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Changing climates, changing lives: Voices of a Brazilian Amazon farming community in a time of climate crisis

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Data Availability Statement: The data underlying this study contain de-identified transcribed interviews that could still potentially reveal participants' identities due to the specific context. For example, one of the interviewees works for a sustainably managed farming community active in the area, and individuals may be able to associate them with that farming commune. Therefore, access is restricted. The data are stored in the Google Shared Drive 'RO_Interview_Transcript,' managed by the IT staff at the Geography

Abstract

This study examines the lived experiences and adaptation strategies of small-scale farmers in the southwestern Brazilian Amazonian state of Rondônia, amidst escalating climate challenges. Through nine in-depth interviews, it uncovers the impact of unpredictable weather, increased temperatures, and shifting precipitation on agriculture and livelihoods. Participants, ranging from family farmers to agricultural collective members, detail shifts from traditional crop cultivation to more resilient practices like cattle ranching and dairy production. The narratives reveal a deep understanding of local climate volatility and its direct effects on water availability, crop viability, and livestock productivity. Farmers describe adaptation measures including new crop varieties, irrigation systems, and strategic land use to enhance biodiversity and mitigate climate change effects. Despite these adaptations, challenges like water scarcity, high input costs, and the need for technical assistance remain prominent. Farmers emphasize the need for stronger support systems, highlighting community solidarity, governmental aid, and access to sustainable technologies and education as essential for climate adaptation. They call for policies providing equitable resources and support, underscoring the importance of inclusive climate governance that acknowledges the unique vulnerabilities and contributions of Rondônia's agricultural sector. This research contributes to understanding how climate change reshapes rural Amazonian communities, arguing that ongoing deforestation and climatic changes threaten regional agricultural stability. It advocates for targeted policy interventions to provide technical assistance for sustainable farming and climate adaptation, alongside mechanisms to support fair market pricing. These measures are essential for enhancing the resilience and sustainability of local farming communities amidst climate change.

Department of San Diego State University. Researchers interested in accessing the data can send a request to geog-techstaff@sdsu.edu. Approved requestors will be provided a download link to the appropriate transcript.

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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 [1]. 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 enhance the livelihoods of vulnerable communities effectively 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 [2, 3]. This approach aligns with Brazil's National Adaptation Plan's goals [4], 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 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 being employed by agricultural communities 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 particularly important 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 [5]. This period saw an increased reliance on shifting cultivation, which, in the absence of adequate governmental planning for sustainable land use, escalated deforestation rates [5, 6]. This type of 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 [7, 8]. 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 [9–11]. While they have been heavily critiqued, these efforts reflect the ongoing attempt to balance agricultural productivity with environmental preservation in Rondônia, against a backdrop of market variability and climatic challenges.

Degradation of forests in Rondônia is alarming. 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 patterns of climate, and ameliorate infectious diseases [12]. Therefore, understanding the extent of deforestation in Rondônia is critical [13]. 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 [14]. 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). Research found that Rondônia displayed one of the largest reductions in total latent heat flux, or evapotranspiration for the Amazon Basin [15]. 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 [16].

Future projections of climate for the Amazon lead to a drier and more drought-prone state with increased dry season length [17–19]. Global climate models show good agreement on the direction of changes for a drier state and warming may increase the likelihood of exceptionally hot drought. There is also high confidence that there will be an increase in the number of dry days and drought frequency [20]. 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). Increase in likelihood of extreme events could alter and degrade Amazonian forests [21].

Amazon forests are in transition as seen through historic and future drought and increase in the dry season length [22]. In 2023, the agricultural sector in Brazil faced acute drought conditions [23], posing significant challenges to farming communities. The drought's severity impacted water levels in rivers and streams, crucial for both 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 [24]. 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 [25]. Forests are also under a substantial threat from ranching, farming, road building and logging [26]. 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. [27], who ask the question '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'. This 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 [28–35] and in Brazil [36–39]. 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. Similar to other regions facing climate-induced challenges, small-scale farmers in Rondônia must

adapt to shifting environmental conditions, such as irregular rainfall and increased temperatures. Adaptation strategies like those observed in regions of Bangladesh, where community-based approaches like rainwater harvesting have successfully addressed water scarcity and salinity issues [40], underscore the importance of localized solutions. These strategies offer valuable insights for promoting resilience in Rondônia's agricultural systems. Local adaptation strategies are important to document, and can be biodiversity friendly, economically viable, and socially acceptable [33], 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 [41]. This body of research is still developing, especially for Latin American countries which are vulnerable to climate change [42]. The review by Fierros-González and López-Feldman [42] 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 policy making. This approach is in line with the goals of enhancing climate risk reduction and improving coordination among public agencies and the community [43], offering a more informed basis for designing adaptation policies that are responsive to local needs and conditions.

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 [44]. 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.

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 cultural context and communication preferences of the participants, ensuring their full understanding and voluntary participation. Before the interviews began, the project and its objectives were clearly described to each participant. Two authors were present at all times to witness the consent process, and verbal consent was obtained and agreed upon before any recording commenced. All personal identifiers were removed or altered to ensure anonymity and confidentiality of the information provided by the participants. This study was reviewed by the San Diego State University Institutional Review Board (IRB) under protocol number HS-2023-0199. It was determined to be 'Not Subject to IRB Review,' but all ethical obligations and privacy considerations were strictly followed. Additional information regarding the ethical, cultural, and scientific considerations specific to inclusivity in global research is included in the Supporting Information (S1 Text).

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, and a dry season 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 1). 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 of cassava, soy, coffee, and milk, generating over $17,000 Brazilian Reais 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 29,000 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 Brazilian Reais 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 Brazilian Reais 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.

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 carried out these 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, with the assistance of a local collaborator from the Universidade Federal de Rondônia (UNIR). We contacted known and unknown farmers, connected with a local farming union, and interviewed their president to ensure we captured a broad range of perspectives. 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, with experiences ranging from 25 to over 50 years. Additionally, Table 1 showcases each interviewee's background, agricultural focus, and their approaches to adaptation and strategies amidst climate change.

Each interview lasted between 45 minutes and 1.5 hours, was conducted face-to-face, and was recorded for accuracy. The variation in interview length was due to the open-ended nature of the questions, allowing participants to guide the depth and direction of the conversation. This approach ensured that each participant could elaborate on topics most relevant to their experiences and insights. We discussed a variety of topics, from personal farming experiences and observations of climate change to the impacts on agricultural practices, necessary adaptations, and farmers' emerging needs. The semi-structured format of these interviews, inspired by six main questions from previous studies [36, 45–48], 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 [49–51]. The guide used for the interviews is provided in the supplementary information (see S2 Text). Following the interviews, we reached out to the farmers via WhatsApp to gather additional information, which are included in the manuscript.

We decided on nine interviews based on the qualitative social sciences' principle of data saturation in a study of lived experiences, where a new information threshold of $\leq$5% is typically reached after 6–7 interviews [50, 52]. This method ensured that our sample size was sufficient

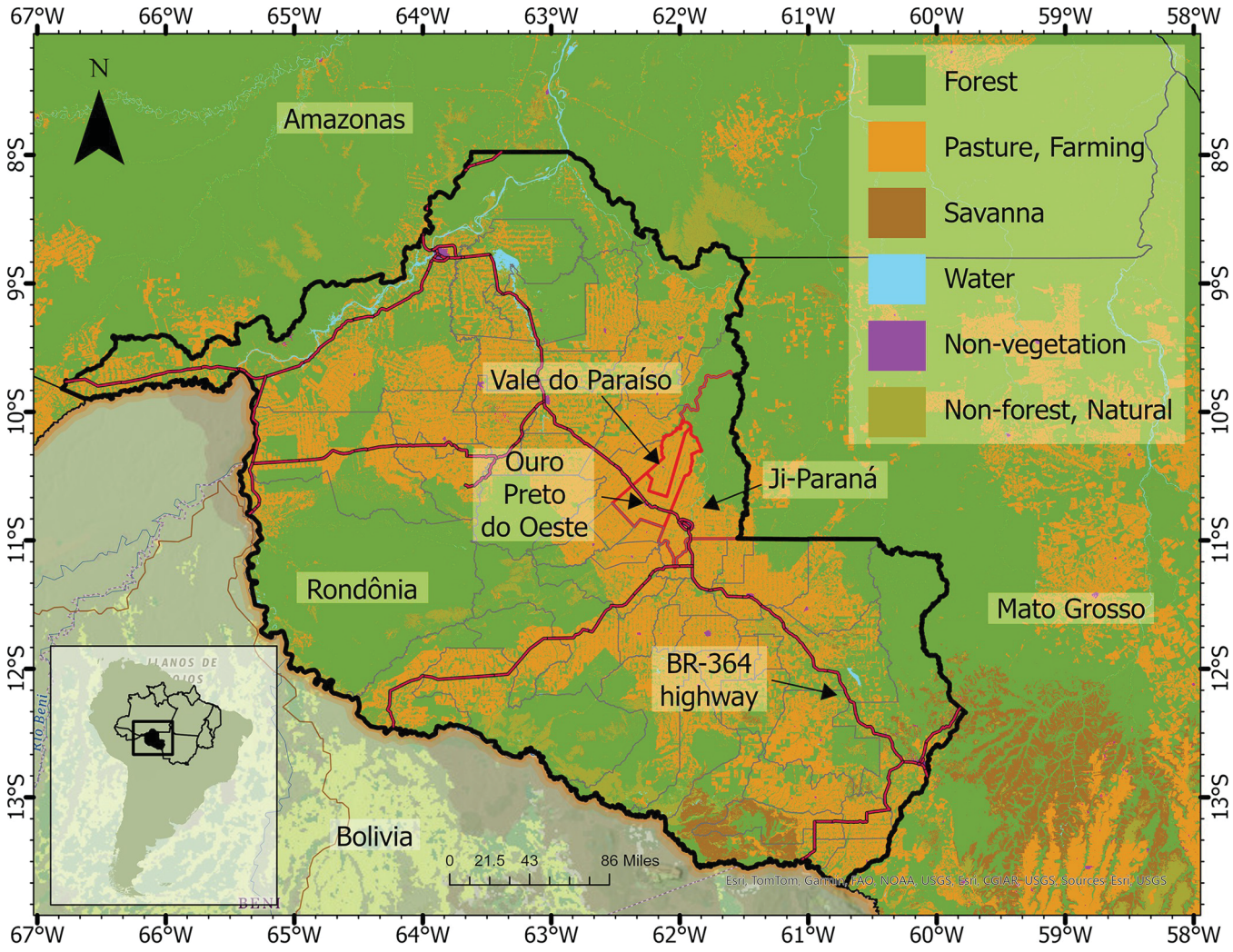

Fig 1. Study area map and corresponding land cover for Brazilian states. (Land cover categories have been reclassified to reflect 6 major types. Original land cover classifications are from Mapbiomas: https://brasil.mapbiomas.org/en/).

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to uncover significant themes relevant to our research questions. Conducted in Portuguese with the aid of a translator from UNIR, these interviews provided a comprehensive understanding of the participants' viewpoints. While our small sample size does not allow for statistical generalizability, the depth of the interviews allowed us to explore a broad range of experiences from a diverse group of farmers and agricultural leaders. Though a larger sample size or alternative sampling method could strengthen generalizability, the richness of the qualitative data offers meaningful insights into the climate adaptation challenges faced by small-scale farmers in Rondônia.

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 analysis we identified analytic categories or codes that emerged from within the text [44]. 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. Although we did not directly verify the participants' responses with external data, we used literature in the discussion section to confirm that the main climate change perceptions shared by participants were consistent with findings from other regional studies on climate impacts. The goal of this study is not to validate their experiences but to understand their perspectives, as their adaptation strategies are shaped by these personal viewpoints, regardless of external validation.

Results

The emerging themes from our interviews, outlined in Fig 2, highlight shifts towards livestock and dairy, sustainable practices, and community cooperation amidst climate change and economic challenges. Additionally, Table 1 showcases each interviewee's background, agricultural focus, and their approaches to adaptation and strategies amidst climate change. The following subsections will expand upon the major themes in Fig 2.

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*

Table 1. 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 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

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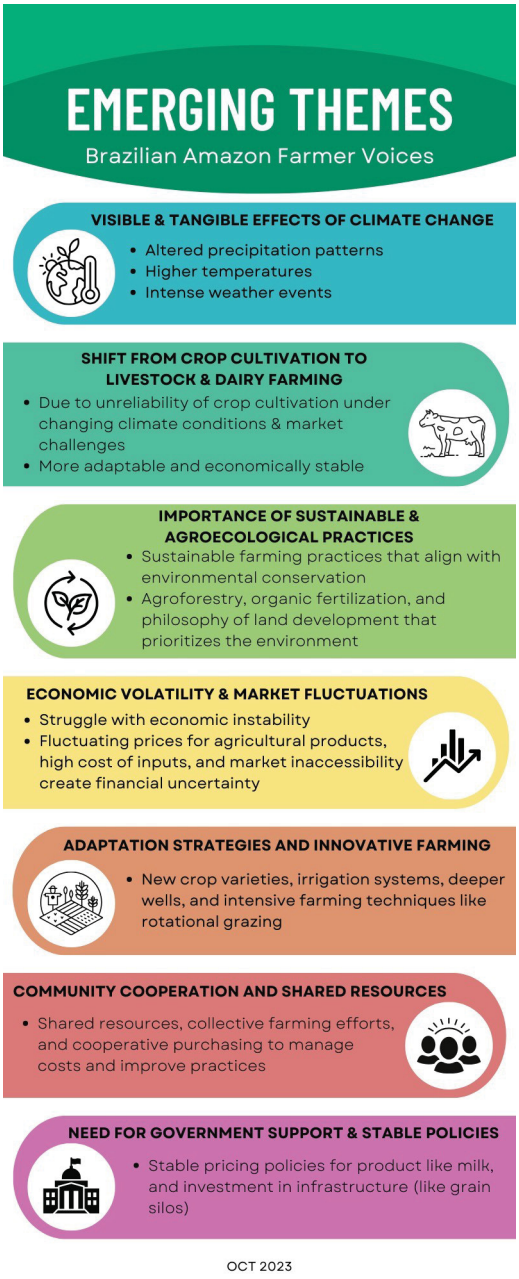

Fig 2. Emerging themes from interviews.

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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

Fig 3. 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.

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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 form the river, but it's all dry now."*

In addition to water scarcity, the rise in temperatures and extreme heat presents a challenge to 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. More specifically, 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 3), as stated by interviewee 5, *"there is some relationship with 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. 20 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.

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 productions 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."*

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 the farmers. This shift is largely 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 as a response to these economic challenges, moving towards more sustainable and financially viable agricultural practices. The benefits of switching to dairy farming is 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.

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 farmer's techniques is the integration of agroforestry, organic fertilization, and a holistic philosophy of land development that places importance on 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) participant's collective approach to transform previously degraded pastures into vibrant ecosystems through sustainable practices.

Agroecology was another dominant theme, where practices such as agroforestry and the use of organic fertilizers were prevalent. This is particularly evident in the way some farmers draw 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. The engagement with agricultural family schools to share these principles highlights the critical role of education in fostering sustainable agricultural 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 up bird feeders around their farm for local animals, stating that *"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 overall adaptation strategies outlined in Table 2.

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

Table 2. 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

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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.

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 to prevent crop burn, and the introduction of more resilient seeds has become common. The construction of wells and dams to secure water sources is a testament to the proactive approach farmers are taking towards 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 4. 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."*

Leveraging community and expert support has proven crucial in navigating the economic uncertainties brought by 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 has 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, farmers in Rondônia are demonstrating remarkable resilience and adaptability. Their efforts, detailed in Table 2, highlight a determined response to environmental and economic pressures.

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*

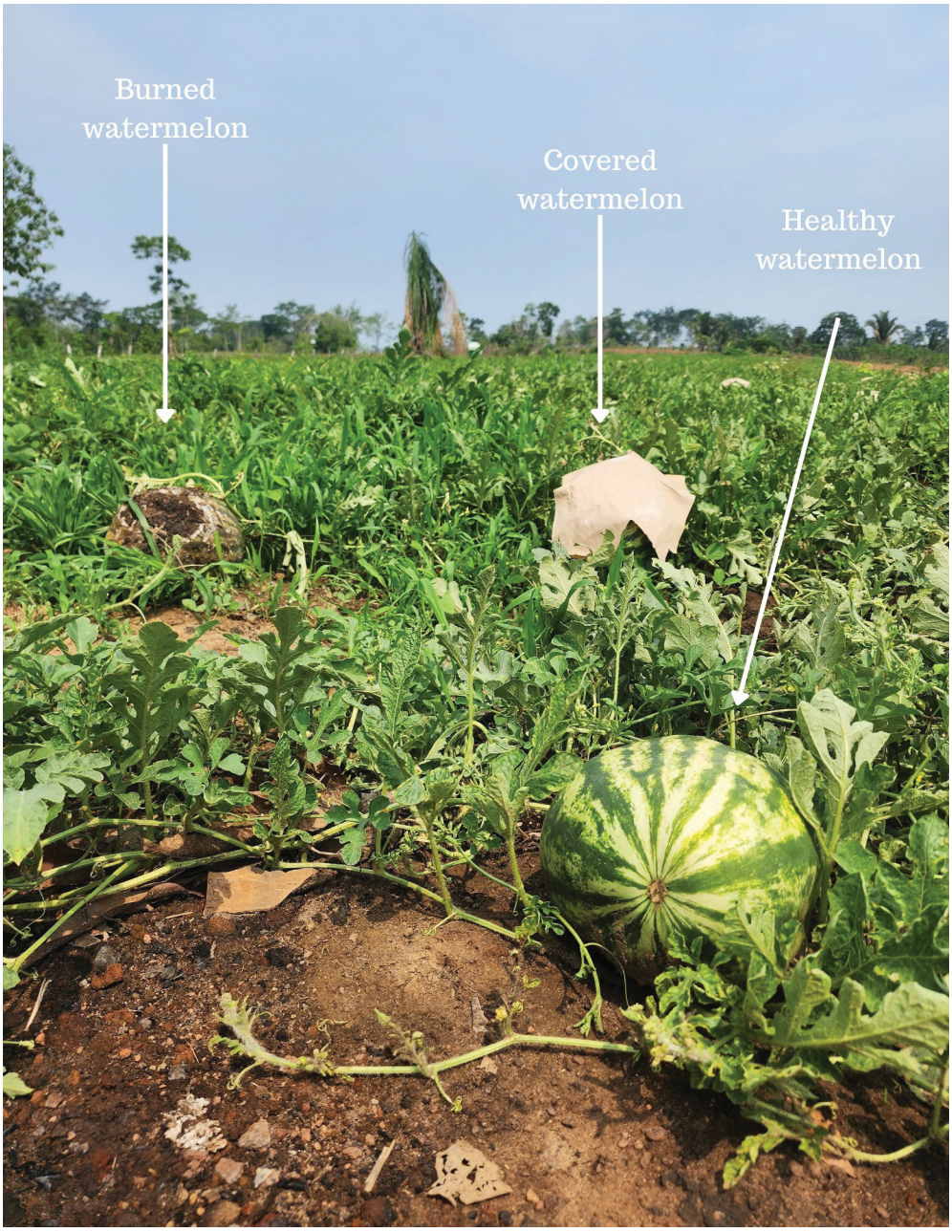

Fig 4. Watermelon crop with protective covering from the intense heat. In this photo you can see a burned watermelon, a covered watermelon, and a healthy watermelon (Vale do Paraíso, RO, BR. October 2023).

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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 2).

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 funding for local organic fertilizer production. 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 5).

> *"[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.

Vignette

The previous section highlighted major themes spanning the nine interviews. However, to provide more nuanced, in-depth understanding of the perspectives and decision-making

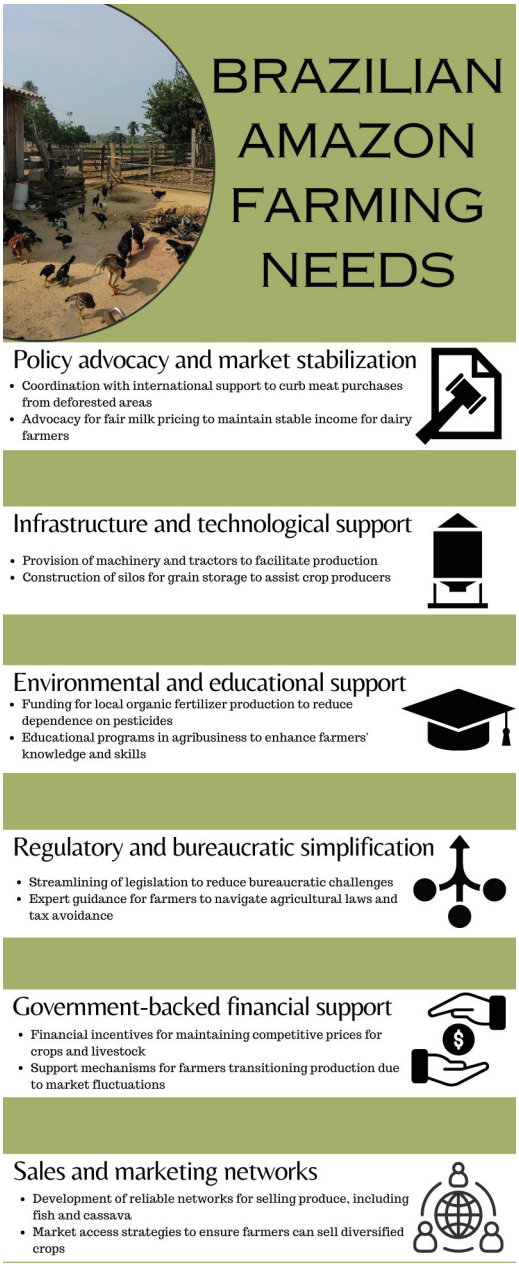

Fig 5. Brazilian Amazon farming needs. Revealed through interviews conducted October 2023.

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processes of a specific individuals and households, this section includes a vignette from Interviewee 9.

Interviewee 9: 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 the introduction of 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 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 explained pictorially in Fig 6.

During the wet season (December, January, 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 given 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, which is 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 not only informs their day-to-day operations but also contributes to the long-term resilience and productivity of the farm. 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.

The case of Interviewee 9 serves as a practical example of the broader themes identified across the nine interviews, particularly in terms of resilience, adaptive management, and collaboration. The transition from coffee to livestock and the implementation of rotational grazing, coupled with collaborative efforts to manage feed and resources, echo the themes of adapting to climatic and market changes. Additionally, Interviewee 9's engagement with agricultural extension services like SENAR reflects the critical role that external support plays in helping farmers implement sustainable practices, a key theme highlighted across several interviews.

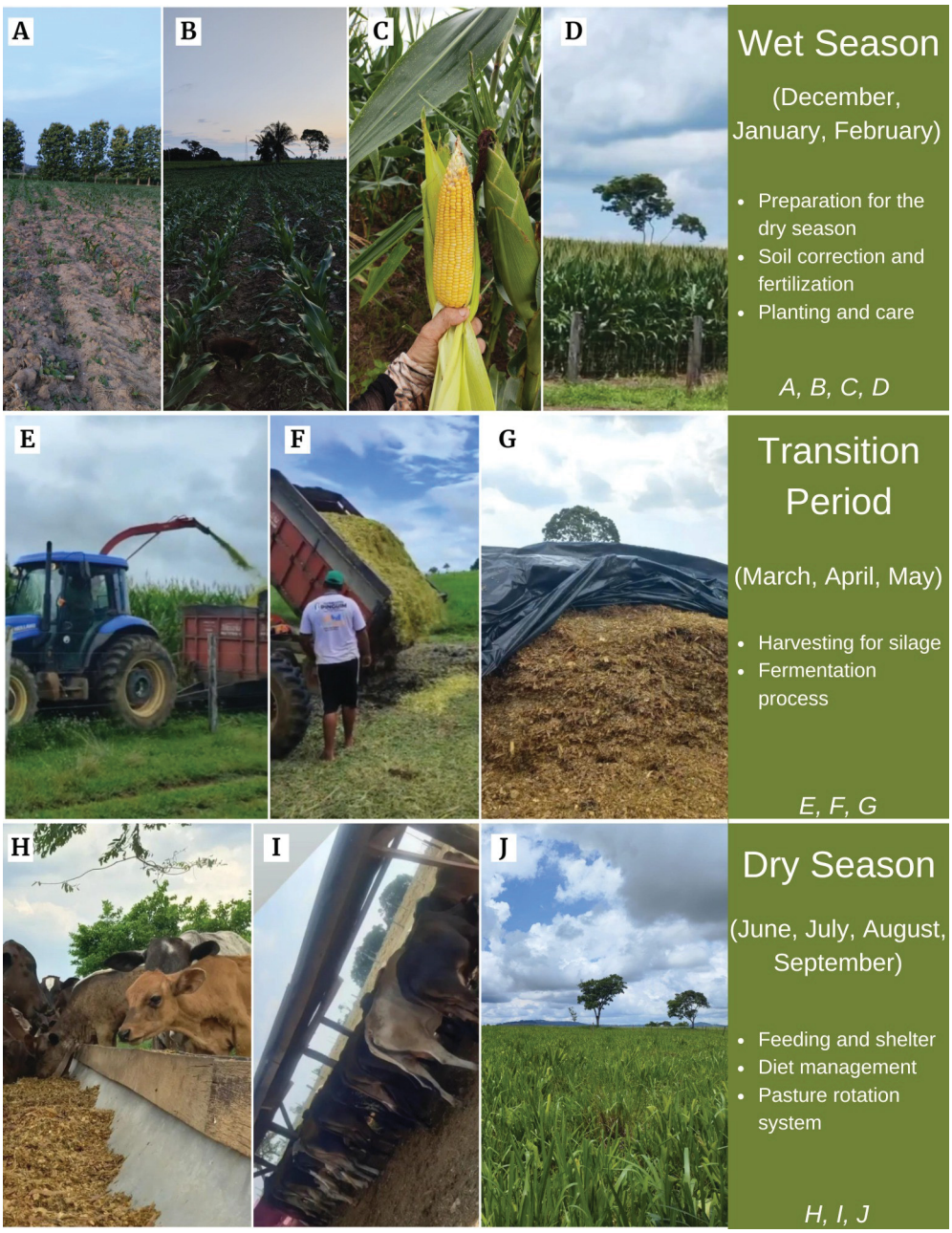

Fig 6. Interviewee 9's rotational grazing strategy. The wet season (December, January, February) (panels A, B, C, D), the transitional period (March, April, May) (panels E, F, G), and the dry season (June, July, August, September) (panels H, I, J). Preparation of planting corn (A), second fertilization (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).

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Discussion

Adapting to change: Climate impacts and agricultural shifts

The manifestation of climate change on agriculture in Rondônia was observed by our interviewees, who note significant deviations in weather patterns, resonating with the broader

climatic shifts observed across the Brazilian Amazon, due to both deforestation and global warming. 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 [38, 53, 54]. Biophysical records also show an intensification of temperature, drought, and extreme events across the region [55–60]. However, regional variances are apparent, with areas experiencing more pronounced changes than others, potentially reflecting localized deforestation impacts and microclimate variations [61, 62]. For example, Funatsu et al. 2019 [63] 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 [16, 64]. 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 [65, 66].

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 and 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 [67]. 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 both climate and market pressures [68, 69]. 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 [70, 71], with a 60% decline in suitable unshaded coffee plantations for Brazil by 2050 [72]. It has also been found that transforming forests into agricultural land can lead to increased wealth and resources for small-scale farmers [73]. However, research in East Africa has shown the opposite results, with many farmers preferring to transition from livestock to modern, irrigated agriculture as a means to cope with increasing drought [41, 74]. 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 [41, 75]. 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 [76].

Historical factors, including deforestation and settlement expansion, and global warming have directly contributed to the climate challenges currently faced by farmers and have shaped the adaptation strategies they employ. The introduction of new crop varieties and irrigation systems represents a significant shift towards climate-smart agriculture, aimed at sustaining crop production despite the growing incidence of drought conditions [77, 78]. However, while farmers reported changes in their irrigation practices, we did not collect specific details on the irrigation frequency or whether surface or groundwater was used. Some participants mentioned bringing water from nearby rivers or streams, but further research is needed to gather more precise information on irrigation practices. 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 [79–81]. For example, Multsch et al. 2020 [82] 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. While the introduction of new crop varieties and irrigation systems is crucial for immediate adaptation to climate change, their long-term sustainability depends on careful management. Over-reliance on irrigation could strain water resources, especially in regions already facing water scarcity, as noted by Multsch et al. (2020). Economic pressures, such as fluctuating market prices and the costs of adopting new technologies, may also impact the feasibility of these strategies over time. To ensure their sustainability, these strategies must be supported by robust policies that promote efficient water use, provide financial assistance to farmers, and encourage adaptive planning that anticipates future climate and economic uncertainties. Alternatively, the adoption of rotational grazing systems, underscores a commitment to sustainable land use and the health of livestock, critical for maintaining productivity [83, 84], especially because more than half of Brazilian livestock production is on degraded pastures. It has also been found that dairy intensification on small-scalle farmers in the Brazilian Amazon has been correlated with reduced deforestation, helping to meet climate policy objectives of preserving marginal forests [85]. 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 are responding 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 [86–89]. 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 [90]. 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 [91].

Economic and ecological resilience

Changing climate conditions, economic volatility, and market fluctuations pose significant challenges, compelling farmers to adapt by transitioning from traditional crop cultivation to more stable endeavors like livestock and dairy farming. 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 [92]. A case study from Brazil, conducted by Piao et al., 2021 [93], 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 play a pivotal role in this transition. In addition to policies and government collaboration, incorporating technological advancements in dairy production, as evidenced by Simões et al., 2017 [94], suggests a promising strategy for enhancing economic resilience by potentially reducing the amplitude and duration of milk price oscillations. 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 [95].

In Rondônia's shifting agricultural scene, the adoption of agroecology and community-driven adaptation strategies is essential for addressing the challenges of climate change and market fluctuations. Agroecology, emphasizing the integration of ecological principles into

sustainable, environment-friendly farming systems, 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 [96–98]. Ewert et al., 2023 [98] found that the success of agroecology and 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 [99, 100]. However, Rondônia's escalating deforestation and climate shifts, marked by rising temperatures and reduced rainfall, pose increasing threats to agricultural sustainability. Without targeted interventions against ongoing deforestation, of both protected and unprotected lands and climate change, the conditions faced by farmers could deteriorate further, undermining efforts toward sustainability and resilience [16, 64]. 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 [1, 101–103].

Implications for policy makers

The essential policy implications stemming from 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. For example, insights from Bangladesh, where improved irrigation systems and climate-resilient crop varieties are being adopted [40, 104], could inform similar interventions in Rondônia. The success of rotational grazing systems in Paraná State offers another model that could be adapted to reduce deforestation and improve livestock productivity. 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.

Conclusions

This study underscores the need for equitable policy interventions to support vulnerable agricultural communities in Rondônia. By demonstrating how climate change is driving shifts in farming practices, it emphasizes the importance of a dual approach: providing technical assistance for sustainable farming and market support mechanisms to ensure fair pricing and economic stability. This strategy addresses both immediate and long-term climate challenges, promoting resilience and sustainability in agricultural communities. While the proposed policies offer a promising framework for enhancing climate resilience in Rondônia, several challenges may arise during their implementation. Financial constraints, particularly for small-scale farmers, could limit the adoption of new technologies, while political resistance or insufficient policy enforcement may slow progress. Additionally, the technical capacity of farmers

to adopt sustainable practices needs to be strengthened through targeted training programs. Addressing these challenges will require coordinated efforts between local governments, international organizations, and community stakeholders to ensure the long-term success of these policies.

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. Additionally, we did not collect specific socioeconomic data such as income levels, education, or access to markets, which could further influence farmers' ability to adapt to climate change. Future research should consider expanding the scope to include these socioeconomic factors and longitudinal studies to 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.

Supporting information

S1 Text. Inclusivity on global research questionnaire.
(DOCX)

S2 Text. Interview guide, focusing on 6 major themes.
(DOCX)

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