expand understanding of interactions among ecological and social systems and of the functioning of the Terrestrial System • Foster generation of inputs for formulation of public policies targeted at mitigation, adaptation, and reduction of vulnerability to climate change	1, 2
Coordination and cooperation among public agencies and society	• Target public: municipal levels, vulnerable communities, general public	2
Identify and propose measures to promote adaptation and reduction of climate risk	• Enhance methods for modelling of climate risk • Regional vulnerability analysis (indices), climate-risk maps (local, regional, and national), classification of the regions of Brazil in terms of climate risk for the main agricultural activities, identify priority areas • Identification of adaptation measures, integrated with development of methods and crops, with a view to increasing agricultural resilience in priority areas	2, 3

This dissertation addresses the urgent need for enhanced climate prediction products, seasonal climate outlooks, and downscaling products to manage climatic extremes such as droughts and heatwaves. With a focus on the Brazilian Amazon, this research aims to improve climate services by advancing climate science, thus laying a foundation for delivering accurate and valuable climate information to end-users. The objectives of this research are to (1) assess the ability of thirteen Coupled Model Intercomparison Phase 6 (CMIP6) models to simulate precipitation in the Amazon River Basin; (2) examine the climatic impacts of deforestation in unprotected areas of the Amazon; and (3) explore the adaptation strategies of small-scale farmers in Rondônia in response to altered climatic conditions. The questions of this research are (1) How well do thirteen CMIP6 models simulate the precipitation regime in the Brazilian Amazon River Basin for a near-historical time period, and which models perform best according to various metrics including spatiotemporal analysis, Taylor skill score, climatology comparison, and EOFs?; (2) What are the climatic impacts of deforestation in unprotected areas of the Amazon on air temperature, precipitation, and evapotranspiration during the dry season, and how do these changes influence risk at the municipal level in Rondônia?; and (3) How are small-scale farmers in Rondônia adapting to altered climatic conditions, and what are the key perceptions, agricultural practices, and adaptive strategies they employ in response to climate change impacts? Each of these studies contributes to our understanding of climate variability and change in the Amazon and serves as crucial input for climate services aimed at improving water and food supply management. The research is designed to provide local insights for climate adaptation policy, supporting Brazil's efforts to prepare its natural, human, productive, and infrastructure systems for a changing climate.

The first objective of assessing the ability of thirteen CMIP6 models to simulate precipitation in the Amazon River Basin is described in Chapter 2 and is titled "Evaluation of the CMIP6 performance in simulating precipitation in the Amazon River Basin". Through spatial pattern mapping, Taylor diagram analysis, and empirical orthogonal function analysis, this study evaluates the models' effectiveness in capturing precipitation variability, providing essential insights for agricultural and hydrological planning. The second objective of exploring the adaptation strategies of small-scale farmers in Rondônia in response to altered climatic conditions is discussed in Chapter 3, titled "Changing climate, changing lives: voices of a Brazilian Amazon farming community in a time of climate crisis". Through qualitative interviews, it investigates the shifts in agricultural practices from traditional crops to cattle ranching and milk production, emphasizing the need for supportive policies that enhance sustainable farming and climate resilience. In Chapter 4, titled "Risk in the Rainforest: Mapping the impact of unprotected Amazon deforestation", an advanced climate-land surface model was used to quantify changes in near-surface air temperature, precipitation, and evapotranspiration, and integrates climatic, agricultural, demographic, and socioeconomic data to map out agricultural risk to climatic changes. Lastly, Chapter 5 provides a comprehensive summary of results, highlights key findings, and offers concluding remarks.

Chapter 2. Evaluation of the CMIP6 performance in simulating precipitation in the Amazon River Basin[1]

2.1 Introduction

The Amazon rainforest provides a wealth of ecosystem goods and services (Foley et al., 2007a), including regulation of climate and water feedbacks (Lima et al., 2014), agricultural and timber goods, hotspot for biodiversity (Dale et al., 1994; Hopkins, 2007), watershed services (Wu et al., 2017a), regulation of rainfall regimes (Martinelli et al., 1996), and climate change regulation by acting as a carbon sink (Chambers et al., 2001). Brazil contains almost 60% of the Amazon rainforest and relies heavily on rainfall, which is produced, in part, by local sources of evapotranspiration from vegetation (Salati & Vose, 1984; Zemp et al., 2014). However changes in climate and land use and land cover change have led to changes in the precipitation regime, which impact socio-economic activities, including natural resources and resource usage (Krol & Bronstert, 2007) and food production (Parry et al., 2004). Unfortunately, due to socio-political and economic reasons (Philip Fearnside, 2017; Hecht, 1985; M. A. Pedlowski et al., 1997a) forests have been cut down and deforested at an unprecedented rate since the 1970s. Land use and land cover change has led to an Amazon basin-wide transition to a disturbance-dominated regime ultimately leading to changes in energy and water cycles (Davidson et al. 2012). In addition, natural fluctuations in climate have created changes in the onset, demise and duration of monsoon system for South

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America (Jones & Carvalho, 2013; E. T. Sena et al., 2018) and drought conditions have intensified (Chaudhari et al., 2019; Erfanian et al., 2017; Jiménez-Muñoz et al., 2016b) with dry events projected to increase in the future (Duffy et al., 2015). Based on these findings, the Brazilian Amazon is a region where the precipitation regime is important to study and simulate properly as moisture and rainfall play a large role in maintaining proper climate regulations.

Global Climate Models (GCMs) are numerical simulations useful to understand past, present, and future patterns, changes, and trends in rainfall. The Coupled Model Intercopmarison Project Phase 6 (CMIP6) represents the most up to date climate modeling data for these types of studies. CMIP6 is organized by the World Climate Research Programme (WCRP) and runs sets of experiments to produce historical, present, and future scenarios for the global climate modeling community (more information about WCRP CMIP can be found at https://www.wcrp-climate.org/wgcm-cmip). This research used the most recent climate model data CMIP6 (Eyring et al., 2016), which contains a historical simulation of the recent past used in modeling evaluation based on a previous phase version CMIP5 (Taylor et al., 2012). These models have capabilities to solve complex processes, including model response to different forcing, land use change, geo-engineering, an updated set of Shared Socioeconomic Pathways (SSPs) for future analysis, and advanced schematic options for clouds, circulation, regional phenomena, ocean, land, and ice. Studies have found that CMIP6 models have improved on CMIP5 simulations for climate extremes and their trend patterns (H. Chen et al., 2020), monsoon rainfall representation (Gusain et al., 2020), mean precipitation at seasonal to interannual timescales (Zamani et al., 2020), and extreme precipitation in the wet season (C. A. Chen et al., 2021). Although CMIP6 models improved some aspects, compared to CMIP5, improving biases and correcting deficiencies in simulating the precipitation regime and occurrence are still necessary (C. A. Chen et al., 2021; Li et al., 2019).

Past research on South America has concluded that CMIP models simulate rainfall variability and trends well (Alves et al., 2020; Lovino et al., 2018; Rivera & Arnould, 2020). Although models are shown to reproduce the observed climatology for historical periods, there are still systematic errors (dry biases) when models simulate precipitation variability for the Amazon (Alves et al., 2020; Gulizia & Camilloni, 2015). In addition, rainfall variations simulated by CMIP5 show that Amazon rainfall responds to sea surface temperature changes due to the modulation of the Intertropical Convergence Zone (ITCZ) (Villamayor et al., 2018). (Barreto et al., 2020) shows that 9 CMIP5 models could capture the dominant mode of rainfall variability obtained from the principal component analysis, although models had difficulty simulating the spatiotemporal patterns of regional precipitation. Research also shows that subsets of CMIP models perform better than individual models (Babaousmail et al., 2021; Gulizia & Camilloni, 2015; Lovino et al., 2018; Rivera & Arnould, 2020), although single GCMs perform better in certain evaluation criteria (Gulizia & Camilloni, 2015). Although studies have focused on past CMIP phases for the entire continent of South America or regions within, this paper expands on past analysis and uses the most current phase of CMIP, phase 6, and additional evaluation metrics, like Empirical Orthogonal Function (EOF) analysis. Also, the Brazilian Amazon represents an important region to study to maintain water, food, and energy security, as rainfall plays a role in these functions.

This study is designed to evaluate the ability of 13 CMIP6 models to simulate the seasonal precipitation regime of the Legal Brazilian Amazon near-historical time period from 1981 to 2014 and answers the question: How well do thirteen CMIP6 models simulate the precipitation regime in the Brazilian Amazon River Basin, and which models perform best according to various metrics including spatiotemporal analysis, Taylor skill score, climatology comparison, and EOFs for 1981 - 2014? Performance is determined by multiple metrics, including spatiotemporal analysis, Taylor skill score, climatology comparison, and EOFs. The best-performing models are identified based on each criterion, and these can be used to examine historical, past, and future patterns in precipitation. This study is structured as follows: Section 2 describes the driving climate mechanisms of the study area, the observational datasets, CMIP6 models, and the evaluation methodology. Section 3 covers the results and discusses the performance of models, as well as their deficiencies. Section 4 outlines the main conclusions and takeaways from the analysis. This paper creates a baseline for future work to be carried out using a subset of the 13 CMIP6 models to simulate the precipitation regime for a region that relies heavily on rainfall for many ecosystem, agricultural, and daily functions. This study represents the first precipitation regime evaluation of these CMIP6 models for the Brazilian Amazon.

2.1.1 Study Area

The Brazilian Amazon (**Fig. 1**) is the portion of Brazil that encompasses the Amazon Rainforest, two-thirds of which lies in Brazil. The Brazilian Amazon contains mainly Zone A tropical climates: Af (tropical rainforest without a dry season), Am (tropical monsoon), Aw (tropical savanna with a dry winter), and the very eastern portion of the Brazilian Amazon contains As (tropical savanna with a dry summer) and BSh (semi-arid, low latitude and altitude). This region is important for carbon and oxygen cycles, moisture dynamics, natural resources, species diversity, and many more ecosystem services (Foley et al., 2007a). But, this region has been heavily deforested since the 1900s with some states losing close to 40,000 km^2 or 42% of their entire forest composition since 2008 (F. G. Assis et al., 2019). Most of the deforestation is due to cropland creation or other agriculture practices and has significant implications for changes in the precipitation regime (Bonini et al., 2014; Butt et al., 2011; Khanna et al., 2017; de Oliveira et al., 2019). In general, clearing forests leads to the drying of the region, which results in less evapotranspiration and higher temperatures. However, the results are still uncertain for many areas of the Brazilian Amazon. Therefore, it is very important to understand the historical precipitation regime and to evaluate climate model capabilities to simulate the rainfall patterns for this region. In addition to a domain-wide analysis, this study will analyze a split domain for the Brazilian Amazon, focusing on the northern (NAZ) and southern (SAZ) Amazon. These regions have well-identified seasonal precipitation cycles and consist of similar climate structures, and have been used in other regional analyses of South America (Alves et al., 2020; Nobre et al., 2016).

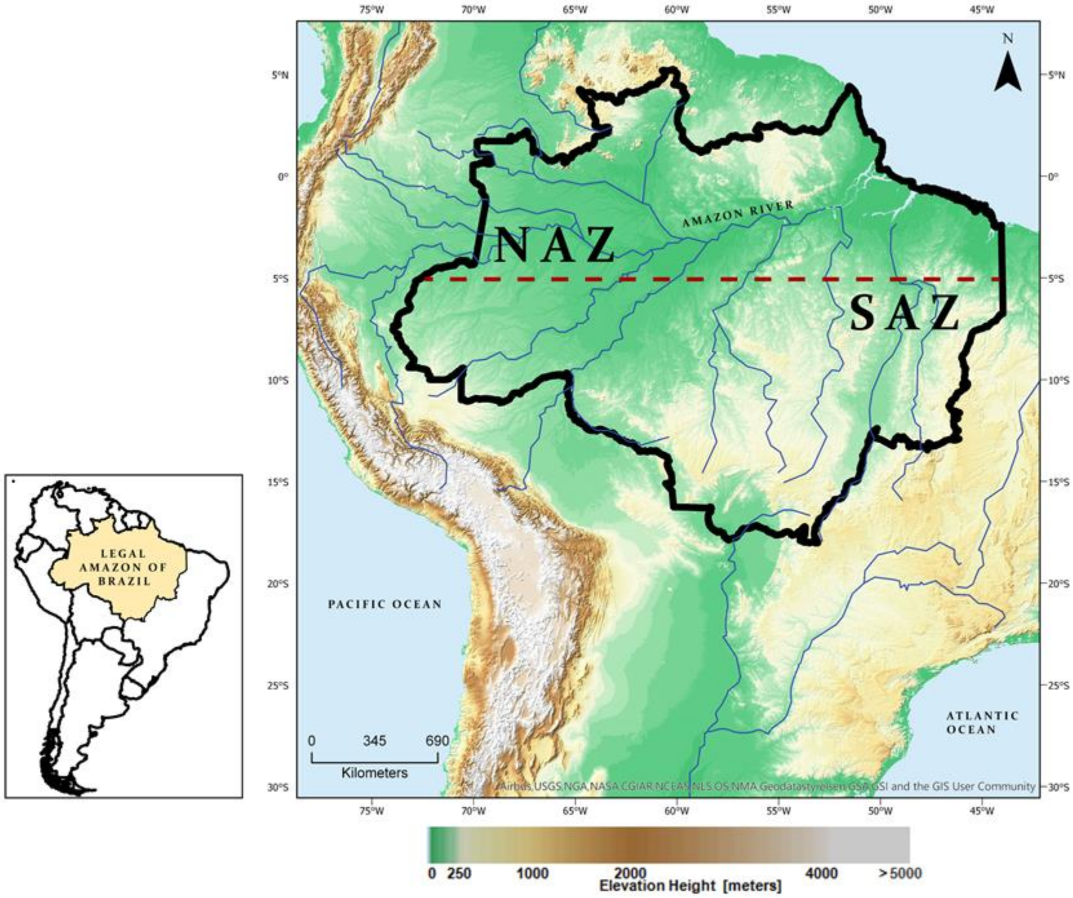

Fig. 1 Brazilian Amazon study area with red dotted line indicating a split domain for further analysis. Northern Brazilian Amazon (NAZ) and Southern Brazilian Amazon (SAZ).

2.2 Data and Methods

2.2.1 Observational datasets

Three observational datasets will be used to evaluate CMIP6 model results. The primary dataset will be the Climate Hazards Group Infrared with Station data (CHIRPS), which contains 35 years of quasi-rainfall data that combines satellite imagery and station data to create a rainfall time series (Funk et al., 2015). The second will be the University of Delaware (UDEL), which contains long-term datasets from 1900 using station data of monthly total rain gauge-measured precipitation (Willmott & Matsuura, 2001). The third is CPC Merged Analysis of Precipitation (CMAP), which contains five kinds of satellite estimates (GPI, OPI, SSM/I scattering, SSM/I emission, and MSU) and rain gauge data (Xie & Arkin, 1997). In addition, Global Land Data Assimilation System (GLDAS) precipitation and evapotranspiration (ET) and 20th Century Reanalysis v2C (20cRv2C) surface pressure, specific humidity, meridional and zonal wind data are used to analyze moisture flux convergence (MFC) ratio (precipitation/ET) and MFC biases. GLDAS relies on satellite and ground-based observational products and produces land surface states and flux datasets from land surface modeling and data assimilation. 20cRv2C relies on a combination of observations rerun with the National Center for Environmental Protection Global Forecast System 2008ex model with 28 pressure levels and updated physical parameterizations (G. P. Compo et al., 2011; Gilbert P. Compo et al., 2006; Giese et al., 2016; Hersbach et al., 2020a; Hirahara et al., 2014; Reynolds et al., 2007; Whitaker et al., 2004). All datasets were used for model evaluation comparison and contain data from 1981-2014. CHIRPS is used when only one observational dataset is needed for evaluation because it represents one of the best rain gauge substitutes for precipitation datasets (Paredes-Trejo et al., 2017).

2.2.2 CMIP6 models

(Eyring et al., 2016) provides a thorough overview of the Coupled Model Intercomparison Phase 6 (CMIP6) models and addresses the experimental design and organization of all experiments and simulations. The models represent the climate science community's most up-to-date climate model simulations. Eyring et al. (2016) concluded that the results from the CMIP6 experiments will represent the best global representation of past and future climate and lead to many significant advances to climate science and the science community at large.

This study uses a subset of 13 CMIP6 models to evaluate the representation of the historical Brazilian Amazon precipitation regime for 1981-2014. Model types include atmosphere-ocean general circulation models (AOGCM) with additional model components, such as aerosols (AER), chemistry (CHEM), and biogeochemistry (BGC). **Table 2** presents the 13 models, their type, corresponding institution, location, and reference. The historical experiment was used for evaluating precipitation evaluation, as this experiment is traditionally used when compared to observational datasets (Rivera & Arnould, 2020). A total of 3 members from each model were selected to create an ensemble mean used in this evaluation. SAM0UNICON was the exception and only contained one member used as the mean for this model. All models were regridded to 0.25° x 0.25° using bilinear interpolation to keep datasets consistent. This method has been used for model evaluation in South America in multiple studies (Rivera & Arnould, 2020; Zazulie et al., 2017). It has been found that using other methods, like nearest-neighbor, did not significantly improve the results (Rivera and Arnould, 2020).

Table 2. GCMs used in the evaluation include type, institution (location), and corresponding reference.

Model Name	Type	Institution (Location) and reference
BCCCSM2MR	AOGCM	Beijing Climate Center (China) (Wu *et al.*, 2019)
BCCESM1	AOGCM AER CHEM	Beijing Climate Center (China) (Wu *et al.*, 2019)
CanESM5	AOGCM	Canadian Center for Climate Modeling and Analysis (Canada) (Swart *et al.*, 2019)
CESM2	AOGCM BGC	National Center for Atmospheric Research (NCAR) (United States) (Gettelman *et al.*, 2019)
CESM2WACCM	AOGCM BGC	National Center for Atmospheric Research (NCAR) (United States) (Gettelman *et al.*, 2019)
E3SM10	AOGCM AER	Lawrence Livermore National Laboratory (LLNL) (United States) (Golaz *et al.*, 2019)
ECEarth3	AOGCM	EC-Earth Consortium (Europe) (Doblas-Reyes *et al.*, (2018)
ECEarth3Veg	AOGCM	EC-Earth Consortium (Europe) (Doblas-Reyes *et al.*, (2018)
GISSE21G	AOGCM	Goddard Institute for Space Studies (NASA-GISS) (United States) (Kelley *et al.*, 2020)
GISSE21H	AOGCM	Goddard Institute for Space Studies (NASA-GISS) (United States) (Kelley *et al.*, 2020)
MIROC6	AOGCM AER	Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Japan) (Tatebe *et al.*, 2019)
MRIESM20	AOGCM AER CHEM	Meteorological Research Institute (Japan) (Yukimoto *et al.*, 2019)
SAM0UNICON	AOGCM AER BGC	Seoul National University (South Korea) (Park *et al.*, 2019)

2.2.3 Evaluation methodology

To evaluate the ability of CMIP6 models to simulate the historical precipitation regime for the Brazilian Amazon, results were compared to observations for the period 1981-2014. We selected this period because it incorporates recent updates in the Global

Telecommunications System and recent satellite-derived improvements in data collection. To evaluate annual cycles, we used the following statistical metrics: root mean square error (RMSE), bias, and the spatial and temporal Pearson relation coefficient. Both the monthly averages and anomalies of precipitation were evaluated. A Taylor diagram (Taylor, 2001) was produced for the entire Brazilian Amazon to give an overall idea of model performance for the region.

In addition to the model performance comparison, we performed EOF analysis to characterize the precipitation intraseasonal variability of the 13 CMIP6 models. To quantify the EOF eigenvector sampling error, we used the method described in (North et al., 1982). Finally, the Taylor Skill Score (Xia *et al.*, 2015 and Taylor (2001) was used to give an overview of model performance (Eqn.1). where S is the skill score, R is the correlation between the simulated and reference datasets, R_0 is the theoretical maximum correlation (assumed to be 1), and σ is the standard deviation of the simulated dataset.

$$S=4(1+R)/[\sigma+(1/\sigma)]^2 (1+R_0) \qquad (1)$$

2.3 Results

2.3.1 Domain analysis

Spatial monthly mean averages for the entire year for the three observational datasets and all 13 GCMs from 1981-2014 are shown in **Fig. 2**, while standard deviation is presented in mm/day to illustrate daily differences in precipitation; seasonal differences are not accounted for in these figures but are analyzed in the section 2.3.2. Observed rainfall shows wetter conditions in the northeast and northwest along the equatorial latitude and dry conditions in the southern and eastern sections of the domain. The mean values for the entire Brazilian

Amazon range from 50 mm/month to over 250 mm/month for the observed datasets. Most models display a much drier condition in the north and northeast portion of the study region with monthly averages below 60 mm/month, except MRIESM20 and SAM0UNICON. MIROC6 and MRIESM20 appear to overestimate precipitation patterns west of 55°W and north of 10°S with averages of 250 or more mm/month, while observation shows monthly values closer to 150-200 mm/month. CanESM5 shows the driest northern bias compared to observation, with much of the northeastern portion showing around 50 mm/month values. GISSE21G and GISSE21H show scattered dry biases throughout the entire domain, especially in the southern region, with values closer to 50 mm/month than 100-150 mm/month in the observed domain. The ensemble means, and SAM0UNICON show the best spatial representation of precipitation with no large dry biases and a uniform precipitation state throughout the study domain. However, the ensemble mean has a dry bias in the north due to most models underestimating precipitation here.

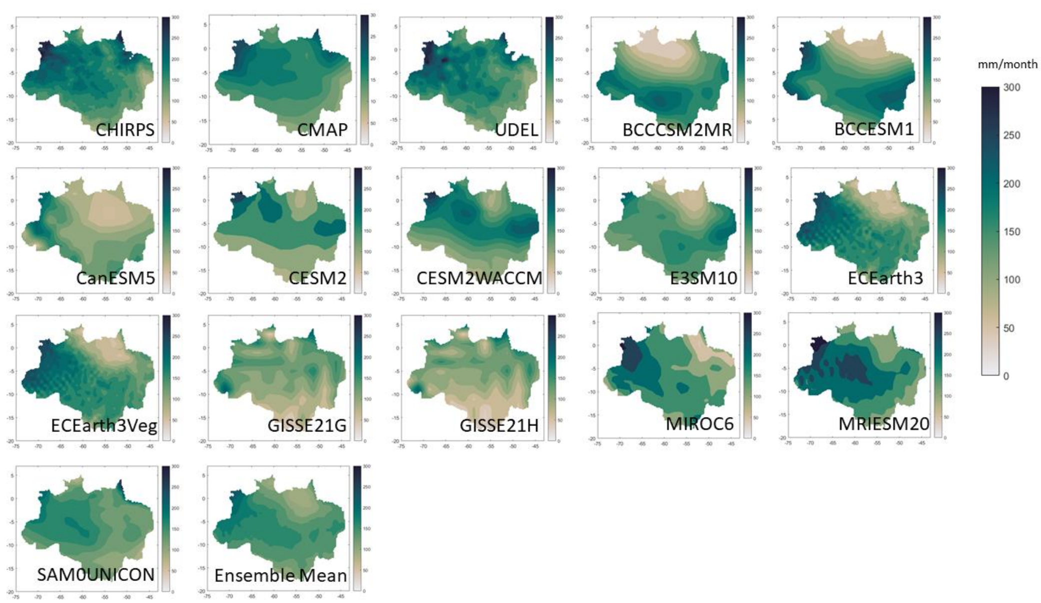

Fig. 2 1981-2014 mean monthly precipitation for observation and GCMs [mm/month].

The monthly standard deviation for each dataset is shown in Fig. 3 in mm day-1 for 1981-2014 to test for model performance of precipitation variability. CHIRPS and UDEL show very similar spatial characteristics with higher variability in the southern and northeastern portions of the study domain of up to 8 mm day-1. In comparison, CMAP shows less variability overall of a few mm. Models that show lower variability in the northern Brazilian Amazon include BCCCSM2MR, BCCESM1, E3SM10, ECEarth3, ECEarth3Veg, GISSE21G, GISSE21H, and MIROC6. BCCCSM2MR, E3SM10, MIROC6, and MRIESM20 show higher variability by 3-4 mm day-1 in the southern portion of the domain. Models that show higher variability in the eastern region, along the coastal portions of the domain, include BCCESM1, CESM2, CESM2WACCM, E3SM10, MRIESM20, and the ensemble mean. Again, based on spatial mean analysis of the entire period, SAM0UNICON and the ensemble mean produced the best representation of the mean monthly precipitation standard deviation.

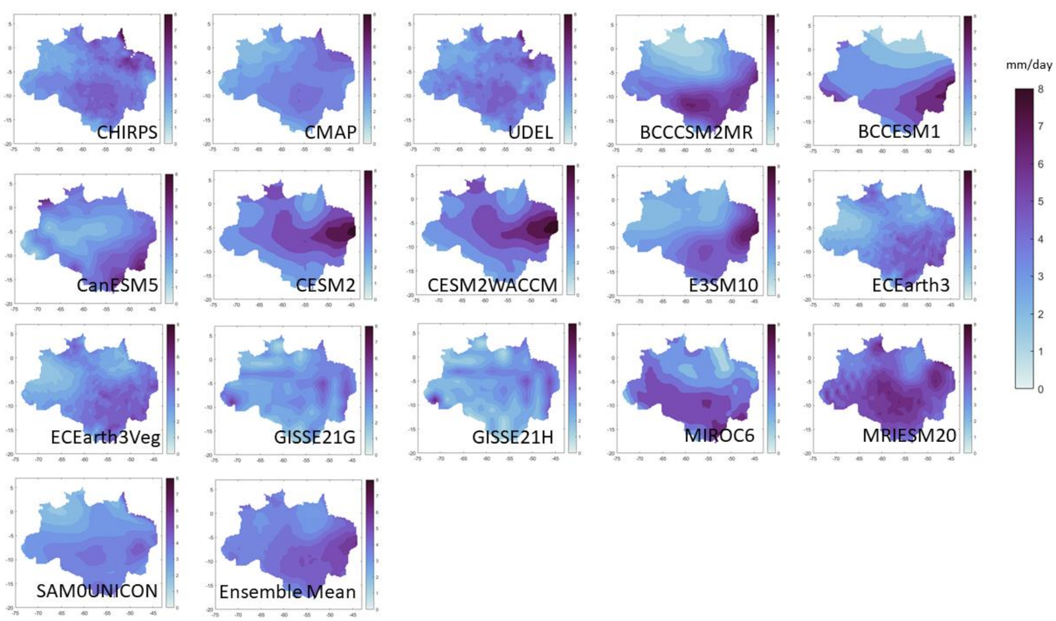

Fig. 3 1981-2014 monthly precipitation standard deviation for observation and GCMs [mm day-1].

Taylor diagrams provide information on the normalized standard deviation and centered root mean square, along with the correlation coefficient of the spatial aver-aged time for all models and observational datasets for the entire Brazilian Amazon (**Fig. 4**). This analysis allows for a general comparison of all datasets for the whole study domain. The reference observation dataset used in this analysis is CHIRPS. In general, models and the two additional observational datasets performed adequately compared to CHIRPS. All models had a correlation coefficient above 0.8 and had a standard deviation between 0.5 and 1.5 mm day-1. The best performance was the ensemble mean, with SAM0UNICON, GISSE21G, and E3SM10 close to the reference dataset. From this diagram, the models that overestimated monthly averages of daily means for this time period are MIROC6, CESM2, CES2WACCM, and MRIESM20. Models that underestimated domain average precipitation are the ensemble mean, GISSE21G, SAM0UNICON, E3SM10, GISSE21H, BCCCSM2MR, CanESM5, ECEarth3Veg, ECEarth3, and BCCESM1. Models with a high correlation of around 0.92 but a high standard deviation of about 1.3 mm day-1 are CESM2, CESM2WACCM, and MRIESM20. The model with the highest correlation coefficient is the ensemble mean with a value of 0.93, and the model with the lowest value is BCCESM1 at 0.82. The ensemble mean performed best for the entire Brazilian Amazon.

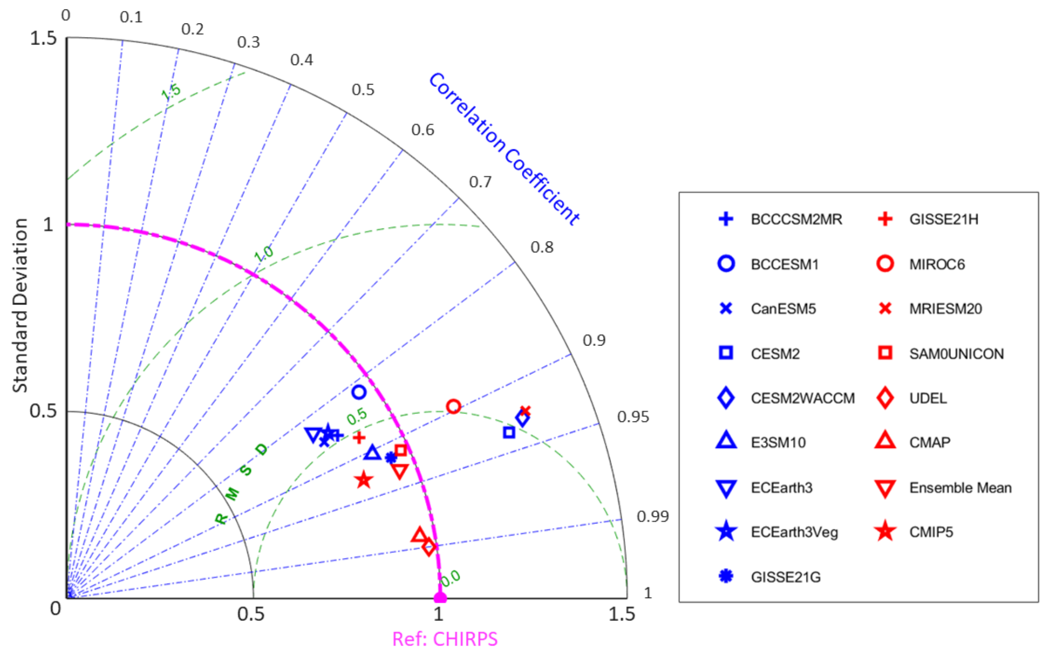

Fig. 4 Taylor diagram of daily precipitation for the Brazilian Amazon from 1981-2014 [mm day-1]. CHIRPS is the reference dataset and symbols indicate models, observation, and ensemble mean. Results have been normalized to CHIRPS standard deviation.

2.3.2 Northern (NAZ) and Southern (SAZ) Amazon regions

The climate of the Brazilian Amazon is characterized by a monsoonal regime with a marked dry and wet season cycle. SAZ has a much more defined dry and wet season when compared to NAZ (**Fig. 5**), with model results following the dry and wet trends of the observed cycle. SAZ has a dry season in JJA and a wet season in DJF, while NAZ has a dry season in ASO and a wet season in MAM, according to the observed datasets. For NAZ, models tend to overestimate precipitation during the dry season and underestimate during the wet season, except for CESM2, CanESM5, MRIESM20, CESM2WACCM, and MIROC6, which overestimate during the later portion of the wet season. Ensemble mean for NAZ performs best during AMJJAS but still overestimates the dry season and underestimates the beginning of the wet season. For SAZ, models could capture the wet and dry seasons with higher accuracy. However, the deviation from the mean is higher for this region, with anomalies above 6 mm day-1 for both the dry and wet seasons. Most models underestimate dry season precipitation for SAZ by about 1 mm day-1, except for GISSE21G, GISSE21H, and CanESM5, which overestimate dry season precipitation. Models tend to produce too much rainfall at the start of the wet season and have both over and underestimates during the peak of the wet season. Observations for NAZ show a range of around 6 to 7 mm day-1 and 9 mm day-1 for SAZ over the annual climatology. Individual models show greater range, but the ensemble mean range for NAZ is 5 mm day-1 and 8 mm day-1 for SAZ, which is much closer to observations than individual model climatologies. The ensemble performed very well for this region and only seems to underestimate precipitation in SO and overestimate during December. Overall, models captured the dry and wet season cycles, although the performance was more accurate for the SAZ compared to NAZ climatology.

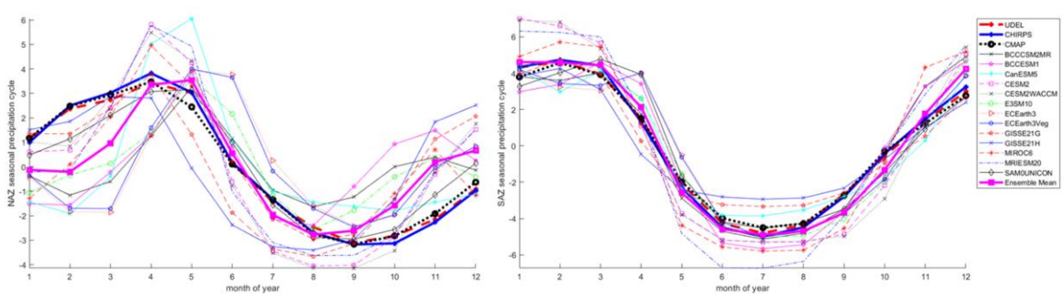

Fig. 5 Annual cycle of anomalies for Northern Amazon (left) and Southern Amazon (right) precipitation for 1981-2014 [mm day-1].

Cumulative distribution function (CDF) results in **Fig. 6** are used to identify whether models can capture extreme precipitation (minimum and maximum features in the CDF). In general, models underestimate NAZ precipitation, especially BCCCSM2MR and

MRIESM20. Ensemble mean captures NAZ minimum precipitation values well and exhibits clustering effects around 3 to 4 mm day−1 and 6 to 8 mm day−1 but does not capture maximum precipitation. The models that capture NAZ maximum precipitation are CanESM5, CESM2, CESM2WACCM, GISSE21G. GISSE21H overestimates NAZ maximum precipitation. Models capture SAZ minimum precipitation well because SAZ is drier and contains many observations of no rainfall. Therefore, models capture the minimum value of observations well. Most models underestimate SAZ precipitation up to a threshold of 5 mm day−1 but then diverge after this value and exhibit over- and under-estimating higher precipitation observations. The ensemble mean performs relatively well, although clustering effects occur more often for SAZ than NAZ. Models over- and under-estimate maximum precipitation with BCCESM1, BCCCSM2MR, ECEarth3Veg, and E3SM10 capture the right tail best. CESM2, CESM2WACCM, MRIESM20, and MIROC6 all overestimate SAZ maximum precipitation. MRIESM20 follows the distribution of NAZ best, despite its overestimation of extreme precipitation, while ECEarth3Veg follows the distribution of SAZ best, although it overestimates precipitation values from 5 to 8 mm day−1. Ensemble mean follows the distribution of SAZ better than NAZ, although it exhibits clustering effects.

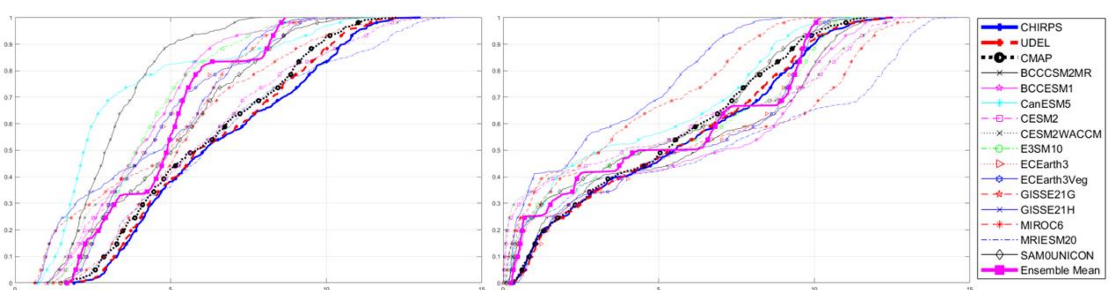

Fig. 6 Cumulative distribution for northern Amazon (NAZ—(left) panel) and southern Amazon (SAZ—(right) panel) precipitation for 1981–2014 [mm day−1].

RMSE-bias and RMSE-correlation coefficient diagrams further illustrate the relationship between these performance metrics for the models (**Fig. 7**). For NAZ domain, MRIESM20, CESM2, CESM2WACCM, MIROC6, and SAM0UNICON performed the best with an approximate RMSE of 2.25 mm day-1, a bias ranging from -1.5 - 0.2, and an approximate correlation coefficient of 0.75. For SAZ, the best-performing models were the Ensemble Mean, BCCCSM2MR, E3SM10, ECEarth3, ECEarth3Veg, BCCESM1, CESM2, CESM2WACCM, MIROC6, and SAM0UNICON. CESM2, CESM2WACCM, MIROC6, and SAM0UNICON were also some of the best-performing models for NAZ. The top five performing models for SAZ had an approximate RMSE of 1.27 mm day-1, a bias ranging from -0.36 - 0.34, and a correlation coefficient of 0.95. The models had a larger RMSE for NAZ with the largest RMSE error +1.4 mm day-1 greater than the largest RMSE for SAZ. In addition, biases for both NAZ and SAZ showed a similar range, with biases ranging from 3.5 mm day-1. Errors were larger for NAZ, as models tended to underestimate precipitation here. The agreement was not as unanimous for SAZ, as models tended to overestimate and underestimate precipitation. Overall, the top models include CESM2, CESM2WACCM, MIROC6, SAM0UNICON, BCCCSM2MR, E3SM10, BCCESM1, ECEarth3, ECEarth3veg, and the Ensemble Mean. Although BCCCSM2MR, E3SM10, BCCESM1, ECEarth3, and ECEarth3Veg did not perform as well for NAZ.

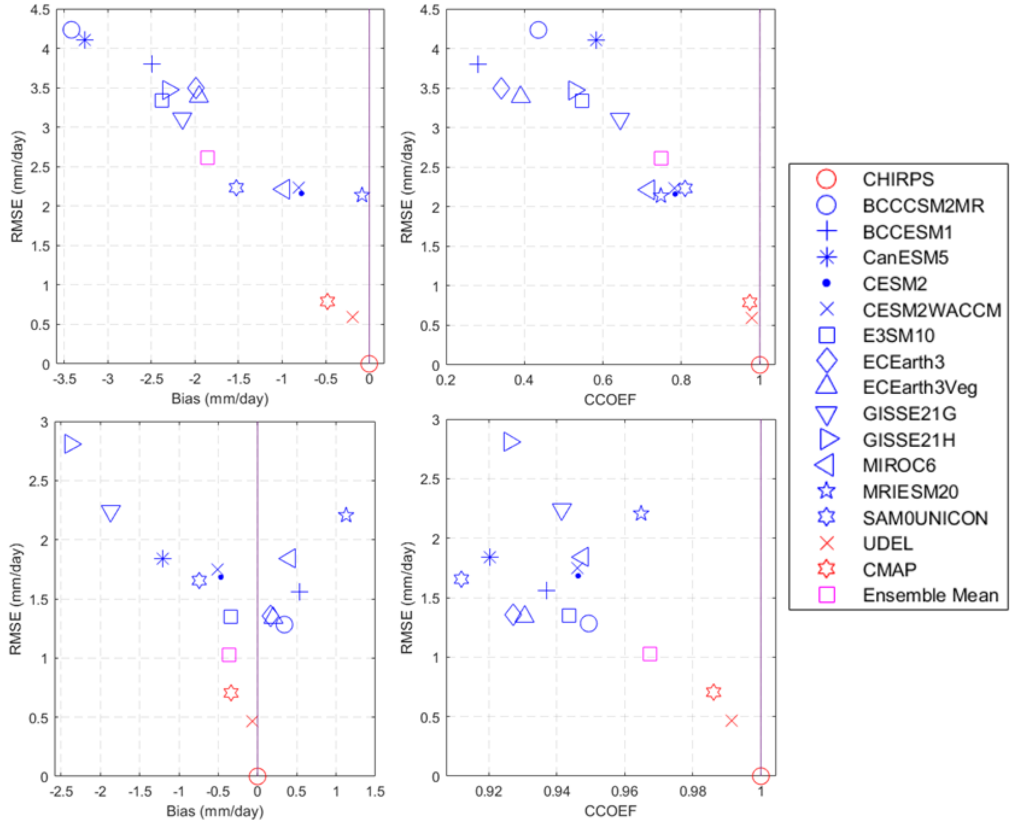

Fig. 7 RMSE versus bias (left) and RMSE versus correlation coefficient (right) for 1981-2014 [mm day-1] for Northern Amazon (top panels) and Southern Amazon (bottom panels).

2.3.3 EOF analysis

To compare with past research that has analyzed the main modes of annual precipitation variability for this region, we used EOF analysis by removing the mean (not the seasonal cycle). We computed the EOFs using MATLAB to process the 1981-2014 monthly data. Only the two first modes of EOF analysis are described in this section, as together, they explain over 67% of the precipitation variability (**Fig. 8** and **9**). The explained variance was calculated by projecting the original data onto the EOFs, transposing and multiplying the result, extracting the diagonal elements, and normalizing them to sum to one or 100%.

The first EOF (**Fig. 8**) explains approximately 52.9% within observational datasets and around 68% for CMIP6 models and follows a temporal pattern similar to the annual precipitation cycle, with a dry season around JJA and a wet season mainly in the months of DJF. There is a dipole nature to this eigenvector around the equator for the 0 value of the eigenvector, and it represents how these two regions of South America differ in terms of the temporal evolution of the SAMS. The SAMS is largely responsible for the annual cycle of precipitation. The SAMS' temporal structure is confirmed from the EOF time coefficient, or the principal component (PC) time series (Fig. 10). Overall, models capture this mode of variability well. However, some models overestimate the precipitation over the Andes mountains on the western coast of South America. In addition, models place too high of an explanation (%) onto this first eigenvector, up to +19.8% for MIROC6 and +26% for the ensemble mean. The higher percentage of variability captured by the first EOF in the models indicates that they place too much emphasis on the dominant mode of variability, suggesting a bias towards this mode and potentially oversimplifying the complexity of precipitation patterns.

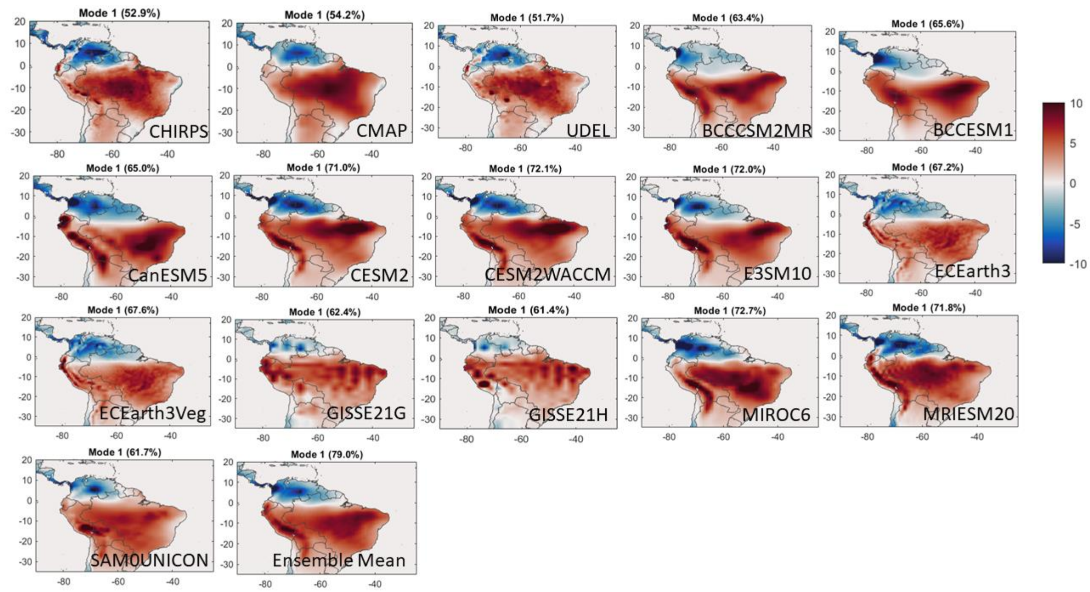

Fig. 8 EOF one for each dataset (1981-2014) with long-term mean removed.

The second EOF (**Fig. 9**) explains approximately 14.4% within observational datasets and around 12% for CMIP6 models and most likely follows the pattern of a transition between the SAMS and the North American Monsoon System (NAMS) (Arias and Fu, 2010). There is a tripole nature to this eigenvector with an out-of-phase band around -8° to 8° of latitude for the positive values and represents how these two regions of South America differ regarding the temporal evolution of the SAMS. The SAMS originates in the southeast portion of South America over the mountainous region of the Brazilian Highlands. It moves northward over South America, bringing precipitation as it travels to North America. During austral winter (JJA), the ITCZ is dominant, with most precipitation in the northern region of South America and Brazil. This is the spatial pattern we are seeing in this second EOF. The PC time series shows a delay in the onset of the wet season for this eigenvector, with observations showing its onset around April and May and models showing a similar pattern, except BCCESM1 and GISSE11H. This delay signals SAMS's time evolution across Brazil's vast land area. Models seem to capture the tripole nature of the transitional SAMS, excluding BCCSM2MR, BCCESM1, and GISSE21H. Models are more accurate in placing the correct explanation (%) for this mode. CESM2, CESM2WAACCM, GISSE21G, MIROC6, MRIESM20, SAM0UNICON, and the ensemble mean captured the second eigenvector most accurately. It is also important to note that the second EOF may be related to the South Atlantic Convergence Zone (SACZ), but we did not evaluate the oceanic component for EOF analysis, so we cannot explore this modality further.

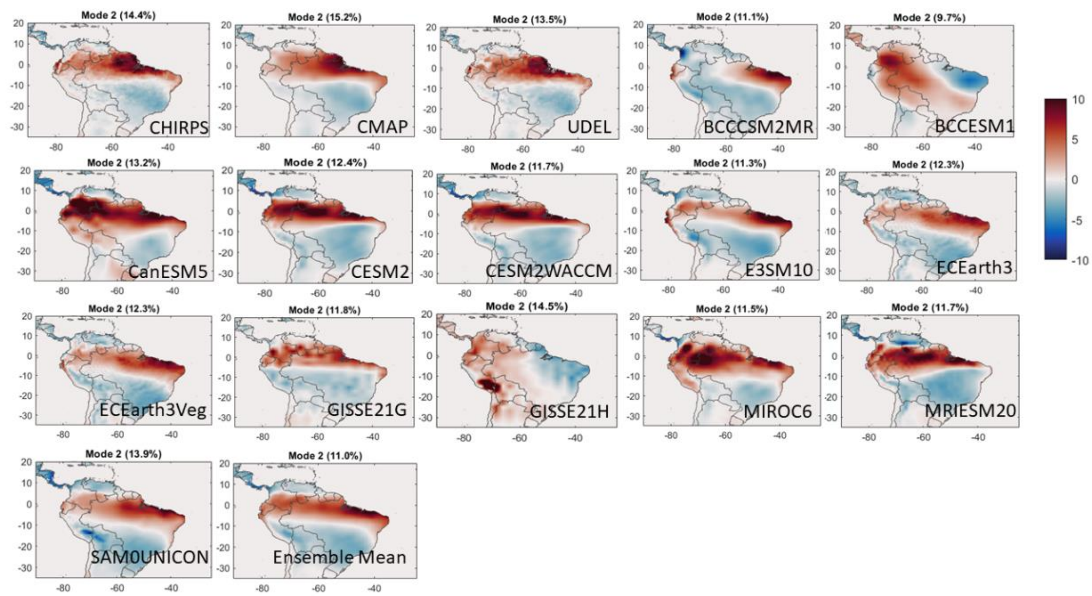

Fig. 9 EOF two for each dataset (1981-2014) with long-term mean removed.

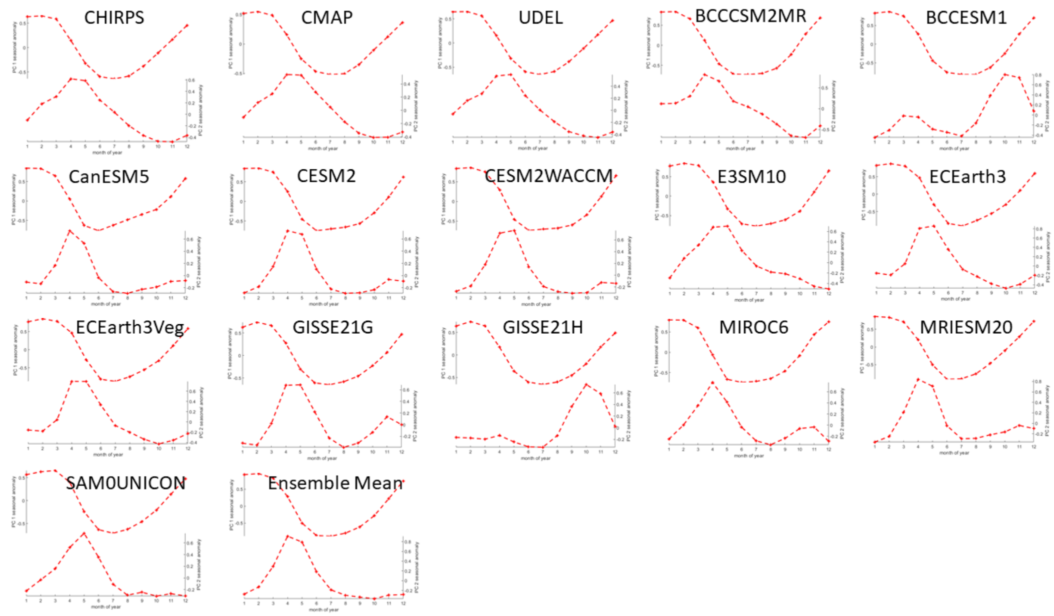

Fig. 10 EOF time coefficient of first two modes for each dataset.

Overall, models captured the seasonal cycle and dipole nature of SAMS. However, the variance explained by models was much higher than observation, up to +26% for the ensemble mean (**Fig. 11**). On average, EOF 1 1 explained 52.9%, while eigenvector 2 explained 9.3% of the variability. Models had a combined eigenvector 1 explanation of 67.2% (14.3% higher than observation) and 12.1% explanation for eigenvector 2 (2.8% higher than observation). Models diverge more concerning the progression of the second EOF's time coefficient (PC). Although some models, like CESM2, CESM2WAACCM, GISSE21G, MIROC6, MRIESM20, SAM0UNICON, and the ensemble mean, could simulate the mapped eigenvector well.

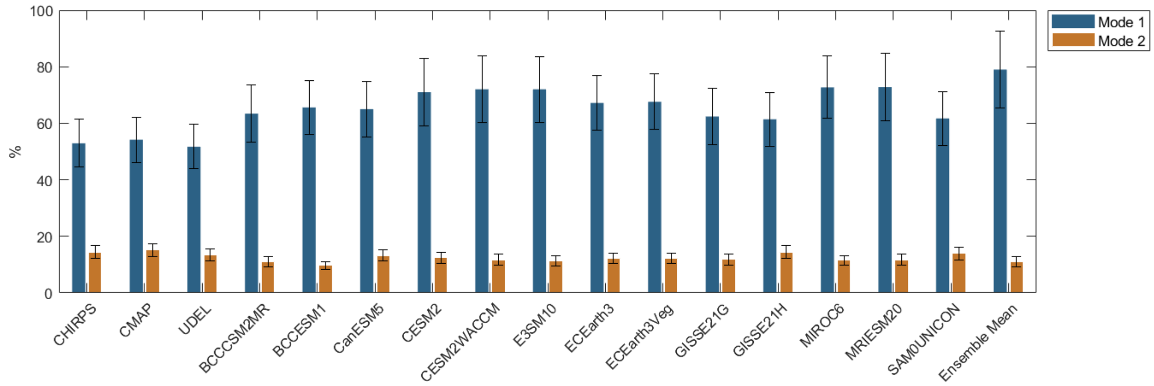

Fig. 11 Explained variance of eigenvalue with sampling error bars.

2.3.4 Taylor skill score and ranking

To evaluate overall model effectiveness, the Taylor skill score was calculated for all GCMs and the ensemble mean for both NAZ and SAZ (**Fig. 12**). Overall, models performed best in SAZ compared to NAZ. All models for SAZ scored 0.87 or better, and the highest score was the ensemble mean with a score of 0.98. The top models for SAZ, according to Taylor skill score, are ECEarthVeg (0.97), BCCCSM2MR (0.97), CanESM5 (0.96), E3SM10 (0.96), E3SM10 (0.96), and SAM0UNICON (0.96). Performance was lower for NAZ, with the scores ranging from 0.47 to 0.88. The models that scored higher skill score for NAZ include SAM0UNICON (0.88), CESM2 (0.87), CESM2WACCM (0.86), MRIESM20 (0.86), and MIROC6 (0.85). The ensemble mean score for NAZ is 0.79 and performed 7th best. When both domains are considered, the top models are CESM2, CESM2WACCM, MIROC6, MRIESM20, and SAM0UNICON. When users take this into consideration, model ensembles can be constructed based on the highest-performing GCMs for this region.

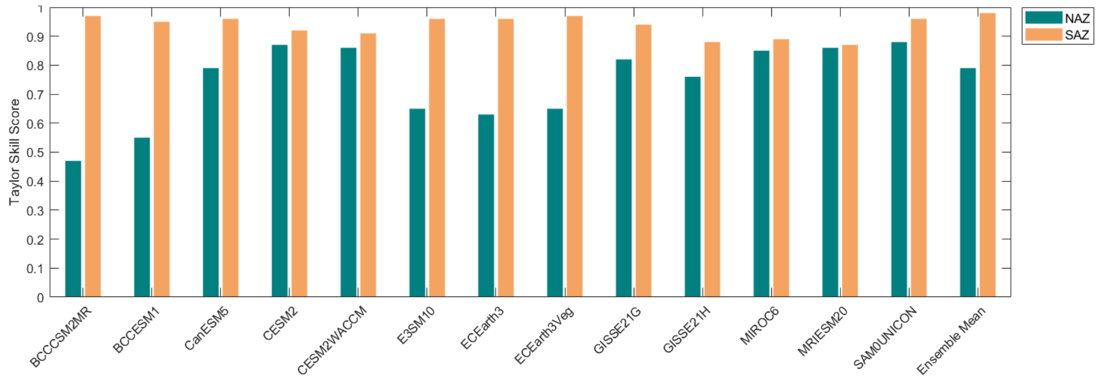

Fig. 12 Taylor skill score for NAZ (green) and SAZ (orange) for all GCMs compared to CHIRPS observational precipitation for 1981-2014.

2.3.5 Moisture source ratio analysis

To explore GCM performances, we use moisture source ratio analysis to investigate how CMIP6 models partition the source of rainfall moisture between surface source (evapotranspiration) and atmospheric source (moisture flux convergence (MFC)) for both northern and southern subdomains (**Fig. 13**). Observations show that NAZ ET/PR ratio is lower than SAZ by an average of 0.11. Therefore, there were greater amounts of moisture from precipitation compared to ET values compared to SAZ. SAZ showed a greater source of ET than NAZ, as the ratio values are larger. Models show a higher mean of 0.21 for NAZ and 0.01 for SAZ. Models were better at capturing the SAZ partition of precipitation sources between the surface and atmosphere for 1981-2014.

For NAZ, the top performing models (based on the difference in ratio from the average of GLDAS and 20cRv2C ratio values) are CESM2 (0.05), CESM2WACCM (0.05), MIROC6 (0.14), MRIESM20 (0.14), ECEarth3 (0.17), and ECEarth3Veg (0.16). For SAZ, the top performing models (based on the difference in ratio from the average of GLDAS and 20cRv2C ratio values) are CESM2 (-0.02), CESM2WACCM (-0.02), E3SM10 (-0.02), ECEarth3 (-

0.02), and ECEarth3Veg (-0.02), MRIESM20 (0.00), the ensemble mean (0.01) and MIROC6 (0.03). Models have been shown to underestimate PR (Fig. 13). This analysis reveals that models generally exhibit positive biases, resulting in ET/PR ratios larger than GLDAS and 20cRv2C. Despite generally higher values of simulated ET, the models might not produce enough moisture from convergence flux to simulate PR accurately, resulting in low PR compared to CHIRPS, CMAP, and UDEL. This is not the only research that has found that models tend to underestimate PR, as other studies have shown that CMIP models tend to underestimate precipitation in this region (Gulizia & Camilloni, 2015). More work needs to be completed to analyze the physical mechanisms and schemes within each model that produce the biases in precipitation, ET, and MFC, which is beyond the scope of this paper. Understanding the underlying physics of each GCM is an important component of model evaluation, which individual modeling teams can contribute towards.

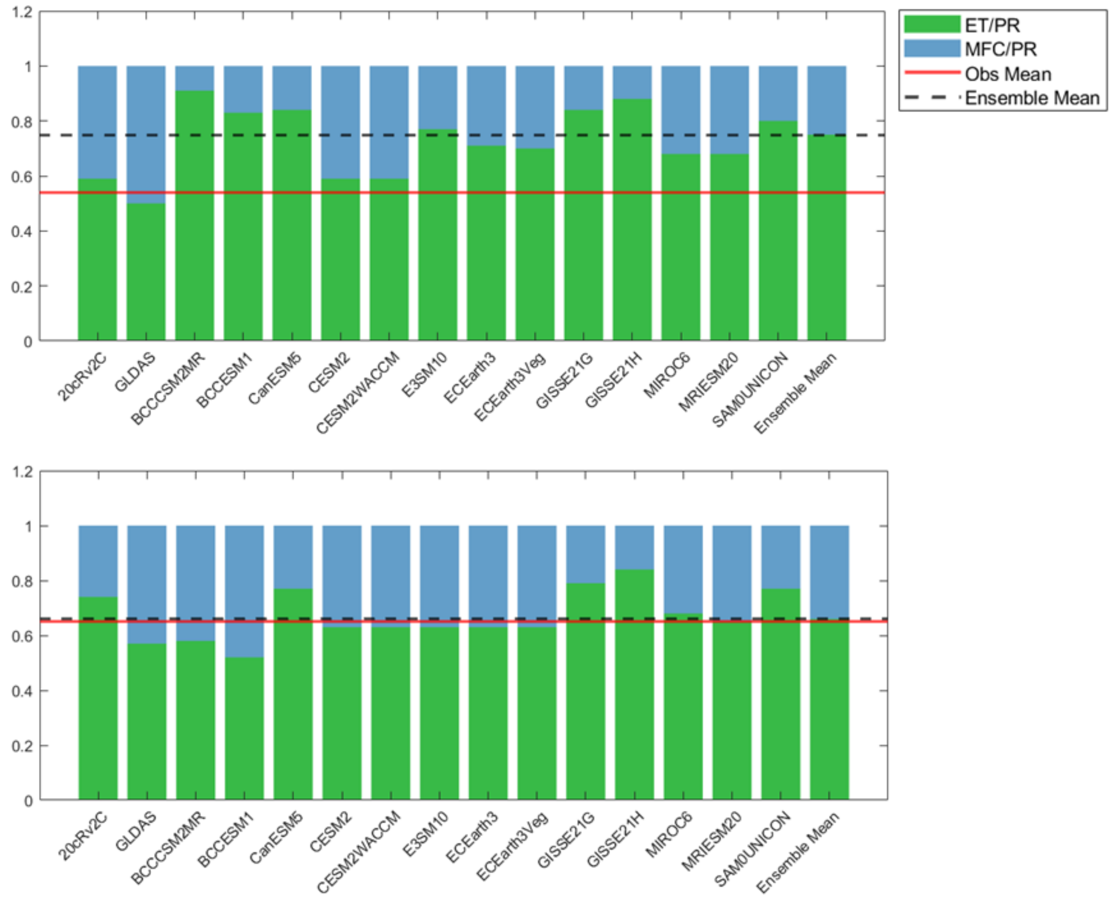

Fig. 13 1981-2014 ET/PR (green) and MFC/PR (blue) ratio analysis with observation mean (red line) and ensemble mean (black dashed line) ET/PR analysis for NAZ (top panel) and SAZ (bottom panel) for GLDAS and 20cRv2C reanalysis, and GCMs.

2.4 Conclusions

The Brazilian Amazon is an important region to study, as it provides a significant amount of resources, not just locally but globally. The precipitation regime and the significance it represents for the people, environment, and ecosystem is one of the Amazon's most significant ecosystem goods (Worldbank, 2016), and therefore should be studied and modeled properly. This study evaluates the ability of 13 CMIP6 GCMs to simulate precipitation for a historical time period (1981-2014) for the Legal Amazon of Brazil. The GCMs were selected from the

CMIP6 historical experiment simulations and ensemble means were taken to avoid member bias of individual models. Simulations from GCMs are evaluated using spatial pattern mapping, Taylor diagram analysis and Taylor skill score, annual climatology comparison, and EOF analysis. Using multiple analysis metrics allows for a holistic approach to model evaluation, and no one model performed best for all analyses.

Precipitation analysis from this research for Legal Amazon of Brazil (1981-2014) shows 1) This region displays higher rainfall in the north-northwest and drier conditions in the south. Models tend to underestimate northern values or overestimate the central to northwest averages. 2) SAZ has a much more defined dry season (JJA) and wet season (DJF), and models can simulate this well. NAZ dry season tends to occur in ASO, and the wet season occurs in MAM, so models can also not capture the climatology. Models tend to produce too much rainfall at the start of the wet season and either over- or underestimates the dry season (although the ensemble mean captures the anomalies for SAZ very well). The ensemble mean for NAZ can simulate the decline of the wet season. This means that the models capture the SAMS cycle well but not the migration of the rains to the Northern Hemisphere. 3) EOF analysis of GCMs captured the dominant mode of variability, largely the annual cycle or SAMS. Some models overestimate precipitation over the Andes and place too high of an explanation (%) on the first eigenvector by up to 26% for the ensemble mean. The second mode showed a transition from the SAMS to the NAMS, as there was a delay in the onset of the principle component time series compared to the first. Although there is there is not enough evidence from this analysis, the second EOF could also capture SACZ, although the oceanic component is not present and needs further evaluation. 4) When all evaluation metrics are considered,, the best models are CESM2, MIROC6, MRIESM20, SAM0UNICON, and the ensemble mean.

This paper supports research in determining the most up-to-date CMIP6 model performance of the precipitation regime for 1981-2014 for the Legal Amazon of Brazil, a place rich in ecosystem goods and services. Hopefully, results will aid in understanding future projections of precipitation for the selected subset of models and allow modelers and scientists to create an ensemble of high-performing GCMs for further analysis, as precipitation plays a role in many sectors of the economy, including the ecosystem, agriculture, energy, and water security.

Chapter 3. Risk in the Rainforest: Mapping the impact of unprotected Amazon deforestation[2]

3.1 Introduction

The Brazilian Amazon, a vital global ecological asset, is undergoing profound climate changes due to deforestation and climate variability. This research focuses on the **U**n**P**rotected **A**reas (UPAs) of the Brazilian Amazon, despite covering 15% of the region, were responsible for 36% of illegal deforestation in 2022 (Fabiano Maisonnave, 2022). UPAs are particularly vulnerable to deforestation due to lack of formal protection, making them critical areas for examining the climatic impacts of land cover change. Our guiding question is: What are the climatic impacts of deforestation in unprotected areas of the Amazon on air temperature, precipitation, and evapotranspiration during the dry season, and how do these changes influence risk at the municipal level in Rondônia? We use a regional climate-land surface model to simulate the impacts of deforestation in UPAs on air temperature, precipitation, and evapotranspiration (ET) during the dry season. The study also involves risk mapping at the municipality level, integrating climatic, agricultural, demographic, and socioeconomic data to assess the broader impacts on Rondônia, a vulnerable State in the southwest region of the Amazon basin. Here, we consider the basin-scale climatic changes driven by deforestation in UPAs and explore how these changes influence risk at the municipal level. Our findings indicate a trend towards higher air temperatures and reduced moisture availability, suggesting that UPA deforestation alters the regional climate and poses risks at smaller scales.

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Forest loss in UPAs remains rampant, with primary forest loss in 2020 hitting its highest levels of the decade. The Brazilian Amazon's forest area decreased from 394 million hectares in 2000 to 366 million hectares in 2021, representing a loss of 28 million hectares. This decline was predominantly concentrated in UPAs, accounting for approximately 95% of the total forest area loss during this period (Qin et al., 2023). Since 2019, environmental law enforcement has significantly weakened, exacerbating deforestation and environmental degradation (Gonzaga, 2022). This decline in governance effectiveness is evident from the substantial rise in illegal activities within Indigenous territories and other protected lands, underscoring the urgent need for robust environmental policies and governance to safeguard these critical ecosystems (Indigenous Missionary Council (Cimi), 2021; Spring, 2021).

Since 2000, Indigenous Territories and Protected Areas (PAs) have expanded significantly in the Brazilian Amazon, encompassing 43% of its land and approximately half its forest area (Qin et al., 2019). Despite this growth, these areas face threats from relaxed environmental regulations and developmental pressures post-2012, with mining posing substantial risks (Begotti & Peres, 2019; J. Ferreira et al., 2014; Silveira et al., 2018; Villén-Pérez et al., 2022). Brazil led the global expansion of terrestrial PAs from 2003 to 2009, contributing to curb 74% of the deforestation rates (Jenkins & Joppa, 2009). Yet, political resistance has led to frequent downgrading, downsizing, or degazetting of many PAs over the last decade, destabilizing the balance between conservation and development (E. Bernard et al., 2014; P. M. Fearnside, 2005; J. M. L. F. Ferreira et al., 2008; Kirby et al., 2006; de Marques & Peres, 2015; Pack et al., 2016; Silva, 2005; Walker et al., 2009). Recognized globally for their efficacy in biodiversity conservation, PAs help maintain species populations, reduce habitat loss, and preserve crucial carbon stocks, thereby contributing to climate change mitigation and supporting millions through enhanced legal compliance and livelihoods (Bertzky et al., 2012; Dudley et al., 2014; Joppa et al., 2008; Kauano et al., 2017; Watson et al., 2014). Studies show that PAs significantly lower deforestation rates than UPAs, with reductions ranging from 1.6 to tenfold (Cabral et al., 2018; Nepstad et al., 2006). Nonetheless, deforestation continues, fueled by illegal activities, especially in undesignated or private lands, contributing significantly to environmental degradation and placing Brazil as a leading contributor of carbon emissions from such activities in 2022 (Global Forest Watch, 2024; Woodwell Climate Research Center & IPAM Amazonia, n.d.).

Rondônia, a Brazilian state facing severe threats to its PAs, witnessed the revocation of 11 areas (3% of the state’s total area) in 2018 without public consultation or technical studies, indicating the influence of local political interests over conservation efforts (P. Fearnside & Vilela Cruz, 2018; Gesisky, 2018). This region, among the most deforested in the Amazon, experienced significant forest cover loss within its PAs due to agricultural expansion and infrastructure developments, with PA Downgrading, Downsizing, and Degazettement (PADDD) events increasingly facilitating deforestation (Ribeiro & Veríssimo, 2007). Despite the global carbon benefits provided by these areas, demonstrated by higher carbon storage in PAs versus UPAs (Cassidy, 2021), enforcement of environmental protections remains inadequate due to insufficient resources, rendering these areas vulnerable to encroachment by various economic actors (Tesfaw et al., 2018; WWF, 2007). The effectiveness of PAs varies significantly, with state-protected areas in Rondônia demonstrating minimal impact in preventing deforestation compared to federal and indigenous lands, highlighting the governance level's importance (Herrera et al., 2019). Additionally, legal challenges persist as companies like JBS SA face lawsuits for environmental damages linked to activities in these PAs (F. Maisonnave & Valente, 2023; El Pais, 2023). The ongoing reduction of legal protections and management effectiveness poses a significant risk, undermining conservation efforts and facilitating further environmental degradation (Keles et al., 2020). Rondônia illustrates the intricate interplay between conservation, economic pressures, and governance, emphasizing the urgent need for strengthened protections and resources to safeguard these vital ecosystems (Caldas et al., 2019).

Continued deforestation in the Amazon is driven by the expansion of cattle ranching, agricultural activities, road networks, and erosion of environmental regulations and enforcement, among other contributing factors. Despite a 22% reduction in deforestation rates between 2022 and 2023, these activities have historically accelerated deforestation. This deforestation modifies precipitation patterns, prolonging dry seasons and delaying wet seasons, underscoring the crucial role of forest moisture recycling and regional ET in maintaining climatic balance (Bonini et al., 2014; Butt et al., 2011; Costa & Pires, 2010; Jose A. Marengo et al., 2018; Mu et al., 2021). These disruptions degrade ecosystems and increase the likelihood of extreme rainfall and droughts while also altering local and regional climates by reducing ET and convective precipitation and intensifying downwind convection (Alves et al., 2017; Bagley et al., 2014; Khanna et al., 2017; da Rocha et al., 1996; De Sales et al., 2020; Shukla et al., 1990; Wu et al., 2017b). The resultant shifts in energy fluxes and diminished ET are pushing the Amazon towards a hotter, more variable climate, particularly in its deforested southern and eastern regions, suggesting the Amazon may have already entered a new climate regime (Barkhordarian et al., 2019; V. Dubreuil et al., 2019; Esquivel-Muelbert et al., 2019;

Wang et al., 2021). These dynamics highlight the urgent need for more robust protective policies and informed interventions to safeguard this vital ecological asset.

3.2 Materials and Methods

3.2.1 Study Area

This study focuses on assessing the impacts of deforestation, specifically in the unprotected areas (UPAs) of the Brazilian Amazon (**Fig. 14**), on climate variables including wind, temperature, precipitation, and ET. The risk analysis focuses on Rondônia, a State that is symbolic of the vulnerability faced by the Amazon due to its rapid land-use changes. In the 1970s, the population of this region grew significantly, spurred by the construction of a major highway that improved accessibility throughout the State. This juxtaposition of spatial scales allows for a detailed examination of the broader climatic shifts within the Amazon and the localized risks in an already vulnerable State.

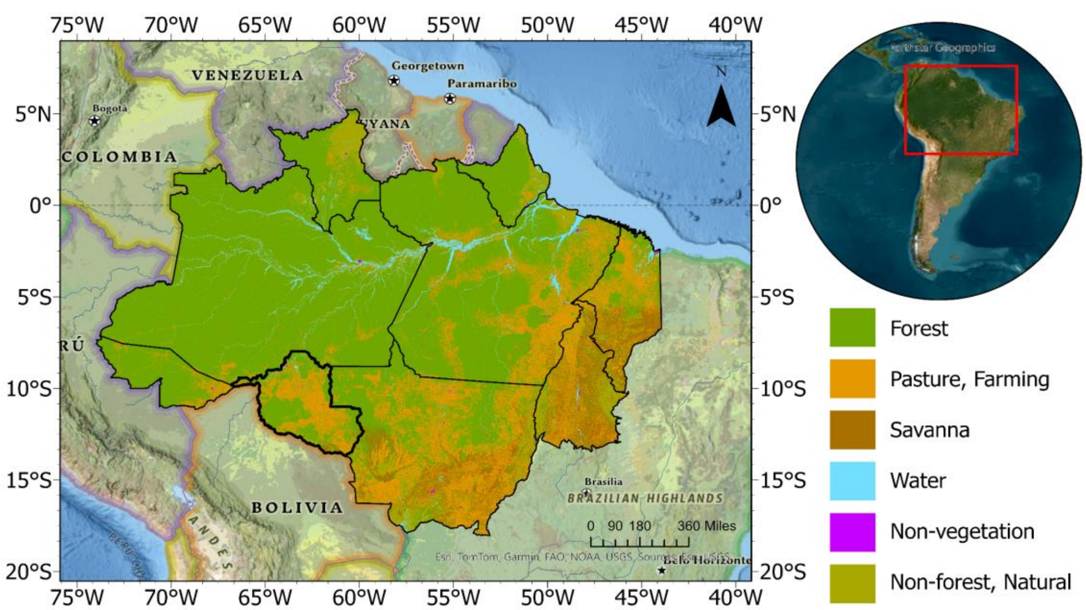


Fig. 14 Location of the study area and land cover type. Rondônia located in the Southwest, indicated by the thick outline.

3.2.2 Modeling system

We utilized the Weather Research and Forecasting (WRF) regional climate model, coupled with the Simplified Simple Biosphere (SSiB) land surface model (LSM), to study the effects of deforestation on climate in the Brazilian Amazon (Powers et al., 2017; Fernando De Sales et al., 2019; Skamarock et al., 2019; Xue et al., 1991; Zhang et al., 2012). This land-climate model, WRF-SSiB, operates at 18 km resolution on a single unnested grid (**Fig. 15**) with WRF Single-moment 6-class scheme for microphysics (Hong, 2006), RRTMG radiation scheme (Iacono et al., 2008), and the New Tiedtke cumulus scheme (Zhang & Wang, 2017). This model simulates changes in wind, moisture, and temperature regimes. The European Centre provides initial and lateral boundary conditions for the model for Medium-Range Weather Forecasts (ECMWF) reanalysis ERA5, which offers a high-resolution reconstruction of the global atmosphere (Bell et al., 2021; Hersbach et al., 2020b). The model was run from May to September 2015-2019 under two scenarios: control (CTL) and UPA deforestation. Each scenario included five ensemble members to introduce variability and assess results consistency. The ensemble members began on sequential days starting May 1, 2015, with May excluded from analysis each year for model spin-up. The study focuses on the dry season months of June to September (JJAS).

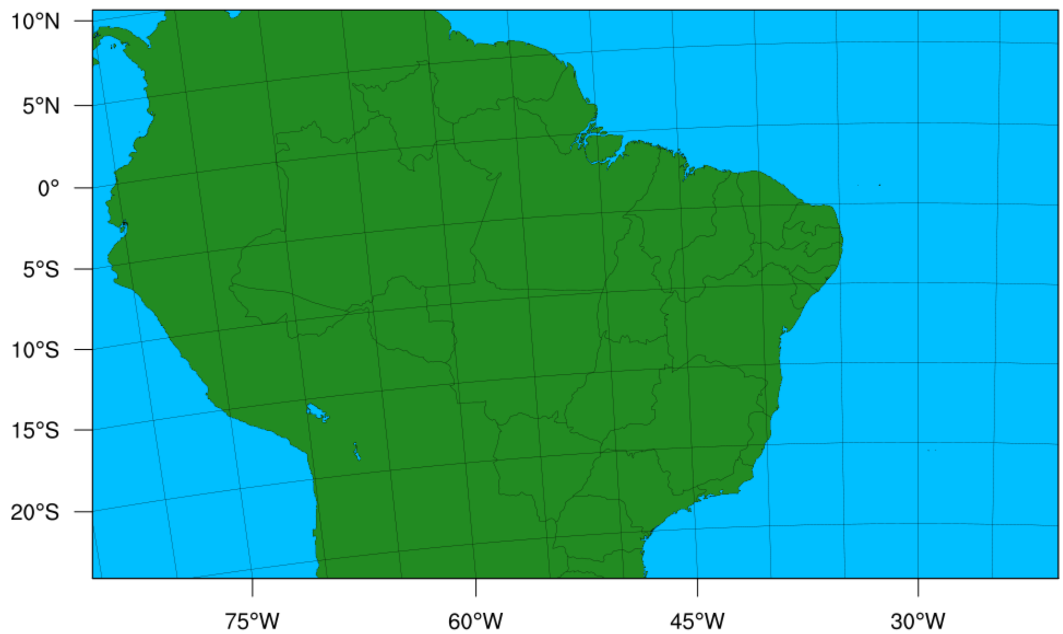


Fig. 15 Modeling system domain

3.2.3 Deforestation representation

We developed a map to identify unprotected forest areas (UPAs) at higher risk of illegal activities and diminished protection using data from the Brazilian National Institute for Space Research (INPE) Terrabrasilis dataset (http://terrabrasilis.dpi.inpe.br/en/download-2/). Within ArcPro, shapefiles for various layers, including conservation units, Indigenous areas in the Legal Amazon, and deforestation metrics, were integrated. The UPAs were delineated by identifying regions with existing forest cover that are neither within conservation units nor Indigenous areas and have not been deforested, marked as green in **Fig. 16**. These UPAs were then incorporated into the WRF-SSiB modeling system to assess regional climate impacts of deforestation. For comparison, the observed deforestation layer from Terrabrasilis for 2017 was used in the control simulation, shown in pink in **Fig. 16**, to provide a baseline for analyzing the effects of UPA deforestation.

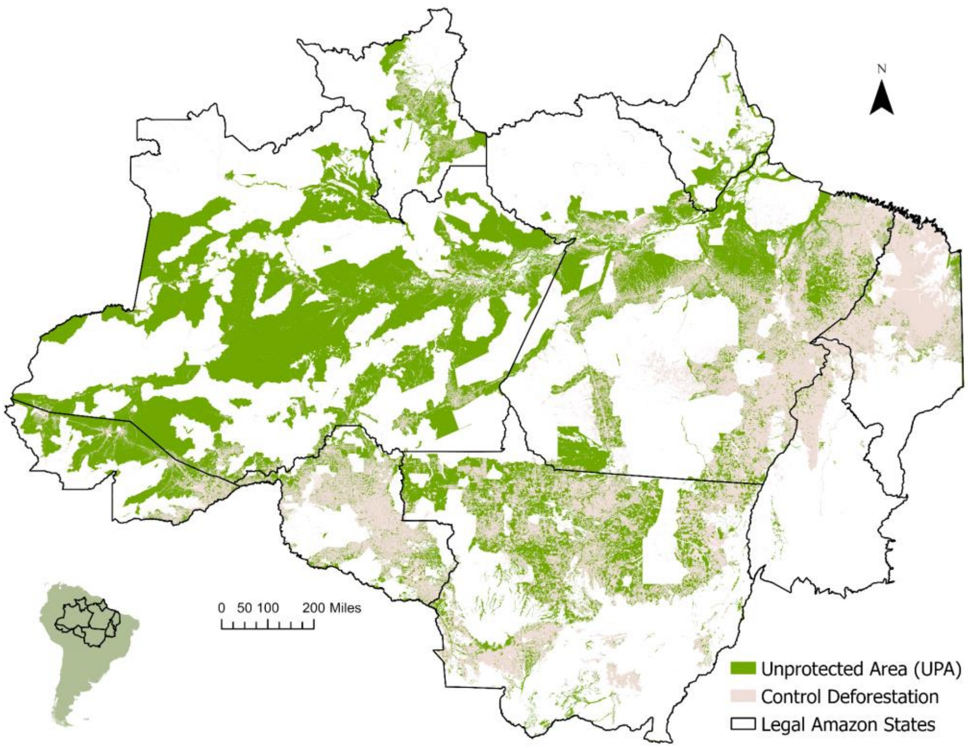


Fig. 16 Map of unprotected areas and control deforestation in the Legal Amazon to be implemented in WRF-SSiB model.

SSiB contains 13 vegetation types derived from the International Satellite Land Surface Climatology Project (ISLSCP) the University of Maryland Global Land Cover Classifications (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=969). To simulate land cover conditions following deforestation, we replaced the areas of forest within the UPA map with groundcover. **Table 3** contains the parameter information for both forest and deforested cover (Xue et al., 1991).

Table 3. Vegetation parameter

Parameter	Forested	Deforested
Vegetation height (m)	35.0	0.6
Leaf area index	5.0	1.6
Vegetation cover fraction	0.98	0.90
Rooting depth (m)	1.0	0.5
Roughness length (m)	2.7	0.08
Zero-plane displacement (m)	27.4	0.26

3.2.4 Observational data

We validated the modeled air temperature using the Climate Research Unit (CRU) dataset, which offers high-resolution temperature records at 0.5° resolution from station data (Harris et al., 2020), and the Copernicus Atmosphere Monitoring Service (CAMS) datasets with approximately 0.7° resolution that combine satellite observations, in-situ measurements, and model data (Inness et al., 2019). Precipitation validation employed three datasets: the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) providing quasi-global estimates at 0.05° resolution (Funk et al., 2015), the CPC Merged Analysis of Precipitation (CMAP) that merges satellite and gauge data at 2.5° resolution (Xie & Arkin, 1997), and the CRU dataset at 0.5° resolution. All datasets were evaluated at the monthly temporal scale.

3.2.5 Analysis

3.2.5.1 Basin-wide analysis

We calculated the differences in critical climatic variables—temperature, wind, ET, and precipitation—between the CTL and UPA deforestation scenarios during the dry season months (JJAS). To understand the mechanisms behind precipitation changes, we analyzed the vertically integrated moisture flux and convergence from the surface to 900 mb, offering a detailed examination of the climate system's response to deforestation and illustrating the potential climatic changes.

3.2.5.2 Risk mapping

Risk maps for Rondônia were developed, correlating climatic changes with agricultural and socio-economic data at the municipality level. This involved integrating criteria, including simulated precipitation, temperature, and ET changes. Agricultural criteria such as cattle and milked cow count, and socioeconomic and demographic factors, including population density and Gross Domestic Product (GDP) per capita, were also included (**Table 4; Supplementary Information (SI) Fig. 1**). The analysis utilized both bivariate maps and multi-criteria maps to assess vulnerability to climatic changes.

Table 4. Risk analysis data sources

Data Layer	Source
Precipitation change	WRF-SSiB UPA deforestation simulation
Temperature change	WRF-SSiB UPA deforestation simulation
Evapotranspiration change	WRF-SSiB UPA deforestation simulation
Cattle count	https://sidra.ibge.gov.br/home/ipca15/brasil
Milk Cow Count	https://sidra.ibge.gov.br/home/ipca15/brasil
GDP per capita	https://www.ibge.gov.br/en/statistics/full-list-statistics.html
Population density	https://www.ibge.gov.br/en/statistics/full-list-statistics.html

Bivariate maps categorized each variable into three levels (low, medium, high) and cross-tabulated into a 3x3 matrix to visually represent combinations like low-low or high-high using a color gradient, indicating varying risk levels across municipalities. Utilizing natural breaks for categorization provides a spatial depiction of risk. Such maps are useful in illustrating the compounding effects of interrelated variables like near-surface air temperature change and population density on heat vulnerability. Although population density is a valuable indicator for depicting heat risk, it was not included in the multi-criteria maps. The focus of the multicriteria was primarily on agricultural and economic factors, specifically GDP and livestock numbers, which are more directly relevant to the objectives of assessing agricultural impacts and vulnerabilities in rural areas. The utility of bivariate mapping is well-documented and allows for an intuitive understanding of two variables (Dunn, 1989; Kebonye et al., 2023; Tripathy et al., 2024).

We utilized a multi-criteria analysis to evaluate the potential impact of climatic change on agriculture and vulnerable populations at the municipal level in Rondônia. The study considered six criteria to define risk: changes in precipitation, air temperature, and ET due to UPA deforestation, cattle and milk cow counts, and GDP per capita. The weightings, calculated through the Analytic Hierarchy Process (AHP), highlighted climatic changes as the primary risk drivers, with agricultural productivity and GDP playing significant roles in vulnerability assessment (Cutter et al., 2003; Pohekar & Ramachandran, 2004; R. W. Saaty, 1987). AHP involved constructing and normalizing a pairwise comparison matrix (**Tables 5** and **6**), calculating criteria weights (**Table 7**), and assessing the consistency of judgments by ensuring a consistency ratio (CR) below 0.1 (if the ratio is smaller than 10%, then the inconsistency in the matrix is acceptable as per (T. L. Saaty, 2016)). We also tested for sensitivity for our six criteria (**SI Fig. 2**). Utilizing these weighted criteria, the ArcPro suitability tool mapped municipalities by risk (**SI Eqns 1** and **2**) so that the final map shows areas where precipitation and ET change are negative, air temperature change is positive, cattle and milk cow count are high, and GDP is low. Risk classification employed the Jenks natural breaks method to identify inherent data groupings, data clusters, and outliers, thus optimizing classification and highlighting regions from 'most at risk' to 'least at risk' for targeted planning (Jenks, 1967). The map developed in this research incorporates critical components of risk (IPCC 2022)—hazard, exposure, and vulnerability—within the context of climatic changes. Hazard is represented by changes in climatic variables like precipitation, temperature, and ET derived from climate simulations. Exposure is represented through cattle and milk cow counts. Vulnerability is represented through GDP, reflecting the economic capacity to respond to climatic changes. This map illustrates the potential impacts of climatic variability on agricultural systems, emphasizing areas where the confluence of high climatic variability and agricultural activity increases risk.

Table 5. The Analytical Hierarchy Process (AHP) approach comparison matrix, resulting weights, and CR

Criteria	**Pr**	**T2**	**ET**	**Cattle Count**	**Milk Cow Count**	**GDP**	**Weight**
Pr	**1**	1	2	3	3	5	28.2%
T2	1	**1**	2	3	3	5	28.2%
ET	0.5	0.5	**1**	3	3	5	20.4%
Cattle Count	0.33	0.33	0.33	**1**	1	3	9.4%
Milk Cow Count	0.33	0.33	0.33	1	**1**	3	9.4%
GDP	0.2	0.2	0.2	0.33	0.33	**1**	4.4%

Consistency Ratio (CR) <0.1	**0.02**

Table 6. Scale for pairwise comparison (Saaty, 1987)

Description	Value
Equal importance	1
Moderate importance of one over another	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Preference between intervals	2,4,6,8

Table. 7 AHP steps

Step 1: Sum comparison matrix rows

	Pr	T2	ET	Cattle Count	Milk Cow Count	GDP
SUM	3.37	3.37	5.87	11.33	11.33	22

Step 2: Normalize the pairwise comparison matrix

Step 3: Calculate weights (average of normalized rows)

0.30	0.30	0.34	0.26	0.26	0.23	0.28
0.30	0.30	0.34	0.26	0.26	0.23	0.28
0.15	0.15	0.17	0.26	0.26	0.23	0.20
0.10	0.10	0.06	0.09	0.09	0.14	0.09
0.10	0.10	0.06	0.09	0.09	0.14	0.09
0.06	0.06	0.03	0.03	0.03	0.05	0.04

Step 4: Multiply the comparison matrix by weights

Step 5: Weighted sum

0.28	0.28	0.41	0.28	0.28	0.23	1.77
0.28	0.28	0.41	0.28	0.28	0.23	1.77
0.14	0.14	0.2	0.28	0.28	0.23	1.28
0.09	0.09	0.07	0.09	0.09	0.14	0.58
0.09	0.09	0.07	0.09	0.09	0.14	0.58
0.06	0.06	0.04	0.03	0.03	0.05	0.26

Step 6: Ratio (sum divided by criteria weight)

Pr	6.27
T2	6.27
ET	6.28
Cattle Count	6.15
Milk Cow Count	6.15
GDP	5.75

Step 7: Calculate Lambda max (ratio average)

6.15

Step 8: Calculate consistency index (CI) (Lamda max - n / (n-1))

0.03

Step 9: Calculate consistency ratio (CI/ RI)

Random Index (RI) = 1.24

0.02

3.3 Results and discussion

3.3.1 Model performance

The WRF-SSiB model accurately simulates regional temperature and precipitation from 2015-2019 (**Fig. 17**), showing a minor cold bias of -0.05 °C against the observed mean temperature of 27.2 °C, and a root-mean-square error (RMSE) of 1.7, indicating effective capture of thermal gradients. The model displays a minor wet bias of 0.34 mm/day in precipitation against an observed average of 2.8 mm/day, with an RMSE of 0.83 mm/day. These metrics demonstrate the model's effectiveness in depicting Amazonian climatic conditions and applicability in further risk assessment studies. However, climate modeling inherently possesses uncertainties and biases, especially in regions like the Amazon with sparse observational data (Betts et al., 2008; J. A. Marengo et al., 2010). This scarcity highlights the need for more observational sites to refine models and improve predictions (Anderson et al., 2018).

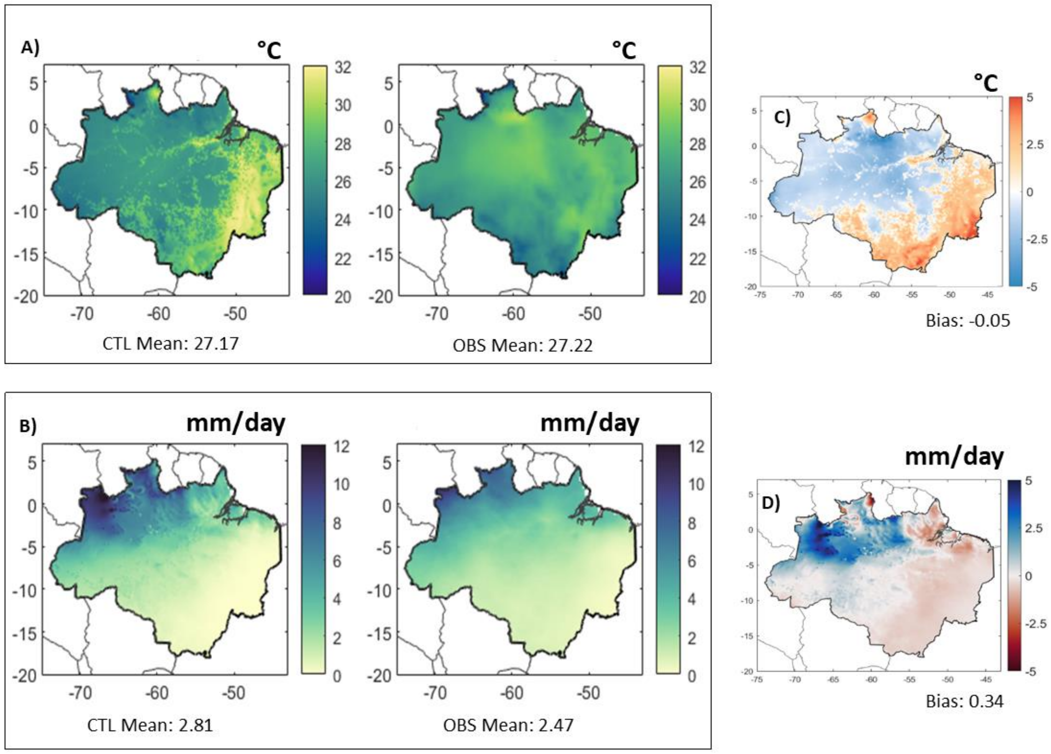


Fig. 17 JJAS (2015-2019) average (A) 2-meter air temperature for CTL and observed, (B) precipitation for CTL and observed(C) 2-meter air temperature bias, (D) precipitation bias.

3.3.2 Basin-wide impacts of deforestation

Air temperature change (**Fig. 18A**) indicates significant warming in deforestation zones, intensified during dry season months. This warming, attributed to reduced ET and possibly reduced cloud cover, extends regionally beyond deforested areas by September, underscoring the extensive impact of deforestation on regional air temperatures (Carlos et al., 1991; J. A. Marengo, Nobre, et al., 2010). Box plots (**Fig. 19A**) show a rise in temperature medians and ranges in the UPA scenarios, with sharper increases in UPAs, highlighting the effects of deforestation (**SI Fig. 3A**). The Brazilian Amazon's mean surface air temperature rose by 1.0±0.4 °C due to UPA deforestation. Following the deforestation of UPAs, wind speeds increase due to decreased surface roughness and a warmer interior, leading to intensified easterly winds across the basin (**Fig. 19B**). As the dry season intensifies, extending into September, easterly winds become stronger and shift southwest, becoming more meridional. ET declines by an average of 12±4% across the basin in the UPA deforestation scenario (**Fig. 18C**) as forest conversion to grass diminishes transpiration (Davidson et al., 2012). ET is consistently lower for the UPA run, worsening through the dry season into August (**Fig. 19C**). **SI Fig. 3C** shows that the decrease in ET is more significant over UPA but extends to areas outside of these regions. This study shows that impacts on the edges of deforested patches should be investigated in greater detail.

Precipitation decreases are greatest in the central and northern basin (**Fig. 18D**), with a notable increase in the western region. The reduction in ET likely contributes to decreased local moisture availability, diminishing overall rainfall by 12±8%. **Fig. 19B** illustrates the decrease of rainfall, particularly evident from June-August. The emergence of pressure gradient changes in the southeast corridor is a crucial driver for the northward movement of warm air from the south and east. This exacerbates the heat and diminishes moisture levels as the dry season progresses, leading to elevated air temperatures and decreased ET. Easterly winds accelerate along the deforested tract in the northern basin, which enhances the transport of moisture and increases lower-level moisture flux convergence (MFC) and precipitation in the western regions (**SI Fig. 4**). The increased MFC in the western region of the Brazilian Amazon basin is likely compensating for the local decrease in ET due to deforestation. This is supported by studies such as those by (Coe et al., 2009, De Sales et al. 2020; Mu et al, 2021, Mu et al, 2023), which link changes in wind patterns due to deforestation with alterations in regional moisture convergence and precipitation.

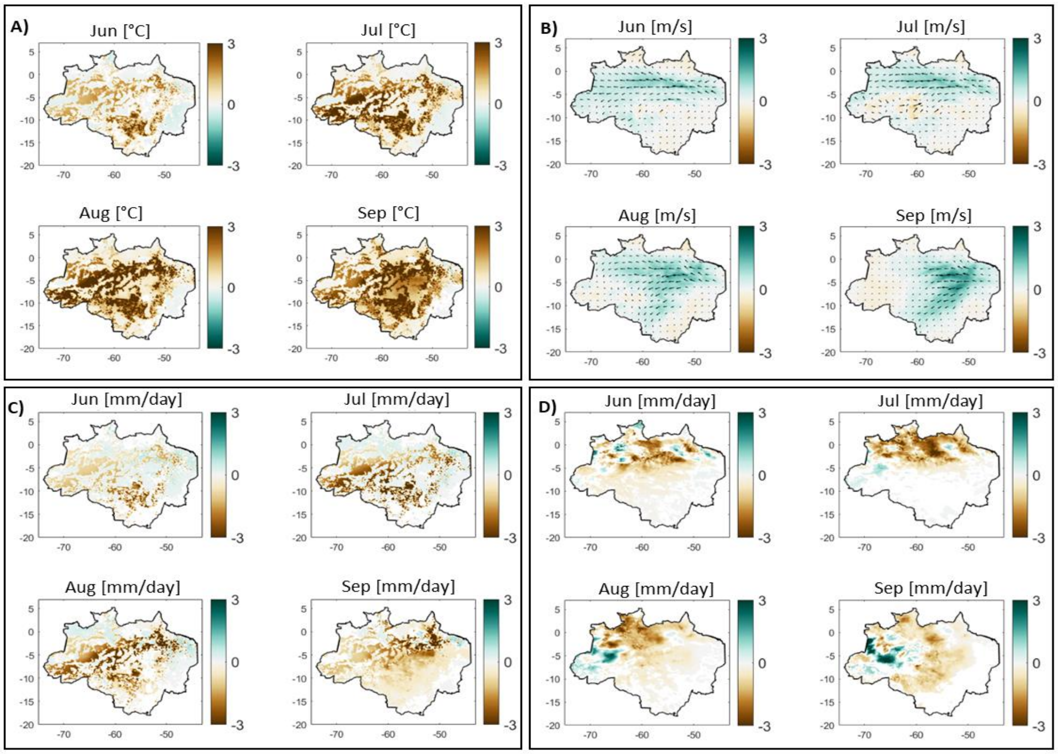


Fig. 18 Difference in JJAS air temperature [°C] (A), 850 hPa wind speed [m/s] (B), evapotranspiration [mm/day] (C), and precipitation [mm/day] (D) for the Brazilian Amazon due to unprotected area deforestation (2015-2019). ***Values were excluded from the above figures where the significance level did not reach 90%. Using a 90% significance level, rather than 95%, is still an acceptable threshold in this context, especially as the focus is on the relative change in variables due to deforestation rather than the precise values of each variable. This level of significance provides a balance between statistical rigor and the practical constraints of the study, allowing for the identification of meaningful changes while acknowledging inherent uncertainties.***

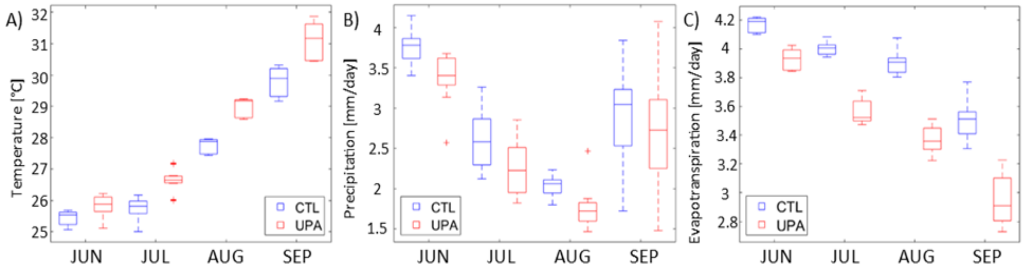


Fig. 19 Boxplots of dry season (JJAS) monthly air temperature [°C] (A), precipitation [mm/day] (B), and evapotranspiration [mm/day] (C) for the control 'CTL' run (blue boxes) and deforestation scenario 'UPA' (red boxes) for the Brazilian Amazon (2015-2019).

3.3.3 Rondônia risk analysis

Past deforestation in Rondônia has led to significant biodiversity loss through habitat destruction, altering rainfall patterns, and endangering its rich biodiversity (Butt et al., 2011; M. A. Pedlowski et al., 1997a). This has compromised agricultural productivity, crucial to the state's economy (Lense et al., 2021). **Fig. 20** illustrates a decrease in mean precipitation by 20±7% (**Fig. 20A**), a reduction in ET by 11±9% (**Fig. 20C**), and a temperature increase of 1.2±0.4 °C (**Fig. 20B**) due to UPA deforestation, indicating potential drought-like conditions that can disrupt agricultural activities, including crop failures and livestock losses, impacting milk production (Monteverde et al., 2024). More in-depth risk analyses of these climatic changes due to UPA removal are presented in the following sections.

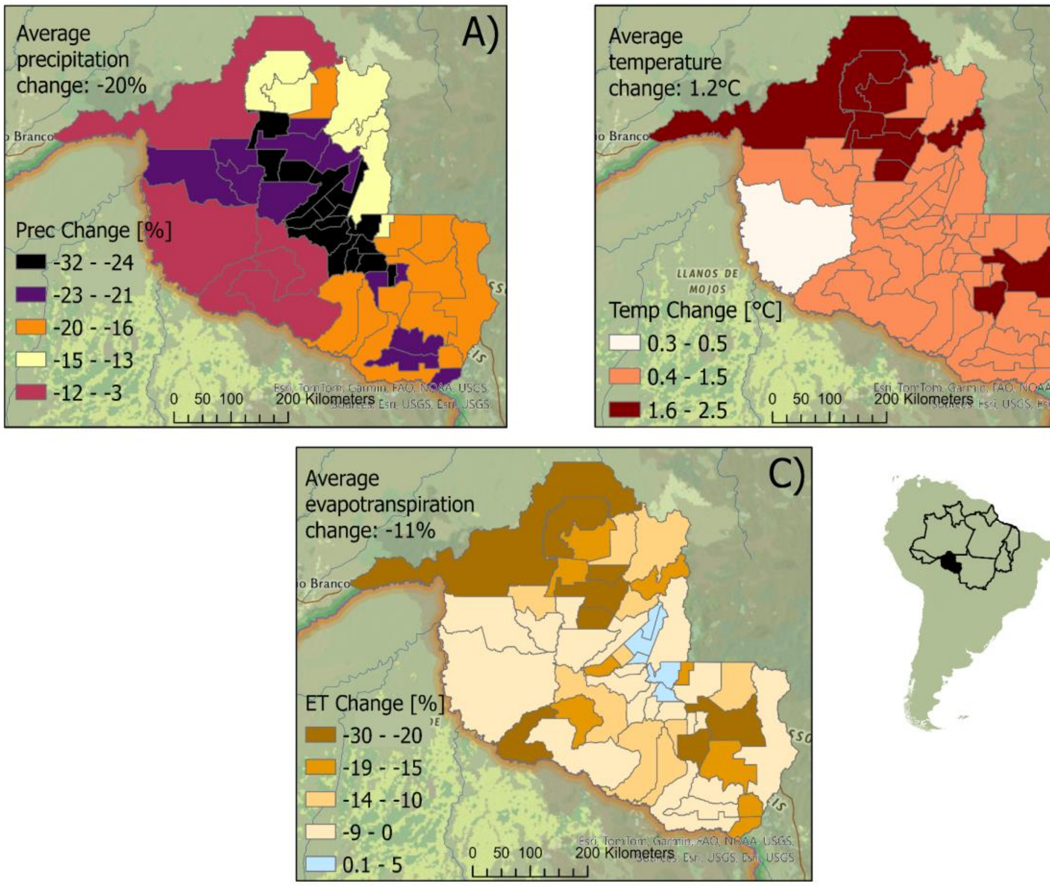


Fig. 20 Difference in precipitation [%] (A), temperature [°C] (B), and evapotranspiration [%] (C) at the municipality level for Rondônia due to unprotected area deforestation in the Brazilian Amazon.

3.3.3.1 Bivariate maps

Urban areas, particularly affected by the urban heat island effect, are warmer than nearby rural areas due to altered land surfaces, heightening health risks during heatwaves (Basu & Samet, 2002; Rizwan et al., 2008). The lack of cooling infrastructure, such as air conditioning, further exacerbates these risks, especially for vulnerable populations, including the elderly, children, and those with health conditions, leading to increased heat-related illnesses (Åström et al., 2011; Ebi et al., 2021; Harlan et al., 2006; Kovats & Hajat, 2008; Loughnan et al., n.d.). In Rondônia, the heat vulnerability map (**Fig. 21A**) highlights areas with high heat vulnerability, particularly along the stretch from Porto Velho to Parecis, including Ariquemes, which has a population density of 22 inhabitants per km² and an observed air temperature increase of 2°C. The northern regions exhibit the highest temperature increases (1.6 – 2.5 °C), whereas the southeastern municipalities, though experiencing smaller temperature increases (0.4 – 1.5 °C), have higher population densities (15 -39 inhabitants per km^{-2}). While the combination of high population density and high temperatures is a strong indicator of heat vulnerability, other factors can also influence this vulnerability, including the availability and quality of housing, socioeconomic status, access to healthcare, and community preparedness for heatwaves, which are not included in our analysis (Ebi & Semenza, 2008; Harlan et al., 2013; Hondula et al., 2012; Uejio et al., 2011).

Higher GDP per capita is often linked to better infrastructure and greater resources for drought resilience (Mendelsohn et al., 2006). In contrast, lower GDP per capita indicates a reduced capacity to handle environmental challenges like drought (Eakin & Bojórquez-Tapia, 2008). Low or decreasing precipitation suggests potential drought conditions (A. P. M. A. Cunha et al., 2019). Bivariate mapping highlights areas where economic constraints and low precipitation increase drought risk, complicating mitigation and adaptation efforts. The drought impact risk map (**Fig. 21B**) shows that the most vulnerable areas are around Ariquemes, with the lowest GDP per capita (21,000 – 29,000 $R compared to the state average of 32,000) and significant precipitation reductions (up to 32%) due to UPA removal. In contrast, Porto Velho experiences moderate precipitation reductions (12%) but benefits from higher GDP per capita (29,000 – 40,000 $R). Other at-risk regions are denoted in light tan and purple colors, including Parecis and areas to the northeast and southwest of Ariquemes, including Indigenous lands 160 km southwest of Ariquemes. Drought risk is also influenced by factors like soil type, water management policies, agricultural practices, and social factors such as community organization and governance, which are not included here. GDP per capita does not reflect wealth distribution, which can impact community resilience to drought.

High ET suggests healthy plant growth and adequate water, as active growth increases plant water transpiration (Rodriguez-Iturbe et al., 2001). Conversely, low ET often results from deforestation and decreased transpiring vegetation cover. Low ET and precipitation signify reduced water availability, potentially stressing agriculture and reducing crop productivity (Basso & Ritchie, 2015). Rondônia's agricultural water stress map post-UPA removal (**Fig. 21C**) identifies areas within a 145 km radius of Ariquemes as highly vulnerable, similar to those shown in Fig. 8B, with precipitation and ET reductions up to 32% and 30%, respectively. Areas with lower risk include protected forests and Indigenous lands 160 km southwest of Ariquemes, which see only moderate decreases in precipitation (12%) and ET (4%). Other vulnerable regions are marked in light red and blue around Parecis and municipalities 80 km to the east and 160 km south. The impact of ET and precipitation on agricultural stress varies with crop types, soil conditions, and farming practices. Future studies could enhance agricultural stress assessments by incorporating additional data like soil moisture, air temperature extremes, crop types, and irrigation practices.

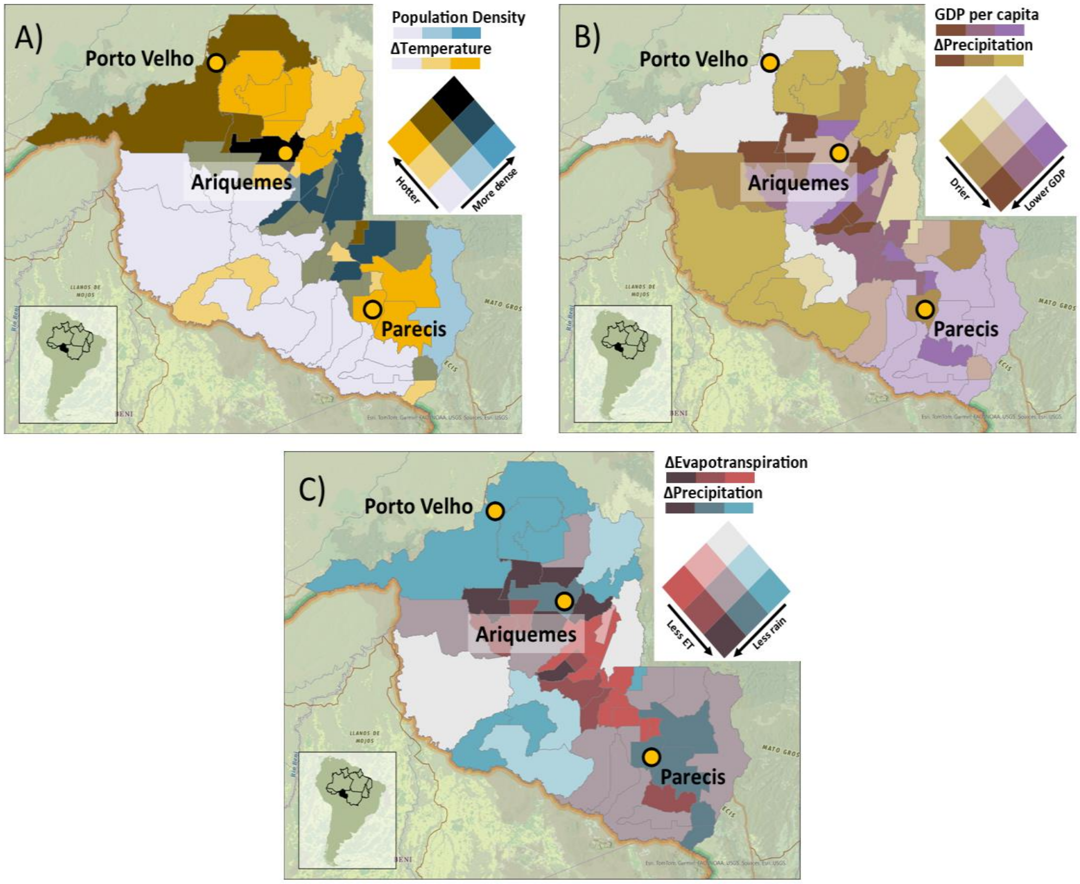


Fig. 21 Risk due to deforestation in UPAs, including heat vulnerability (A), drought impact risk (B), and agricultural stress (C).

3.3.3.2 Multicriteria risk map

Brazil is one of the world's largest producers of cow milk and beef, emphasizing the significance of dairy farming and beef production within its agribusiness sector, with regions like Rondônia contributing notably to this output. Heat stress significantly impacts milk yield and cattle health. High air temperatures combined with high relative humidity and direct solar radiation lead to reduced performance due to heat stress, exacerbated by the animals' high metabolic heat production associated with lactation (A. B. Garcia et al., 2015; Karvatte et al., 2016). Dairy cows in hotter, unshaded areas display altered behaviors, such as increased standing rest and reduced feeding intake, which mitigate discomfort but decrease milk production (Deniz et al., 2020; K. T. de Sousa et al., 2021).

In Rondônia, the municipalities most at risk from climate change due to UPA deforestation include Porto Velho, Ariquemes, and surrounding regions (**Fig. 22**, **Table 8**). Porto Velho, the capital of Rondônia (with almost half a million inhabitants) and a populous hub, could experience the highest level of risk. Parecis and surrounding municipalities face the highest risks in the southern region. Regions at risk comprise 27% of the entire State area and often correlate with higher agricultural productivity, meaning that deforestation could impact cow milk and cattle production. However, we have not quantified the potential reduction in yield due to the projected temperature increases. The municipalities least at risk include a large region to the southwest of Ariquemes and Parecis, including Indigenous territories and conservation units, and comprise 18% of the State area (**SI Fig. 5**), which were not deforested in our simulations. The risk designation in these maps is influenced by the weights assigned to various factors in Table 5; altering these weights (or removing UPA climate change altogether) would shift the areas identified as high risk. Our risk categories (Table 8) are also relative, so the lowest risk category could still experience significant impacts of climate change. Other factors, especially access to government resources, proximity to infrastructure like electricity or roads, and power relations, can significantly impact risk at various spatial scales. Household and individual characteristics can impact risk at the inter- and intra-household scale, including differences by gender, race, ethnicity, and class (Kaijser and Kronsell, 2013). We also do not quantify adaptive capacity, which is critical to mitigating risk impacts (Kelly and Adger, 2000). Due to those complexities, our study does not advocate for the allocation or withdrawal of aid to any specific municipalities; rather, it serves as a visual tool and highlights the municipalities that may be most susceptible to the climatic shifts resulting from UPA deforestation, based on specific criteria of GDP and cattle and milk cow populations.

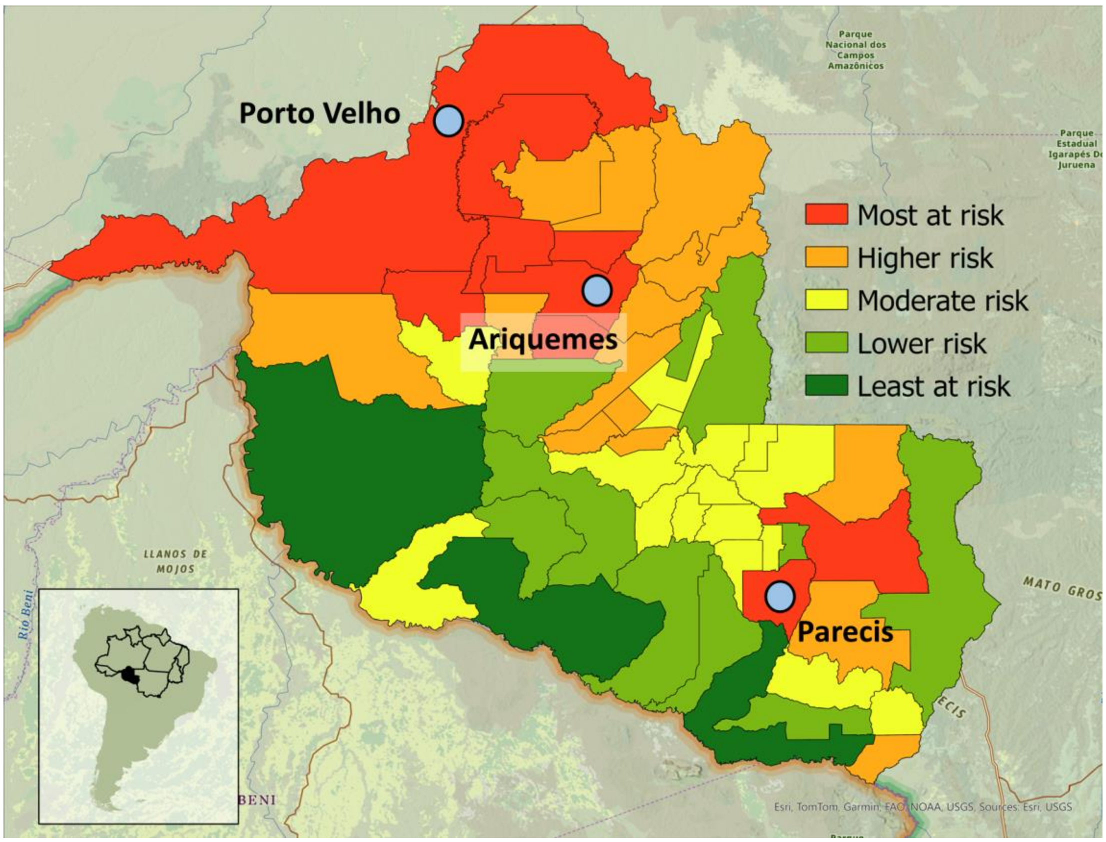


Fig. 22 Municipality risk map for Rondônia due to unprotected area deforestation in the Brazilian Amazon.

Table 8. Rondônia municipality risk ranking (from most at risk to least at risk)

Risk status	Municipalities	Area (km^2)
Most at risk	Ariquemes (most at risk), Porto Velho, Pimenta Bueno, Rio Crespo, Cacaulandia, Alto Paraise, Candeias do Jamari, Parecis, Buritis	63,748
Higher risk	Theobroma, Nova União, Monte Negro, Jaru, Urupá, Vale do Anari, Itapuã do Oeste, Nova Mamoré, Mirante da Serra, Chupinguaia, Machadinho D'Oeste, Cujubim	44,691
Moderate risk	Espigão D'Oeste, Cabixi, Ministro Andreazza, Campo Novo de Rondônia, Santa Luzia D'Oeste, Colorado do Oeste, Nova Brasilândia D'Oeste, Teixeirópolis, Alvorada D'Oeste, Ouro Preto do Oeste, Rolim de Moura, Costa Marques, Presidente Médici, Cacoal, São Felipe D'Oeste, Novo Horizonte do Oeste, Castanheiras	34,158
Lower risk	Corumbiara, Ji-Paraná, Governador Jorge Teixeira, Primavera de Rondônia, Alta Floresta D'Oeste, Vale do Paraíso, Alto Alegre dos Parecis, Seringueiras, Vilhena, São Miguel do Guaporé, Ceregeiras	53,337
Least at risk	São Francisco do Guaporé, Pimenteiras do Oeste, Guajará-Mirim (least at risk)	41,831

3.4 Implications for policy makers

Targeted policy interventions could mitigate the risks identified in the Brazilian Amazon, particularly in high-risk areas highlighted by our bivariate and multi-criteria maps. These may include reducing deforestation and adapting to and managing the risks associated with climatic changes. Integrating these strategies with local and regional development plans is essential to ensure that policy responses are effective and contextually relevant.

Strengthening legal frameworks, such as the Forest Code and the National System of Protected Areas (SNUC), could play a significant role. Beyond enactment, these laws may need strict enforcement, particularly in areas with high population densities and significant temperature increases, as indicated in our risk assessments. Ensuring that protected areas are well-funded and staffed is essential for maintaining their integrity against deforestation pressures (Soares-Filho et al., 2014).

Enhancing monitoring infrastructure, including satellite imagery and ground surveillance, especially in high-risk areas, might enable more effective enforcement of deforestation laws. This focused approach could help ensure that resources are allocated where they are most needed, supporting the sustainability of both human and ecological communities in these regions (Asner et al., 2005; Mullan et al., 2022). Effective management supported by robust monitoring can significantly reduce deforestation and mitigate associated risks (Hargrave et al., 2013; Assunção et al., 2019).

Implementing sustainable agricultural practices, such as rotational grazing, may help reduce environmental impacts and improve climate resilience (Monteverde et al., 2024). Entities like SENAR (National Rural Learning Service) could be valuable in promoting and educating farmers about these methods. While these recommendations aim to address some of the complex challenges facing the Brazilian Amazon, it is important to approach policy implementation with flexibility and a willingness to adapt based on ongoing research and feedback from local communities. To develop inclusive and sustainable solutions, the socio-political context and regional needs should be carefully considered.

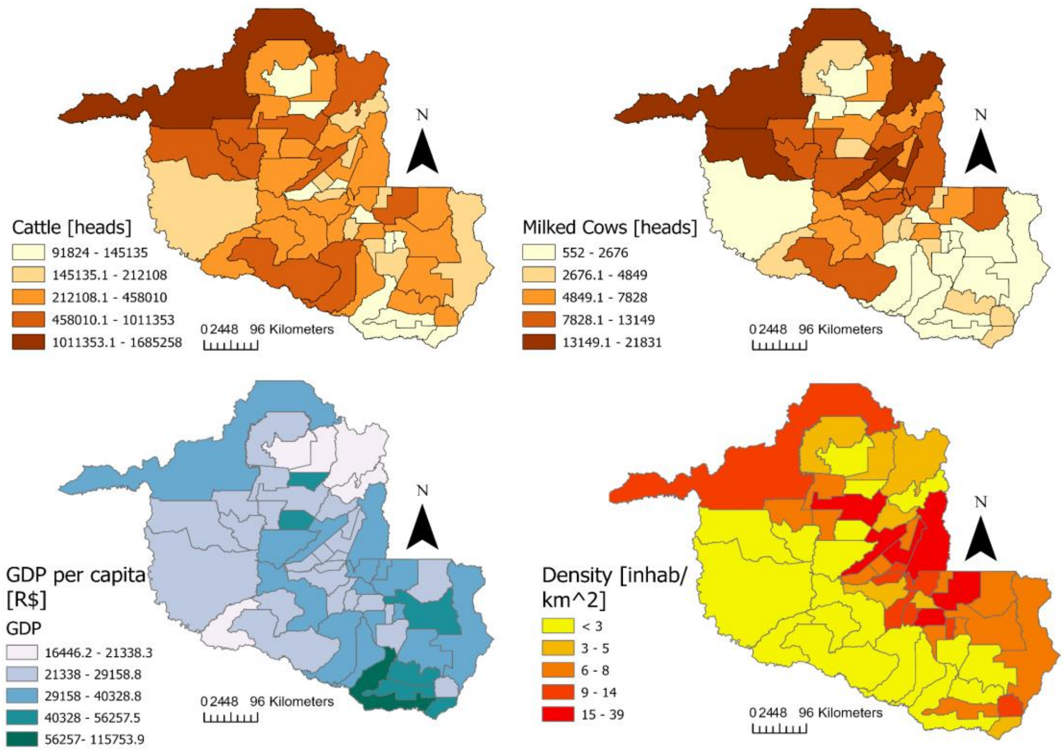
3.5 Conclusions

Deforestation of unprotected areas (UPA) in the Brazilian Amazon alters regional climate during the dry season (June, July, August, September), including increased basin-mean monthly surface air temperature by 1±0.4 °C and decreased precipitation (-12±8%) and evapotranspiration (-12±4%). The analysis of climatic changes in Rondônia due to deforestation in UPAs underscores vulnerability at the municipal level for an already vulnerable Brazilian State, forecasting reductions in rainfall (-20±7%) and evapotranspiration (-11±9%) and surface air temperature increases (1.2±0.4 °C). Several municipalities face heightened relative risk, emphasizing the confluence of climatic changes from simulated UPA deforestation and socio-economic, agricultural, and population density factors.

This research provides policy implications for protecting forests by integrating targeted interventions such as strengthened legal enforcement, improved monitoring infrastructure, and sustainable agricultural practices into local and regional development plans. It is essential to recognize that Protected Areas (PAs) in the Amazon are not immune to various threats that undermine their effectiveness. Despite the establishment of PAs, many need more resources for adequate protection. These underfunding and staffing shortages make PAs vulnerable to deforestation pressures, especially in remote areas with minimal economic and infrastructural interests. The creation of PAs has often been concentrated in regions without immediate deforestation threats, implying that their effectiveness might be overstated. These areas have not been subject to the direct economic pressures seen in the more contested "arc of deforestation" areas.

Moreover, (Assunção et al., 2019) indicated that while PAs and Indigenous territories can significantly reduce deforestation within their boundaries, they do not necessarily decrease overall deforestation across the Amazon. Instead, these areas might merely shift deforestation activities to less protected regions, serving as shields but not solving the broader issue of forest loss. These findings underline the need for strategic, well-resourced conservation efforts. The implications here aim to guide policymakers, stakeholders, and the international community toward practical actions supporting the Brazilian Amazon's preservation and sustainability.

3.6 Supplementary information



SI Fig. 1 Cattle count, milked cows count, GDP per capita, and population density for Rondônia at the municipality level.

$$\left(\frac{Criteria\ value\ for\ municiaplity\ -\ Minimum\ value}{Maximum\ value\ -\ Minimum\ value}\right) \times Critera\ weight$$

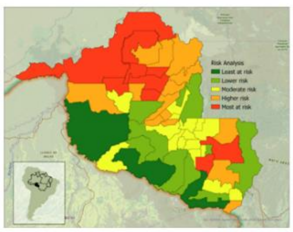
Eqn. 1 Rank for positive influence criteria values (temperature change, cattle count, milk cow count).

$$\left(\frac{Maximum\ value\ -\ Criteria\ value\ for\ municipality}{Maximum\ value\ -\ Minimum\ value}\right) \times Critera\ weight$$

Eqn. 2 Rank for inverse influence criteria values (precipitation change, ET change, GDP).

6 criteria (Climate, Ag, GDP focused) *SELECTED THIS

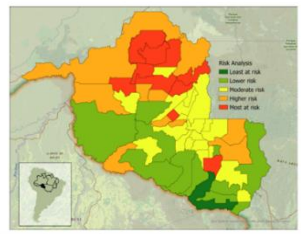
A)



	Pr	T2	ET	Cattle	Milk	GDP	Weight
Pr	1.00	1.00	2.00	3.00	3.00	5.00	28.2
T2	1.00	1.00	2.00	3.00	3.00	5.00	28.2
ET	0.50	0.50	1.00	3.00	3.00	5.00	20.4
Cattle	0.33	0.33	0.33	1.00	1.00	3.00	9.46
Milk	0.33	0.33	0.33	1.00	1.00	3.00	9.46
GDP	0.20	0.20	0.20	0.33	0.33	1.00	4.56
			CR	0.02			

6 criteria (GDP, Climate, Ag focused)

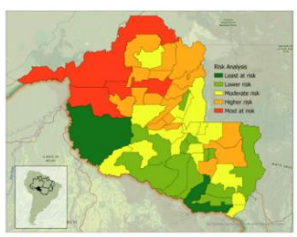
B)



	Pr	T2	ET	Cattle	Milk	GDP	Weight
Pr	1.00	1.00	1.00	7.00	7.00	0.14	13.6
T2	1.00	1.00	1.00	7.00	7.00	0.14	13.6
ET	1.00	1.00	1.00	7.00	7.00	0.14	13.6
Cattle	0.14	0.14	0.14	1.00	1.00	0.11	2.86
Milk	0.14	0.14	0.14	1.00	1.00	0.11	2.86
GDP	7.00	7.00	7.00	9.00	9.00	1.00	53.5
			CR	0.08			

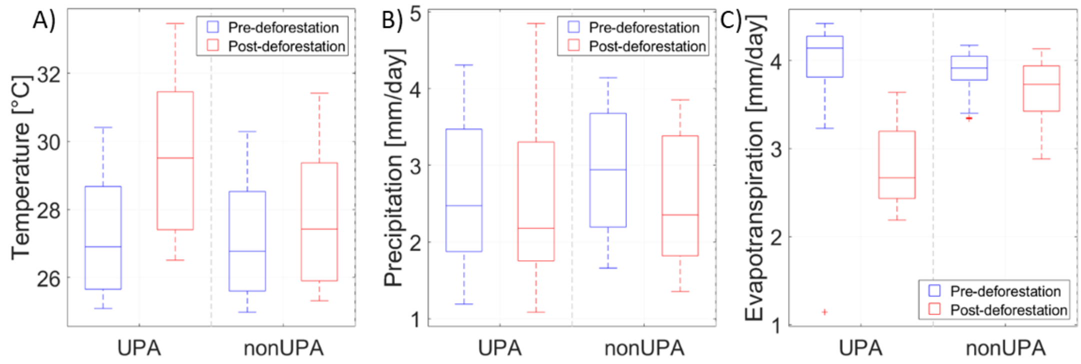
6 criteria Equal weights (Climate, Ag, GDP)

C)

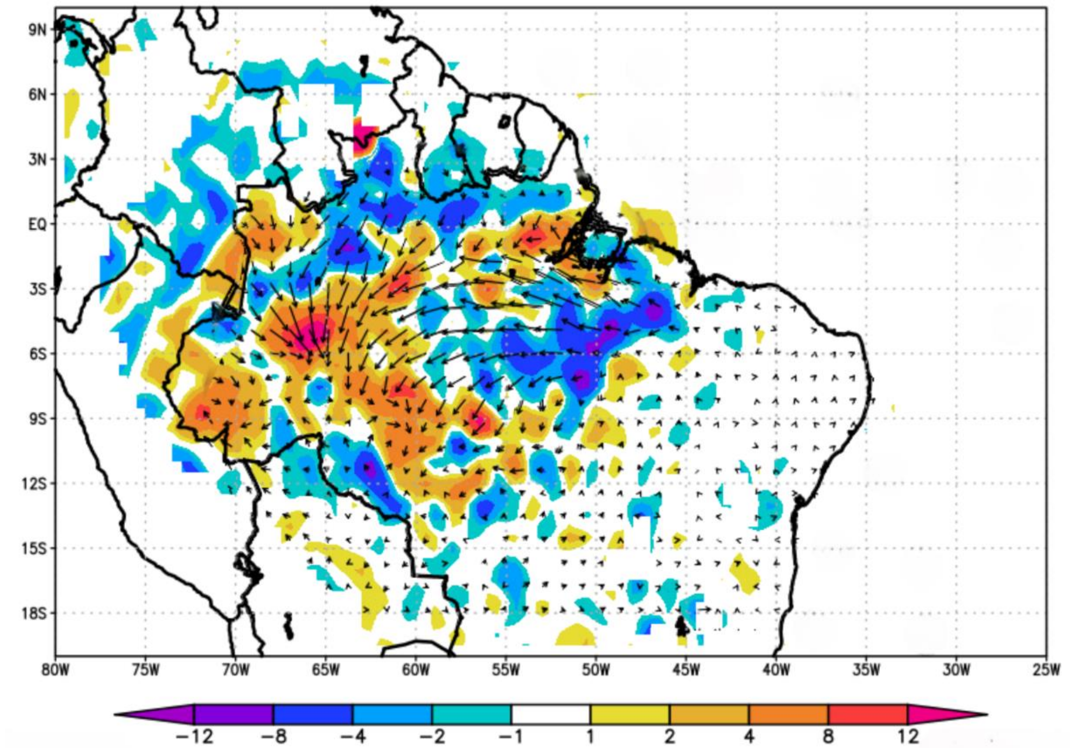


	Pr	T2	ET	Cattle	Milk	GDP	Weight
Pr	1.00	1.00	1.00	1.00	1.00	1.00	16.67
T2	1.00	1.00	1.00	1.00	1.00	1.00	16.67
ET	1.00	1.00	1.00	1.00	1.00	1.00	16.67
Cattle	1.00	1.00	1.00	1.00	1.00	1.00	16.67
Milk	1.00	1.00	1.00	1.00	1.00	1.00	16.67
GDP	1.00	1.00	1.00	1.00	1.00	1.00	16.67
			CR	-0.002			

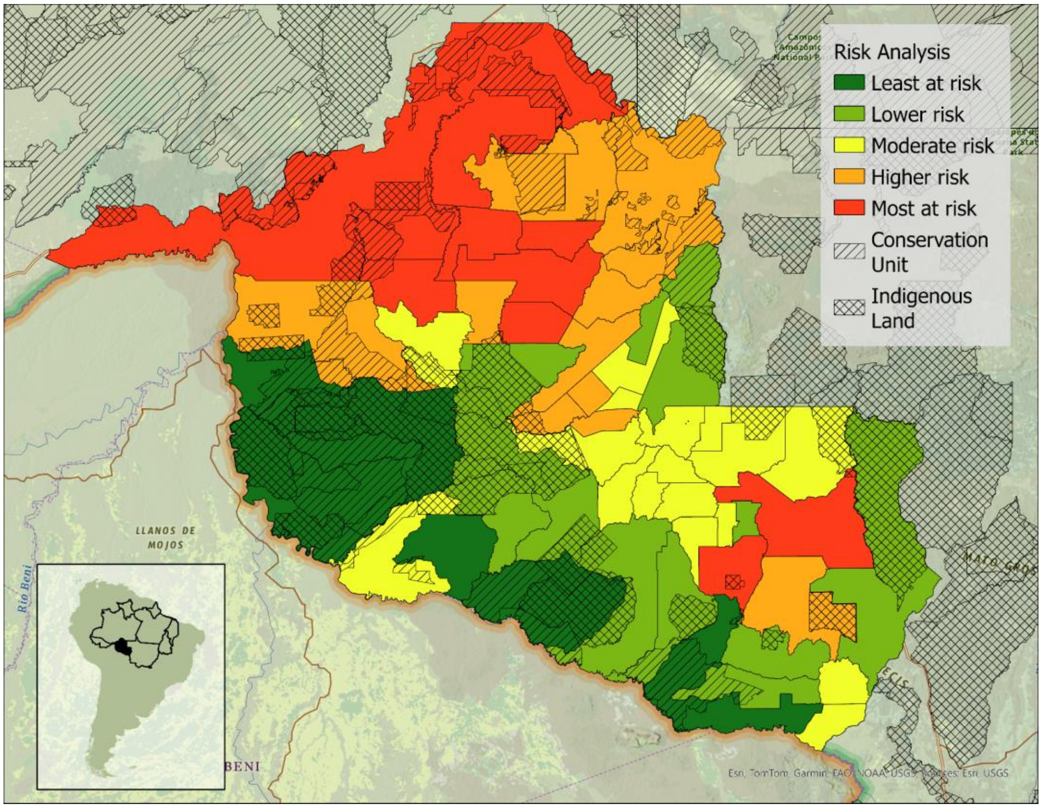
SI Fig. 2 Sensitivity analysis for the six criteria (PR- precipitation change, T2- temperature change, ET- evapotranspiration change, cattle count, milk cow count, and GDP per capita) in the Analytic Hierarchy Process. (A) is focused (in descending order) on climate, agriculture, and GDP (B) is focused (in descending order) on GDP, climate, and agriculture (C), which is an equal weight comparison.



SI Fig. 3 Boxplots of the dry season (JJAS) monthly air temperature [°C] (A), precipitation [mm/day] (B), and evapotranspiration [mm/day] (C) for the control 'CTL' run (blue boxes) and deforestation scenario 'UPA' (red boxes) for unprotected areas 'UPA' versus all remaining lands 'nonUPA' (2015-2019).



SI Fig. 4 Difference in 900 mb moisture flux convergence between the dry season's CTL and UPA deforestation scenarios (JJAS 2015 - 2019).



SI Fig. 5 Risk map for Rondônia overlayed with Indigenous land (green) and conservation unit (pink) regions.

Chapter 4. Changing climate, changing lives: voices of a Brazilian Amazon farming community in a time of climate crisis[3]

4.1 Introduction

The escalating climate crisis in the Brazilian state of Rondônia, located in southwestern Amazonia, underscores the urgency of understanding and supporting the resilience of small-scale farmers to environmental and economic uncertainties (IPCC AR6 WGII, 2022). Importantly, this research directly addresses the compounded impacts of deforestation and climate change on farmer vulnerability and explores adaptation strategies and necessary support mechanisms to mitigate these challenges in this biodiversity hotspot. Through qualitative interviews with rural farmers, we seek to capture local perceptions of climatic change, its effects on agricultural practices and livelihoods, and the adaptive measures employed to confront these shifts. Our investigation is motivated by the need to integrate local insights into broader climate adaptation policies to effectively enhance the livelihoods of vulnerable communities across the Amazon. Evidence shows that adaptation efforts are most successful where national or regional laws are implemented locally and where local efforts are collectively scaled up (Coger et al., 2022; Damsø et al., 2016). This approach aligns with Brazil's National Adaptation Plan’s goals (Brazil Ministry of Environment, 2021), emphasizing the importance of inclusive strategies that promote adaptation and reduce climate risk through coordination among public agencies and society. The paper sets out to answer

[3] This chapter has been submitted to PLoS Climate: Monteverde, C., Quandt, A., Gilberto de Souza Ribeiro, J., De Sales, F. (2024) Changing climates, changing lives: voices of a Brazilian Amazon farming community in a time of climate crisis. Manuscript number: PCLM-D-24-00095

three key questions: How are environmental changes influencing farmer perceptions, agricultural practices, and community dynamics in regions facing deforestation and climate variability? What adaptive strategies are agricultural communities employing to navigate the challenges posed by economic and climatic uncertainties? And what critical support mechanisms and policy frameworks are essential to support farmers' adaptation efforts? These questions are fundamental given the compound impacts of deforestation and climatic change on an agroecosystem of global importance.

Rondônia's transformation from a densely forested area to a landscape significantly altered by deforestation underscores the intricate relationship between socio-political developments, land use, and environmental policies. The inception of settlement expansion in the 1960s and 1970s, facilitated by the construction of the Transamazon and BR-364 highways through the Amazon rainforest, led to rapid population growth and environmental challenges. Because of the new settlements and access to roads, the population exploded from 36,935 in 1950 to 1,130,400 in 1990 (Perdiglao & Bassegio, 1992). This period saw increased reliance on shifting cultivation, which escalated deforestation rates in the absence of adequate governmental planning for sustainable land use (M. A. Pedlowski et al., 1997b; Perdiglao & Bassegio, 1992). This cultivation method led to illegal logging practices, degraded soil quality, and loss of above-ground biomass and tree cover. Initiatives like POLONOROESTE and PLANAFLORO sought to integrate environmental conservation with social development in the latter decades of the 20th century. However, their effectiveness was limited by implementation issues and local resistance, emphasizing the critical role of community engagement in successful conservation strategies (Browder & Pedlowski, 2000; Garrison & Aparicio, n.d.). The 2000s marked a significant policy shift with the establishment of conservation units (CUs) to safeguard biodiversity, alongside the adoption of REDD+ programs and payment for ecosystem services, aimed at aligning economic incentives with environmental stewardship (Biofilica, 2020; M. Pedlowski et al., 2005; Zwick, 2015). While they have been heavily critiqued, these efforts reflect the ongoing attempt to balance agricultural productivity with environmental preservation in Rondônia against market variability and climatic challenges.

In addition to providing basic needs for farmers and agricultural and timber commodities, these forest stands can sequester carbon, regulate freshwater and river flows, modulate regional climate patterns, and ameliorate infectious diseases (Foley et al., 2007b). Therefore, understanding the extent of deforestation in Rondônia is critical (Powell & Roberts, 2010). The construction of roads and the BR-364 highway have influenced the increase in population and rapid rate of deforestation since the 1970s. In 1978, 4,200 km^2 of forest had been cleared, 30,000 km^2 by 1988, and 53,300 km^2 by 1998. Since 2000, Rondônia has lost 26% of its tree cover (Global Forest Watch, 2024). The deforestation in Rondônia follows a predictable pattern, with the first patterns appearing in a fishbone manner and then transitioning to a mixture of forest remnants, cleared areas, and settlements. Changes in the land have impacted regional climate (surface energy fluxes) and hydrology (blue and green water). The research found that Rondônia displayed one of the most significant reductions in total latent heat flux, or evapotranspiration, for the Amazon Basin (Swann et al., 2015). Reduced evaporative cooling leads to drier and warmer conditions, which could potentially place stress on vegetation accustomed to wetter, cooler climates. Agriculture and Rondônia's economy could be negatively impacted if temperatures continue to increase and the land continues to dry with deforestation. In addition, deforestation from unprotected regions outside the state could contribute to increased risk to socioeconomic and demographic factors from climatic change in Rondônia (Monteverde & De Sales, 2024).

Future projections of climate change for the Amazon indicate a drier and more drought-prone state with increased dry season length (Cook et al., 2020; Parsons, 2020; A. C. T. Sena & Magnusdottir, 2020). Global climate models show good agreement on the direction of changes for a drier state, and warming may increase the likelihood of an exceptionally hot drought. There is also high confidence that there will be an increase in the number of dry days and drought frequency (IPCC AR6 WGI, 2021). An increase in rainfall variability could impact extreme events like flooding, which could be amplified by deforestation, which also leads to increased flood conditions by the removal of above-ground biomass and degradation of the soil. An increase in likelihood of extreme events could alter and degrade Amazonian forests (Duffy et al., 2015).

Amazon forests are in transition, as seen through historic and future droughts and an increase in the dry season length (Davidson et al., 2012). In 2023, the agricultural sector in Brazil faced acute drought conditions (UNICEF, 2023), posing significant challenges to farming communities. The drought's severity impacted water levels in rivers and streams, which are crucial for crop irrigation and cattle rearing, leading to decreased agricultural productivity and increased mortality among livestock. As precipitation patterns deviated from historical norms, with unexpected delays in the rainy season and sporadic rainfall, farmers were forced to adapt rapidly to the evolving climate landscape (Rod Nickel et al., 2023). The reliance on artesian wells became more pronounced as traditional water sources dried up, underscoring the urgent need for sustainable water management strategies. The drought's ramifications were not limited to agriculture; the ecological balance of the region was also threatened, highlighting the interconnectedness of environmental health and agricultural viability in Rondônia (André Schröder, 2023). Forests are also under a substantial threat from ranching, farming, road building and logging (Betts et al., 2008). These dynamics stress the necessity of merging agricultural policies with climate adaptation and conservation strategies to ensure the resilience of farming communities amidst escalating environmental and climatic challenges.

This context seamlessly aligns with the discussion initiated by (Hansen et al., 2012), who asks, 'Should the public be able to recognize that climate is changing, despite … variability of weather and climate from day to day and year to year'. Our research emphasizes that 'yes,' it is important and valuable to gain local insight and knowledge on perceptions of climate change and options for adaptation. Although climate change can refer to large-scale changes, the impacts are experienced by individuals at the local level. Research has focused on individual perceptions of climate change and options for adaptation in many regions of the world (Ado et al., 2019; Banerjee, 2014; Battaglini et al., 2009; Brown et al., n.d.; Ishaya & Abaje, 2008; Maharjan et al., 2011; Amy Quandt, 2016; Amy Quandt & Kimathi, 2017) and in Brazil (Barbosa et al., 2020; Foguesatto et al., 2019; Foguesatto & Machado, 2020; Litre et al., 2014). This body of research reveals that 1) individuals are noticing a change in climate and weather patterns, 2) the extent of farmer's awareness and perceptions of climate change impacts influences individual adaptation strategies, 3) there are hindering factors to adoption of adaptation strategies (e.g. access to resources, lack of knowledge of current strategies, lack of capital, lack of awareness and/or knowledge of climate change impacts and causes, etc.), 4) research needs to be scaled-up to enhance region and national policies. Local adaptation strategies are important to document and can be biodiversity-friendly, economically viable, and socially acceptable (Maharjan et al., 2011), but can also be unsustainable. For example, erosive coping refers to livelihood activities (like relying on food aid or charcoal production) that are not sustainable in the long term and can be harmful to the environment or community (Amy Quandt, 2021). This body of research is still developing, especially for Latin American countries vulnerable to climate change (Fierros-González & López-Feldman, 2021). The review by (Fierros-González & López-Feldman, 2021) highlights a critical research gap in understanding farmers' perceptions of climate change in Latin America, emphasizing the need for broader surveys, longitudinal data, and the use of field and choice experiments to better understand and address climate change impacts. Our study in Rondônia, Brazil, fills research gaps by examining local perceptions and adaptation strategies, contributing valuable insights towards enhancing Brazil's National Adaptation Plan and supporting effective policymaking. This approach aligns with the goals of enhancing climate risk reduction and improving coordination among public agencies and the community (Bonatti et al., 2016), offering a more informed basis for designing adaptation policies that are responsive to local needs and conditions.

4.2 Materials and Methods

This research employs an anthropological approach, focusing on qualitative narrative and thematic analysis within a human-social context, following grounded theory principles for data coding and categorization (R. Bernard, 2017). The goal is to weave individual stories into a narrative that uncovers common themes related to the impact of climate change on Rondônia's agricultural community.

4.2.1 Ethics statement

This study was conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments. Informed consent was obtained from all participants involved in the study. Consent was gathered verbally, in line with the participants' cultural context and communication preferences, ensuring their full understanding and voluntary participation. All personal identifiers were removed or altered to ensure anonymity and confidentiality of the information provided by the participants. We submitted this research for International Review Board (IRB) approval through San Diego State University's IRB (Protocol Number: HS-2023-0199).

4.2.2 Study area

Rondônia, located in southwestern Amazonia, Brazil, experiences a tropical climate with a distinct wet season from October to April, characterized by high rainfall and temperatures. The dry season is from May to September, with significantly lower precipitation and cooler temperatures. The study area comprises Ji-Paraná, Ouro Preto do Oeste, and Vale do Paraíso, municipalities within Rondônia (**Fig. 23**). This region witnessed a significant influx of settlers in the 1970s, lured by the area's fertile soils and the construction of the BR-364 highway which enhanced accessibility. Ji-Paraná, with a population over 120,000 (the second largest in Rondônia), produces key agricultural outputs such as cassava, soy, coffee, and milk, generating over $17,000,000 Brazilian Reais from crops and $40,000,000 from milk for the local economy in 2022, as detailed by the Municipal Agricultural Production data (https://sidra.ibge.gov.br/pesquisa/pam/tabelas). Ouro Preto do Oeste, known for its cultural heritage, leads in dairy production with nearly 17,000 milked cows in 2022, surpassing Ji-Paraná's 12,000 and Vale do Paraíso's 8,000, according to the Municipal Livestock Survey (https://sidra.ibge.gov.br/pesquisa/ppm/quadros/brasil/2022). It also produced 29,500,000 liters of milk in 2022, nearly equaling the output of Ji-Paraná and Vale do Paraíso combined. With soy, milk, cacao, and coffee as its main crops, it brought in almost $49,000,000 Brazilian Reais from crops and $60,000,000 from milk in 2022. These outputs reflect the long-lasting agricultural presence in this region. Vale do Paraíso, though smaller, showcases Rondônia's diverse agriculture. With coffee, cassava, banana, and milk as its main crops, it brought in almost $4,000,000 Brazilian Reais from crops and almost $27,000,000 from milk in 2022. Collectively, the municipalities boast over 1 million heads of cattle, with Ji-Paraná contributing nearly half a million, Ouro Preto do Oeste over 400,000, and Vale do Paraíso close to 200,000, emphasizing the region's role in Brazil's agricultural landscape.

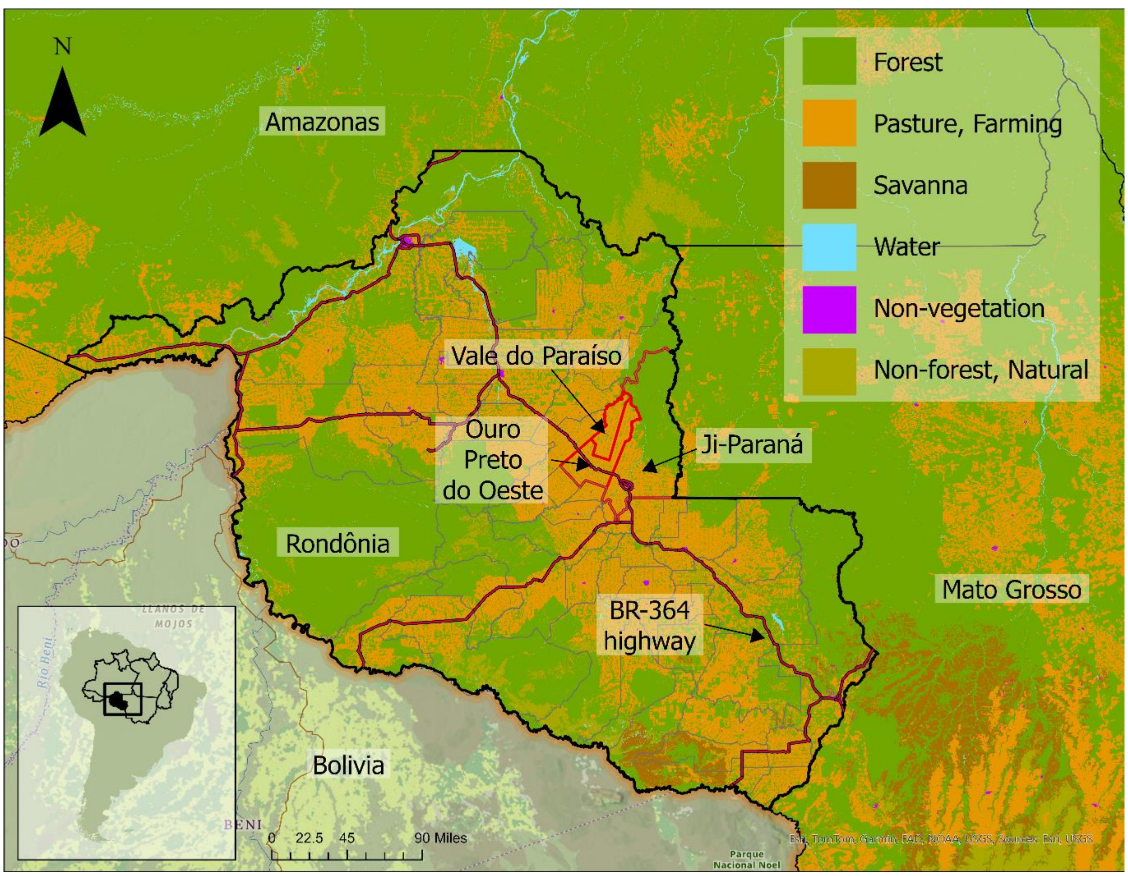


Fig. 23 Study area map and corresponding land cover for Brazilian states (Land cover categories have been reclassified to reflect six major types. Original land cover classifications are from Mapbiomas: https://brasil.mapbiomas.org/en/).

4.2.3 Data collection

We conducted semi-structured interviews with nine participants from Rondônia, Brazil. In October 2023, from Monday the 9th to Thursday the 12th, we conducted interviews at the participants' farms, often on patios overlooking their farms, except for one conducted at a farming union president's office. We chose our interviewees through non-probability convenience sampling, drawing on connections with the Universidade Federal de Rondônia (UNIR), to ensure a range of perspectives within the rural farming sector were represented. Our interviewees included both men and women, leaders of agricultural movements, advocates for sustainable and agroecological practices, and individuals engaged in dairy and crop farming, boasting experiences from 25 years to over 50 years. The farmers interviewed were smallholder rural farmers who managed small to medium-sized plots of land. Many maintained ponds (up to three), their land included multiple crops and livestock, and some had access to equipment such as tractors.

Each interview, recorded for accuracy, lasted 45 minutes and 1.5 hours. We discussed various topics, from personal farming experiences and climate change observations to the impacts on agricultural practices, necessary adaptations, and farmers' emerging needs. The semi-structured format of these interviews, inspired by six main topics from previous studies (**SI Fig. 6**) (Foguesatto et al., 2019; de Matos Carlos et al., 2020; Mitter et al., 2019; Pinho et al., 2022; Yunkura Hameso, 2015), allowed us to explore individual perceptions and experiences in depth, which is in line with the qualitative research objectives of prioritizing data depth and richness (Francis et al., 2010; G Guest et al., 2006; Hagaman & Wutich, 2017)Following the interviews, we contacted the farmers via WhatsApp to gather additional information and follow up on the original 6 guiding topics, which are included in the manuscript.

We decided on nine interviews based on the qualitative social sciences' principle of data saturation, where a new information threshold of ≤5% is typically reached after 6–7 interviews (G Guest et al., 2006; Greg Guest et al., 2020). This method ensured that our sample size was sufficient to uncover the significant themes relevant to our research questions. Conducted in Portuguese with the aid of a translator from UNIR, these interviews aimed to provide a comprehensive understanding of the participants' viewpoints, focusing in-depth on a few perspectives rather than attempting to capture the entire range of experiences in Rondônia's agricultural sector.

4.2.4 Data analysis

Interviews were transcribed using Google's Pinpoint software and translated from Portuguese into English via Microsoft Word Translate for analysis in NVivo software. In our study, we identified analytic categories or codes that emerged from within the text (R. Bernard, 2017). We also drew from a priori assumptions based on the interview guide and literature review. This process facilitated thematic analysis, highlighting key insights on climate change, adaptation strategies, and farmers' needs.

4.3 Results

The emerging themes from our interviews, outlined in Fig 14, highlight shifts towards livestock and dairy, sustainable practices, and community cooperation amidst climate change and economic challenges. Additionally, **Table 9** showcases each interviewee's background, agricultural focus, and approaches to adaptation and strategies amidst climate change. The following subsections will expand upon the major themes in **Fig. 24**.

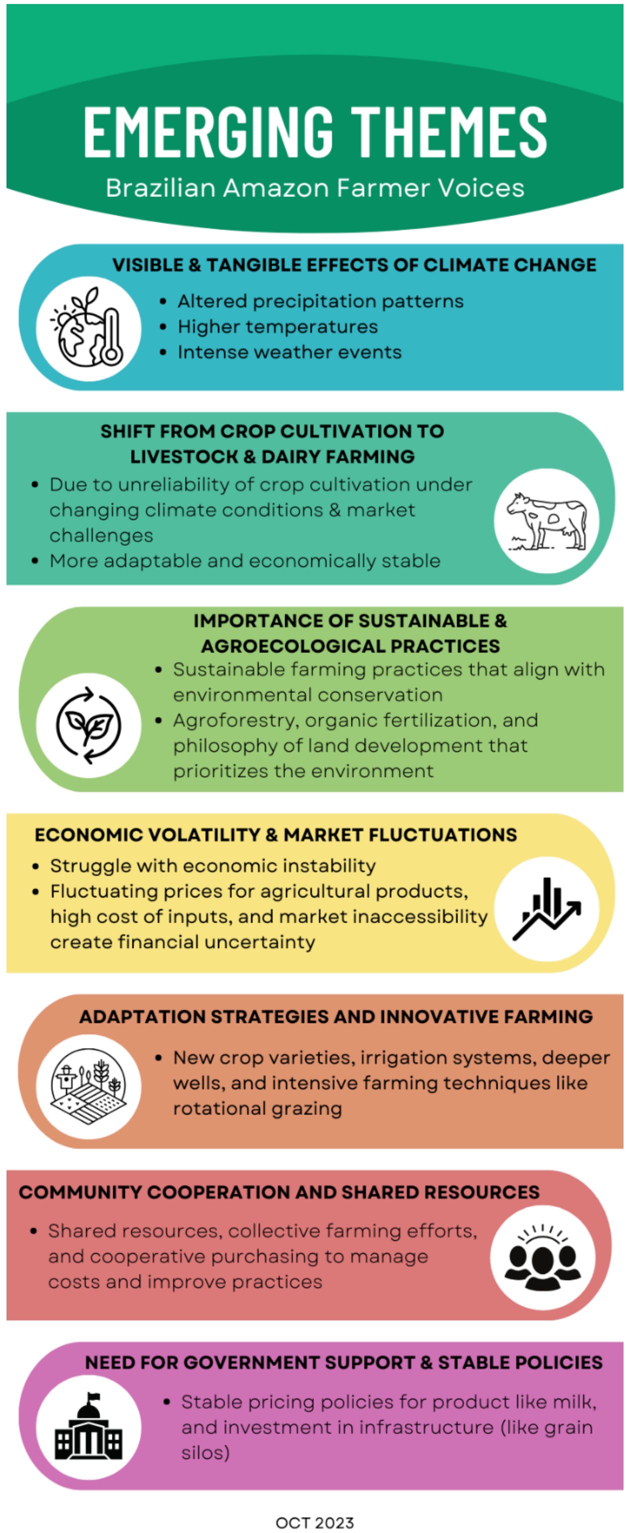


Fig. 24 Emerging themes from interviews.

Table 9. Interviewee background, focus area, and adaptation and strategies to climate change.

Interviewee	Background	Focus Area	Adaptation and Strategies
1	Farmer of 30 years and President of a local farming union	Advocate for sustainable farming	Emphasized organizational representation and policy advocacy
2	Member of MST (Landless Workers Movement) and lifelong farmer of 47 years	Collective farming, agroecology (cocoa, banana, cassava)	Shared production among families focuses on sustainable living
3	13 years of leading agricultural production, shifted to dairy	Dairy farming due to declining crop prices	Highlighted economic necessity and adaptation to climate challenges
4	Lifelong farmer of over 30 years	Watermelon, corn, dairy farming, pig	Noted climate impact on water scarcity and irrigation needs
5	28 years in dairy and beef cattle	Dairy and beef cattle and chicken	Minimally impacted by rainfall variability
6	Diversified farmer with over 36 years of experience	Coffee, fish, cocoa, cassava, watermelon, tangerine, orange, pig, coconut, dairy and beef cattle	Discussed productivity gains and economic challenges
7	47 years as a cacao farmer	Agroecology and sustainable practices (cocoa, banana, beans)	Advocated for education and community engagement in sustainability
8	40 years in dairy farming and crops	Dairy and beef cattle, crop cultivation (mango, avocado, coconut, lemon, orange, cassava)	Highlighted water management challenges and the need for support
9	25 years in farming, shifted to dairy	Dairy production and crop cultivation (corn, cassava, banana, orange, chicken, vegetables)	Adapted through intensive farming methods and seeking technical assistance

4.3.1 Visible and tangible effects of climate change

"Climate change in the past was something we heard was far away. These days, it is happening now, here, and we all can feel it." - Interviewee 6

For precipitation, interviewees chronicled a troubling shift towards unpredictable rainfall schedules, with seasons starting later than usual and resulting in sporadically dry months. For example, interviewee 6 told us, "*This year is different because rain is not dropping. It stays up in the atmosphere and doesn't drop."* In addition, interviewee 7 noted that yearly planting schedules have been altered due to irregular rainfall:

"There have been changes in rain and water levels. In the past, people used fire to clear the area… people had dates to make fires based on rainfall. You also had a schedule for planting beans, corn… you would know when to plant. But no more. The yearly schedule is no longer stable because of the variation in rainfall. Rain used to come in August or September and last until April; now [we] don't know when it will start or end. This year, the rain hasn't fully come. One week there is rain, then three weeks without. No extended periods of rain. Extended periods of dryness. It's irregular."

This alteration has led to critical water shortages, impacting power sources, crop irrigation, and livestock rearing. Interviewee 1 discussed critically low water levels affecting power plants, *stating, "So I think for us who are in the Amazon, these changes are quite visible. If we look at Rondônia for example, last week we were surprised by the news that one of the largest hydroelectric plants…[had] all its turbines locked due to lack of water."* An interviewee highlighted the drastic measures needed to adapt to these new conditions and said, *"water levels have dropped significantly…we've had to dig deeper wells to sustain our crops and cattle, a costly but essential adjustment."* In addition, interviewee 6 recalls,

"There used to be a river, but it's no longer there. It's the climate change! Maybe it will flow with the wet season. In the past dry season, there was water, but not recently. On the dry

season in the past, you could take a shower and clean clothes at the river, but you can't do that anymore. There used to be a hose from the river, but it's all dry now."

In addition to water scarcity, the rise in temperatures and extreme heat challenges crop yields and cattle productivity, as underscored by our interviewees. *"The heat has become unbearable, not just for us but for the plants and animals,"* Interviewee 6 remarked. Interviewee 4 has experienced diminished watermelon yields, stating *that "each year, it feels like the sun burns hotter, and the rain becomes more unpredictable... last year's watermelon crop was a third of what we used to produce."* This illustrates the direct impact of heat on agricultural output. Extreme heat may also impact milk production (see **Fig 25**); as stated by interviewee 5, *"There is some relationship between temperature and milk. During the day, it is so hot the cows find shade under trees and don't come out to eat and graze until 3 PM. Twenty years ago it wasn't a problem, like it is today."* Similarly, Interviewee 8 recalled how *"as a teenager, there was good weather when [I] got here 38 years ago. Climate was more fresh, with rain and wind. Because there was more trees and forest compared to today. Because of the process of deforestation, it is hotter. When you don't have breeze, it's hot. This year is hotter than others."* This highlights the interconnectedness of environmental management and climatic conditions.

Fig. 25 Impacts on cattle and milk during the dry season emphasized by direct quotes from interviewees. This graphic contains images from farmland and livestock of Rondônia, taken October 2023.

A common theme among farmers was the damage to crops due to high wind speeds, with several recounting how unexpected gusts decimated banana plantations or knocked off roofs. For example, interviewee 2 stated *“there are stronger winds between [the] wet and dry season. In 50 years [I] have never seen something like that. Bananas in the dry season stay weak. In recent times, bananas are even weaker and can be knocked down by wind causing economic loss.”*

In addition to the impacts on water scarcity, crop yield, and livestock production, interviewees recounted experiences of regional change and their perceptions of the interconnectedness between deforestation and climatic changes. Interviewees remarked on the changed landscape stating *“When [we] arrived here, all of the land was grass for pasture… the government opened this land for farmers to deforest long ago. This changed the land.”* and noting *“each year it’s hotter”*, *“the sun is hotter”*, and *“this year is hotter than others”*.

These environmental stressors have not only led to immediate economic losses but have also heightened concerns over long-term agricultural sustainability and food security, emphasized by interviewee 1 who said,

"Today family farm area is decreasing. The population in this state is decreasing too. There are now less local producers of food here. Loss of labor and workers creates secondary impacts. Decline in local food production and increase reliance or imports from other cities. Soil and corn are being exported to other countries instead of being used here. Climate change has happened."

4.3.2 Shift from crop cultivation to livestock and dairy farming

"...Coffee became difficult to produce due to the drop in price, the lack of labor, the rise in fertilizer prices, in addition to investments in machinery, making production unfeasible... the financial return did not compensate for the investments and the work of this culture. Little by little we cut down the coffee plants and planted grass to increase milk production, which was still small. From then on, dairy production became [our] main economic activity." - Interviewee 3

The transition from crop cultivation to livestock and dairy farming emerges as a significant trend among farmers. This shift is primarily attributed to the economic pressures and uncertainties associated with traditional crop farming, notably coffee cultivation. Several factors, such as the volatility in coffee prices, escalating labor and fertilizer costs, and the substantial investments required for modern farming machinery, have made crop production increasingly untenable for local farmers.

This underscores the economic challenges driving this strategic shift. Farmers like interviewee 3 have explicitly documented their pivot from coffee to dairy to respond to these economic challenges, moving towards more sustainable and financially viable agricultural practices. The benefits of switching to dairy farming are further illustrated by interviewee 9, who diversified their agricultural focus away from not just coffee but also corn and rice, focusing on milk and cattle production due to the unsustainable costs associated with crop irrigation.

The narrative of dairy farming as a lifeline is echoed across multiple accounts. Interviewee 5 notes milk production as the *"source of life"*, emphasizing its critical role in their economic and nutritional sustenance. Similarly, interviewee 6 and interviewee 8 have found dairy farming to be a more manageable and profitable venture, with interviewee 8 also integrating fruit cultivation for personal consumption, thereby enhancing their food security and dietary diversity.

4.3.3 Importance of sustainable and agroecological practices

"Today [we] are using sustainable farming approach to slowly change and revitalize the land with hard work. It's taken 14 years to get [the forest] where it is today. [We] don't use fire or chemicals, only natural methods which are more difficult. This isn't just a way to earn money, it's a way of life. It's built on the principles of respect and not prejudice. There is no place for unnatural things like damming rivers or trying to go against nature. These communities are in synergy with all nature and the natural world." - Interviewee 2

Central to some of the farmers' techniques is the integration of agroforestry, organic fertilization, and a holistic philosophy of land development that values ecological integrity. Sustainable farming emerged as a pivotal theme, underscoring a departure from practices that exacerbate climate change. This encompasses adopting methods that prevent deforestation and promote the responsible stewardship of land and forest resources. For example, the

Landless Workers' Movement (MST) participants used a collective approach to transforming previously degraded pastures into vibrant ecosystems through sustainable practices.

Agroecology was another dominant theme, where practices such as agroforestry and organic fertilizers were prevalent. This is particularly evident in how some farmers drew on family traditions, like interviewee 7 when he told us that *"in the past [my] father planted different trees 50 years ago. [My] father once practiced deforestation but then realized if everyone does this… it will not work. So [he] developed a sustainable philosophy over a generation of family experience."* This knowledge was passed down through generations to cultivate crops alongside forestry, enhancing biodiversity and ensuring the sustainability of their farming operations. Such practices are not only about maintaining productivity but also about nurturing the land to support future generations. Engaging with agricultural family schools to share these principles highlights the critical role of education in fostering sustainable farming practices. The importance of agroecological practices was further reinforced by efforts like preserving water sources and creating habitats for wildlife. For example, interviewee 8 planted trees near their river and hung bird feeders around their farm for local animals, stating, *"we have to plant trees for animals because the animals have almost nothing left, so they starve."* These efforts illustrate a proactive stance towards farming that contributes to ecological balance and sustainability, adding to the overall adaptation strategies outlined in Table 10.

4.3.4 Economic volatility and market fluctuations

"Milk production is crucial for us; it's a significant source of income for those who don't have another revenue source…the major challenge isn't the climate alone but the milk prices… it fluctuates too much, making it hard for us to predict our earnings and plan

accordingly… Sometimes the market price for milk is so low, yet it demands so much from us. We live with the hope that our efforts in milk production will be well rewarded." - Interviewee 5

A common theme among the interviewees was the struggle with fluctuating prices, especially for commodities like coffee and milk. This instability had forced a shift in agricultural focus, with some farmers moving away from traditional crop cultivation to more stable ventures like dairy farming despite the challenges posed by the variability of milk prices.

Farmers emphasized the importance of regulatory interventions to stabilize market prices and ensure fair compensation. The call for price protection and stable pricing mechanisms was a recurring suggestion to mitigate the economic uncertainties faced by the agricultural community. For instance, the need to *"regulate the pricing of milk!"* was mentioned as crucial for providing financial security and enabling long-term investment and planning. The experiences shared highlight the broader economic pressures that compel farmers to adapt their practices, seeking more profitable alternatives despite the inherent challenges of maintaining production costs and finding reliable markets for their products. Interviewee 9 told us, *"During the coffee harvest season, the price per bag always decreases. Coffee producers always store their product to sell outside of the harvest season. On the other hand, milk prices always drop during the rainy season. Producers then engage in breeding so that cows give birth during the dry season when milk prices are a bit higher. Coffee prices always lower or fluctuate during the harvest season. While milk prices are always a bit higher per liter during the dry period."* When we asked, *"are milk fluctuations easier to manage than* *coffee fluctuations?"*, they responded, *"Yes, milk ones are easier than coffee ones."* Interviewee 3 explained this fluctuation dynamic very well saying,

"Regarding the price of coffee, we end up investing a lot, having to do a lot of work and have to wait all year for the harvest, an annual crop, and when that time comes, coffee prices drop. Milk is a daily crop, you have money every month, even if the price fluctuates, you can produce less and use the milk to make other things, like cheese, being able to sell it and make a profit. In addition, we can sell the cow and calf, if it is too much of a loss for this crop. In a certain way, producing milk is more profitable and less labor intensive than coffee, even with this price fluctuation."

Interviewee 9 echoed this summary, explaining, *"The coffee has [a] collection once a year, and labor every day of the year, and sells the harvest all at once. Milk is produced every day of the year, and [has a] financial return every month of the year."* These explanations illustrate the differences in market impacts on coffee and milk production, emphasizing the more consistent revenue and flexibility of dairy over the annual and more labor-intensive coffee crop.

4.3.5 On-farm adaptation strategies

"As the drought is becoming more and more severe, the water wells run out, and there is no quality water for [the cows]. On our property we have a dam that in droughts causes the water to become dirty and this ends up not being good for the herd, with some animals having diarrhea, which causes them to lose weight and become sick…We have to buy medicine, which is expensive… But in other places on the property we have river water, running water, which is of good quality, so we always prefer to leave the cattle in this place where the water is better for consumption." - Interviewee 3

In addition to some of the adaptation strategies mentioned in other sub-sections, Farmers in Rondônia are employing diverse adaptation strategies on their farms to address the dual challenges of climate change and market volatility, focusing on irrigation adjustments, crop diversification, and sustainable resource management. To combat increased temperatures and irregular rainfall patterns, they have adopted midday irrigation practices for their crops to prevent crop burn, and introducing more resilient seeds has become common. The construction of wells and dams to secure water sources is a testament to farmers' proactive approach to ensuring water availability for their crops and livestock. An example of these adaptation efforts is the use of protective coverings for watermelon crops, as depicted in **Fig. 26**. Interviewee 4 told us *"sometimes we manage to save some of the fruit [from the heat] by covering them with newspaper and with a thin mixture of wheat flour and water that is used as a glue. Today, there are sunscreens that are sold for the fruits. We also have drip irrigation."*

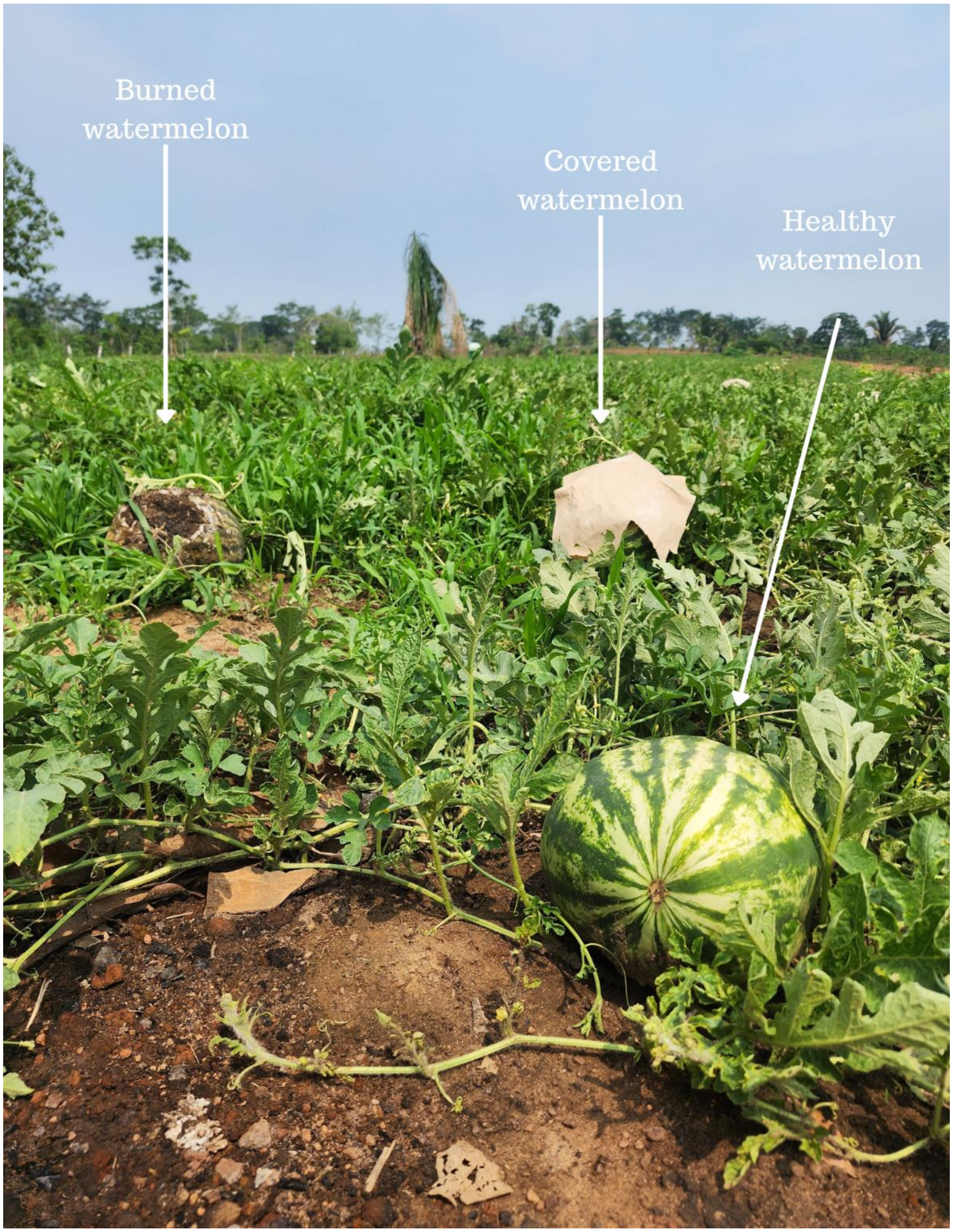


Fig. 26 Watermelon crop with protective covering from the intense heat. In this photo you can see a burned watermelon, a covered watermelon, and a healthy watermelon (Vale do Paraíso, RO, BR. October 2023).

Leveraging community and expert support has proven crucial in navigating the economic uncertainties of fluctuating market prices. Interviewee 9 told us that *“the collective purchase of fertilizers, to lower the cost per bag of fertilizers, by making this purchase in a group, the price is greatly reduced. It comes out very affordable and helps us producers a lot, lowering the cost financially for the property. And we continue to buy, not just fertilizers, but also corn, soy, seeds, and others, even the purchase of good genetic cattle"*, illustrating the power of collective action in reducing operational expenses. The innovative spirit of adaptation is vividly exemplified by Interviewee 9, who introduced a rotational system for pasture management and supplemented livestock feed with corn to enhance productivity. These efforts are detailed further in the vignette section, offering an in-depth look at the practical applications of adaptation strategies. By systematically adopting these innovative farming practices, Rondônia's farmers demonstrate remarkable resilience and adaptability. Their efforts, detailed in **Table 10**, highlight a determined response to environmental and economic pressures.

Table 10. Adaptation themes and strategies

Theme	Strategy
Policy and advocacy	1. Working to create state laws benefiting conservation-focused farming 2. Advocacy for fair prices and public policy protecting farmers
Water management and irrigation	1. Adopting midday irrigation to prevent plant burn 2. Construction of wells into aquifers or dams for water retention (e.g., digging down 60 meters for water) 3. Reforestation around rivers to secure water levels
Crop and livestock management	1. Changing cultivation habits and focusing on market-demanded and climate-resilient crops 2. Planting drought-resistant seeds 3. Switching production from crops to livestock 4. Innovative practices like rotational grazing for increased milk production 5. Using expensive insecticides mixed with salt for livestock health
Technology and knowledge	1. Utilizing technology and knowledge for optimizing production (e.g., increasing coffee yield from 30 to 170 bags per hectare) 2. Consulting with experts and organizations like EMATER (State Technical Assistance and Extension Services), SENAR (National Rural Learning Service), and EMBRAPA (The Brazilian Agricultural Research Corporation) for adaptation strategies

4.3.6 Community cooperation and shared resources

"We are the fruits from our collective efforts." - Interviewee 2

In Rondônia, the essence of community cooperation and shared resources emerged as a pivotal force in supporting the agricultural sector. Organizations such as FETAGRO (Federação dos Trabalhadores Rurais Agricultores e Agricultoras Familiares do Estado), a trade union entity for the representation, articulation and mobilization of rural workers in family farming, demonstrate the power of collective advocacy, working toward policies that reward environmentally responsible farming and ensure economic sustainability for local farmers. Interviewee 1 told us that *"FETAGRO is fighting for public policy that protects farmers. For example, there is a fight for the price of milk. If they lose this fight, they may have to change their production. FETAGRO plays an important role in amplifying farmer voices and advocates for fairer prices."* This approach was mirrored in the communal farming practices championed by members of the MST (Movimento dos Trabalhadores Rurais Sem Terra) movement, as interviewee 2 told us *"Everything we create, from energy to internet, we own and share. It's important because the MST sees how important it is to be together and share production and help one another. For example, the MST can purchase a motorcycle for the entire group to use. Our model is oriented to preserve the forest in our own small way."*

Local fairs and municipal support offered vital platforms for farmers to sell their produce directly, fostering economic stability and facilitating access to essential agricultural resources, such as machinery. This community-driven marketplace underscored the role of local networks in bolstering agricultural livelihoods. Furthermore, collaborative purchasing strategies exemplified the tangible benefits of communal efforts in reducing operational costs and enhancing farming efficiency. For example, interviewee 9 told us that they *"were able to band together with 30 farmers to buy fertilizer cheaper to grow corn to supplement cows"* during the dry season. Interviewees mentioned support from organizations like SENAR (Serviço Nacional de Aprendizagem Rural), EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), and EMATER (Empresa de Assistência Técnica e Extensão Rural) as being crucial, offering technical guidance and resources that enabled farmers to adapt and thrive amidst the challenges posed by a changing climate and market dynamics. Interviewee 8 demonstrated the support from these organizations telling us that *"[My] bananas used to be good. Today there is a problem. The heat is an issue. Can't plant at the same time because you have to learn another crop. I talked to EMBRAPA to learn how to plant bananas."* These relationships with technical organizations also contribute to farmer strategies in the midst of changing climate (Table 9).

4.3.7 Need for government support and stable policies

"Certainly, farmers are vulnerable…today, what the Amazon is experiencing, we really need a lot of help to effectively address the policies...with President Lula, we try to redo the path, but it has been very difficult." - Interviewee 1

Farmers emphasized the necessity of government support for agribusiness education, infrastructure like machinery and grain silos, and stabilization of volatile market prices, particularly for milk. They advocate for assistance in securing water sources and support for environmentally sustainable practices, including local organic fertilizer production funding. The need for straightforward legislation, less bureaucracy, and expert guidance for navigating agricultural policies was clear, highlighting the demand for policies that ensure price stability and reduce administrative burdens. The importance of government-backed financial and institutional support to foster sustainable farming and ensure the economic resilience of agriculture amidst environmental and market uncertainties was underscored by all interviewees (**Fig. 27**).

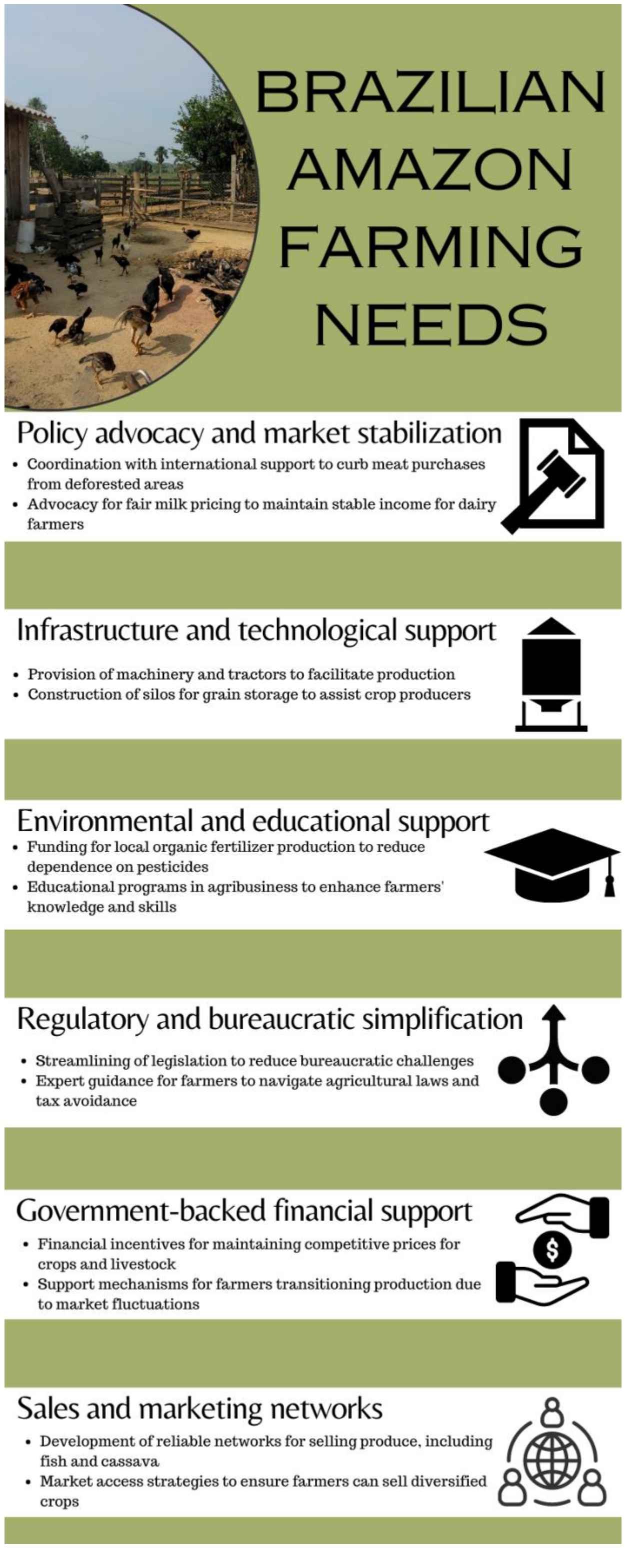


Fig. 27 Brazilian Amazon farming needs. Revealed through interviews conducted October 2023.

"[The] Problem is the price of milk and other crops. There is a lot of variation in price. It's very difficult to maintain, for example coffee. Crop prices fall, which makes the product difficult to sell. So you change production to something like cassava, because the price is down… I invested in 3 ponds for fish, which is good for money… but it's difficult to find [someone] to buy fish and you have to keep feeding them. There's some plan to sell fish, but hard to do that… [there's] no network working well to take production or there are no regular markets to take the fish to sell. There is support from municipalities, [like] EMATER for coffee... There needs to be support for the price of products. Farmers switch production, but there is nobody to buy it! I have 3,000 plants of cassava and coffee, but nobody wants to buy the product."

This farmer's experience highlights the critical need for governmental intervention to stabilize agricultural prices and establish reliable market networks, underscoring the broader challenges of economic volatility and market fluctuations that necessitate a comprehensive support system for sustainable agriculture in Rondônia.

4.4 Vignette

The previous section highlighted major themes spanning the nine interviews. However, to provide a more nuanced, in-depth understanding of the perspectives and decision-making processes of specific individuals and households, this section includes a vignette from Interviewee 9.

4.4.1 Rotational grazing and resilience

Interviewee 9, with 25 years of experience in farming in Rondônia, has transitioned from coffee production to focusing on milk and livestock due to climatic challenges and market demands. Observing significant environmental changes, such as sporadic rainfall and increased temperatures, they adapted by innovating farming practices, including introducing rotational grazing and supplemental feeding with corn and a mineral mix to sustain livestock during the harsh dry seasons. This adaptation was bolstered by collaboration with 30 other farmers to affordably purchase fertilizers, enhancing feed production efficiency. Despite facing bureaucratic hurdles and advocating for stable milk prices in a fluctuating market, Interviewee 9's innovative approach to pasture management and cattle nutrition during the dry season showcases the resilience and the successful integration of traditional knowledge with modern agricultural techniques, highlighting key themes of adaptation to climatic extremes. The management steps throughout the year are outlined below and pictorially in **Fig. 28**.

Fig. 28 Interviewee 9's rotational grazing strategy. The wet season (December, January, February) (panels A, B, C, D), the transitional period (March, April, May) (panels E, F, G), and the dry season (June, July, August, September) (panels H, I, J). Preparation of planting corn (A), second fertilization (B), at the point of producing corn silage (C), ready to be harvested (D), cutting the corn (E), storing the crushed corn (F), after fermentation period of 40 days corn can now be fed to animals (G), the calves receive corn silage in a trough during the dry season (H), cows in a rotated paddock are fed in a trough with corn silage and formulated feed (kernel, corn, soy) (I), the rotated picket area (J) (Ouro Preto do Oeste, RO, BR. Photos courtesy of Interviewee 9).

During the wet season (December, January, and February), efforts focus on preparing the land for corn cultivation, which will be made into corn silage, vital for dry-season cattle feed. This stage involves soil correction and fertilization to optimize plant growth and nutrition. This period is crucial for planting corn, with intensive care at three key growth stages, ensuring plants are well-nourished. As the transition to the dry season (March, April, May) begins, corn is harvested at its nutritional peak for silage, wrapped under 200-micron plastic tarps, and allowed to ferment for about 40 days to serve as a crucial feed source. In anticipation of the dry season, interviewee 9 also adopts a strategic approach to cattle management, making preemptive decisions to sell certain animals. This tactic is employed to circumvent the challenges that arise from feed shortages, ensuring that the herd size remains sustainable throughout the harsher dry season conditions. The less productive cattle are selectively sold for beef, a practice that not only ensures the economic viability of the farm but also allows for the concentration of resources on the higher-yielding members of the herd. Throughout the dry season (June, July, August, September), Interviewee 9 ensures cattle well-being by providing shade, clean water, and a linear feeding space of 1.20 to 1.50 meters per animal to reduce stress, alongside a formulated diet of core nutrients, corn, soy, and silage. A 27-paddock rotational grazing system allows cattle to graze continuously while ensuring vegetation recovery, with each paddock grazed for 24 hours before moving on. This comprehensive year-round strategy exemplifies a blend of resilience and modern agricultural practices, adapting successfully to climatic extremes.

Interviewee 9's technical knowledge is learned from hands-on experience alongside expert advice from agricultural extension programs like SENAR (Serviço Nacional de Aprendizagem Rural). As a member of the local rural workers' union, they contribute a nominal fee that grants access to various services, including technical guidance provided by SENAR. This guidance, offered free of charge, is pivotal for the farmer, especially during the dry season. SENAR's technician visits the farm monthly, advising on essential aspects such as herd management, nutritional strategies for cattle, and land management techniques. This assistance informs their day-to-day operations and contributes to the farm's long-term resilience and productivity. SENAR’s wide-ranging expertise in agriculture and livestock is a key resource for farmers navigating the challenges of sustainable agriculture in Rondônia. Such professional guidance has been instrumental in optimizing cattle breeds for higher production efficiency and resilience to changing environmental conditions.

4.5 Discussion

4.5.1 Adapting to change: climate impacts and agricultural shifts

The manifestation of climate change on agriculture in Rondônia was observed by our interviewees, who noted significant deviations in weather patterns, resonating with the broader climatic shifts observed across the Brazilian Amazon. Studies report similar experiences, suggesting that farmers nationwide are noticing a pattern of changing precipitation, heightened temperatures, and an escalation in weather extremes impacting agricultural activities (Alves De Vasconcelos et al., 2022; Vincent Dubreuil et al., 2017; Litre et al., 2014). Biophysical records also show an intensification of temperature, drought, and extreme events across the region (Jiménez-Muñoz et al., 2016a; Lewis et al., 2011; J. A. Marengo et al., 2011, 2016; J. A. Marengo & Espinoza, 2016; Jose Antonio Marengo et al., 2012). However, regional variances are apparent, with areas experiencing more pronounced changes than others, potentially reflecting localized deforestation impacts and microclimate variations (D'Almeida et al., 2007; Pilotto et al., 2017). For example, (Funatsu et al., 2019) found that rainfall trends and perceptions are often dissonant, but the southern Amazon communities showed a clear perception of decreased rainfall, which matched with measured amounts. When juxtaposed with climate projections of deforestation impacts, farmers' perceptions of increased irregularity in rainfall and hotter temperatures align with model forecasts for the region (Monteverde & De Sales, 2024; F. De Sales et al., 2020). These model projections indicate that farmers in the Amazon will continue to confront amplified weather anomalies, necessitating adaptive measures for continued agricultural productivity and sustainability (Gillian L. Galford et al., 2013; Jose A. Marengo et al., 2021).

A major finding of this study is that farmers are strategically pivoting away from coffee production and towards livestock and dairy farming to adapt to the increasing unpredictability of crop yields, market fluctuations, and prices. The shift towards dairy systems in Rondônia mirrors trends observed in Paraná State, to the south of Rondônia, where, in addition to climatic changes, institutional and market changes have catalyzed a geographic redistribution and intensification of dairy farming, signaling a broader regional development and presenting new challenges across the milk production chain (Bánkuti & Caldas, 2018). The transition from coffee plantations to pasturelands is indicative of broader adaptation strategies that are emerging as farmers seek more stable and resilient livelihoods in response to climate and market pressures (Oosting et al., 2014; Weindl et al., 2015). This movement away from traditional crop cultivation, particularly coffee, resonates with findings in the literature that highlight the vulnerability of coffee production to climate change (Gusli et al., 2020; K. de Sousa et al., 2019), with a 60% decline in suitable unshaded coffee plantations for Brazil by 2050 (Gomes et al., 2020). It has also been found that transforming forests into agricultural land can increase wealth and resources for small-scale farmers (Mullan et al., 2018). However, research in East Africa has shown the opposite results, with many farmers preferring to transition from livestock to modern, irrigated agriculture to cope with increasing drought (A. Quandt & Kimathi, 2015; Amy Quandt, 2021). In this region of the world, this change is likely driven by decades of government policy encouraging the adoption of agriculture alongside changing cultural and social norms (McCabe et al., 2010; Amy Quandt, 2021). Alternatively, in the Brazilian context, this adaptation underscores the need for agricultural policies that support sustainable livestock management and resource efficiency, ensuring environmental balance while securing farmers' futures in the face of a changing climate (E. Garcia et al., 2017).

Farmers are turning to innovative adaptation strategies to counter the escalating challenges of climate change. Introducing new crop varieties and irrigation systems represents a significant shift towards climate-smart agriculture to sustain crop production despite growing drought conditions (Burney et al., 2014; D. A. da Cunha et al., 2012). This transition to irrigated agriculture and the construction of wells and dams, while essential for maintaining productivity in the face of decreasing rain, also sparks a dialogue on the potential repercussions for water availability, downstream conditions, and soil health, echoing concerns that these practices, if not carefully managed, could lead to adverse environmental impacts (de Figueirêdo et al., 2014; Maneta et al., 2009; A. Quandt et al., 2022). For example, Multsch et al. 2020 (Sebastian Multsch et al., 2020) found that irrigating all 45.6 million hectares of Brazil's rain-fed area would strongly impact surface water resources, resulting in more than half that area experiencing critical to very critical water scarcity. Alternatively, the adoption of rotational grazing systems, underscores a commitment to sustainable land use and the health of livestock, critical for maintaining productivity (de Oliveira Silva et al., 2017; dos Reis et al., 2021), especially because more than half of Brazilian livestock production is on degraded pastures. It has also been found that dairy intensification on small-scale farmers in the Brazilian Amazon has been correlated with reduced deforestation, helping to meet climate policy objectives of preserving marginal forests (Caviglia-Harris, 2018). The example of rotational grazing from Rondônia, mirrored by similar practices worldwide, displays the potential for localized strategies to be adapted across diverse agroecological zones, emphasizing the need for a unified approach to climate adaptation and resilience frameworks, ensuring food security and environmental sustainability.

These strategies highlight the dynamic nature of adaptation and the ingenuity with which local farmers respond to climate variability. Studies across Brazil and elsewhere underline the effectiveness of drought-resistant crops, water-saving irrigation, and community-based adaptation in building agronomic resilience (Fan et al., 2017; Herwehe & Scott, 2018; Rivero et al., 2021; Wright et al., 2016). The Intergovernmental Panel on Climate Change advocates for such resilient agricultural practices, recognizing them as vital to ensuring food security and farmer livelihoods in the context of global climate change (IPCC, 2022). Within these adaptation strategies lies the core of community collaboration, which has proven fundamental for cost management and the enhancement of agricultural practices, positioning communal efforts as a cornerstone of climate resilience in rural economies (dos Santos et al., 2020).

4.5.2 Economic and ecological resilience

Changing climate conditions, economic volatility, and market fluctuations pose significant challenges, compelling farmers to adapt from traditional crop cultivation to more stable livestock and dairy farming endeavors. This shift necessitates a framework of policies to stabilize market prices and ensure fair compensation, particularly for products like milk, which are pivotal for the local economy (Farina, 2008). A case study from Brazil, conducted by (Piao et al., 2021), underscores the importance of government and private sector collaboration in transforming traditional dairy chains into sustainable systems. It suggests that knowledge sharing and rural extension services are pivotal in this transition. In addition to policies and government collaboration, incorporating technological advancements in dairy production suggests a promising strategy for enhancing economic resilience by potentially reducing the amplitude and duration of milk price oscillations (Simões et al., 2017). Moreover, legal reforms, enhanced technical support, and stronger producer organizations, particularly through cooperatives and associations, can significantly impact the formalization and market success of dairy sectors in Brazil, mirroring successful outcomes seen in goat and sheep production (Guimarães et al., 2022).

In Rondônia's shifting agricultural scene, adopting agroecology and community-driven adaptation strategies is essential for addressing the challenges of climate change and market fluctuations. Agroecology emphasizes integrating ecological principles into sustainable, environment-friendly farming systems and offers a path toward ecological and economic stability. This methodology, highlighting environmental stewardship and the synergy between living entities and the ecosystem, necessitates a grassroots approach that considers economic, technological, and policy drivers (Bezner Kerr et al., 2023; Ewert et al., 2023; Wezel et al., 2020). (Ewert et al., 2023) found that the success of agroecology and the movement toward more sustainable and resilient agricultural food systems will require a bottom-up approach, from farm to region to globe, and must give attention to drivers related to economy, technology, and policy. Such strategies, exemplified by the collective endeavors of

FETAGRO (farming union) and the MST (Landless Workers Movement), showcase successful climate adaptation and vulnerability mitigation efforts comparable to those observed globally, stressing the role of communal resource-sharing and collaborative decision-making in fostering agricultural resilience (Basel et al., 2020; Owen, 2020). However, Rondônia's escalating deforestation and climate shifts, marked by rising temperatures and reduced rainfall, threaten agricultural sustainability. Without targeted interventions against ongoing deforestation of protected and unprotected lands and climate change, the conditions faced by farmers could deteriorate further, undermining efforts toward sustainability and resilience (Monteverde & De Sales, 2024; F. De Sales et al., 2020). This scenario stresses the need for integrated environmental and agricultural governance to mitigate climate and deforestation impacts on farming and ecosystems, aligning with global calls to bolster community resilience through actionable, localized solutions (Ahmed et al., 2013; Altieri & Nicholls, 2017; Ensor et al., 2018; IPCC AR6 WGII, 2022).

4.6 Implication for policy makers

The essential policy implications stemming from the study results underscore the nexus between climate adaptability and economic viability in agriculture. Key strategies emerging from the results include: (1) Crafting and enforcing policies that bolster climate resilience, encourage sustainable farming and efficient water use, and promote eco-friendly livestock management, considering Rondônia's specific environmental and socioeconomic landscape. Entities like SENAR can play a pivotal role in policy dissemination and education; (2) Establishing fair pricing and market support mechanisms to counteract the economic precarity caused by market volatilities, thereby securing farmer incomes. Organizations such as FETAGRO are crucial for facilitating communication between farmers and governmental bodies; and (3) Advancing sustainable farming through community-driven approaches, drawing on successful models like the MST to build climate resilience.

4.7 Conclusions

This research outlines the experiences of farmers in Rondônia, Brazil, examining their strategies for adapting to climate change, shifting agricultural practices, and the overarching need for supportive policies. This paper provides a nuanced understanding of how agricultural communities respond to environmental challenges through qualitative analysis of interviews from Ji-Paraná, Ouro Preto do Oeste, and Vale do Paraíso. Key findings underscore the tangible impacts of climate change on agriculture, the critical importance of sustainable and agroecological farming methods, and the essential role of community cooperation and policy support in fostering resilience and sustainability in farming practices.

The study highlights the necessity for a dual approach in policymaking: bolstering technical assistance to facilitate adaptation to climate change and sustainable farming practices and implementing market support mechanisms to ensure fair pricing and economic stability for farmers. This multifaceted strategy aims to address climate change's immediate and long-term challenges, promoting resilience and sustainability within agricultural communities.

However, this investigation acknowledges its limitations, primarily its reliance on a qualitative methodology and a small sample size, which may not allow for broad generalizations across all farming communities in Brazil. Future research should consider expanding the scope to include longitudinal studies, which could provide deeper insights into the long-term efficacy of the adaptation strategies identified and explore the evolving nature of policy impacts on agricultural sustainability. Investigating the role of private and public partnerships in enhancing sustainable agricultural supply chains could also offer valuable perspectives on improving the resilience of farming systems against climate change.

In conclusion, this paper calls for urgent action to support the agricultural sector in Rondônia and beyond, highlighting the imperative for integrated approaches that combine policy intervention, technological advancement, and community engagement to navigate the complexities of climate change. As the global community grapples with these challenges, the experiences of Rondônia's farmers emphasize the need for concerted efforts to ensure the sustainability and resilience of agricultural livelihoods in the face of an uncertain future.

4.8 Supplementary information

Fig. 6 Interview Guide

Introduction

- Acknowledgement for taking the time to contribute to the research project
- Ask for permission to record the interview and use data for research project
- Summarize data privacy act and get verbal consent for interview
- Explain expected duration of the interview: 1-1.5 hours
- Summarize aim of the research project
- Emphasize interest in the interview partners' personal experience, perceptions, and attitudes
- Provide overview of the interview guide
- Ask if they have any questions before the start of the interview

Guiding topics and questions

1. Please describe your experience with agriculture in this region

2. Perceived changes in climate conditions

3. Perceived impacts on the farm

4. Implemented adaptation measures

5. Support and barriers to adaptation

6. Would you like to add something we have not discussed yet?

Closing

- Thank you for this interview
- Interested in the final results?

Chapter 5. Conclusions

5.1 Summary of Results

This dissertation aimed to understand the impacts of climatic changes and deforestation in the Brazilian Amazon and its effects on local communities and ecosystems, contributing directly to Brazil's National Adaptation Plan. The following objectives structured the investigation: 1) Evaluate CMIP6 model performance: The first study assessed the ability of thirteen CMIP6 models to simulate precipitation across the Amazon. While some models effectively captured the seasonal distribution of precipitation, others struggled, particularly with the timing and intensity of the dry and wet seasons. The best-performing models were identified, providing a foundation for future climatic projections and policy planning. 2) Identify adaptation strategies of small-scale farmers in Rondônia: The second study focused on how local agricultural practices are evolving in response to changing climatic conditions. Through qualitative interviews, it was found that farmers are shifting towards more resilient agricultural practices, such as cattle ranching, to better cope with increased temperatures and altered precipitation patterns. The need for robust policy support to facilitate these transitions was emphasized. 3) Quantify climatic impacts of deforestation in unprotected areas: The third study quantified the climatic impacts of deforestation in unprotected areas, highlighting significant temperature increases and decreases in precipitation and evapotranspiration. This study underscored the vulnerability of Rondônia to these changes, stressing the urgency of implementing effective conservation strategies and robust legal frameworks to mitigate these impacts.

5.2 Key Contributions and Findings

The findings from this dissertation underscore the complex relationships between climate change, agricultural practices, and deforestation in the Brazilian Amazon. Key contributions include: 1) Improved understanding of CMIP6 model performance: This research contributes to modifying climate models by identifying strengths and weaknesses in precipitation simulation, which is crucial for accurate climate forecasting and resource management. 2) Insights into agricultural adaptation: By documenting the adaptive strategies of farmers in Rondônia, this study highlights the critical role of policy and community cooperation in enhancing agricultural resilience and sustainability. 3) Strategic policy recommendations for deforestation management: analyzing deforestation impacts provides actionable insights for policymakers to strengthen conservation efforts, particularly in unprotected areas, to prevent further climatic destabilization.

Overall, this dissertation provides valuable insights into the regional effects of global environmental changes and offers practical recommendations for policy interventions to mitigate these impacts. Linking scientific research with policy implications contributes to a holistic understanding of sustainably managing and preserving the Brazilian Amazon amidst ongoing climatic and environmental challenges.

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