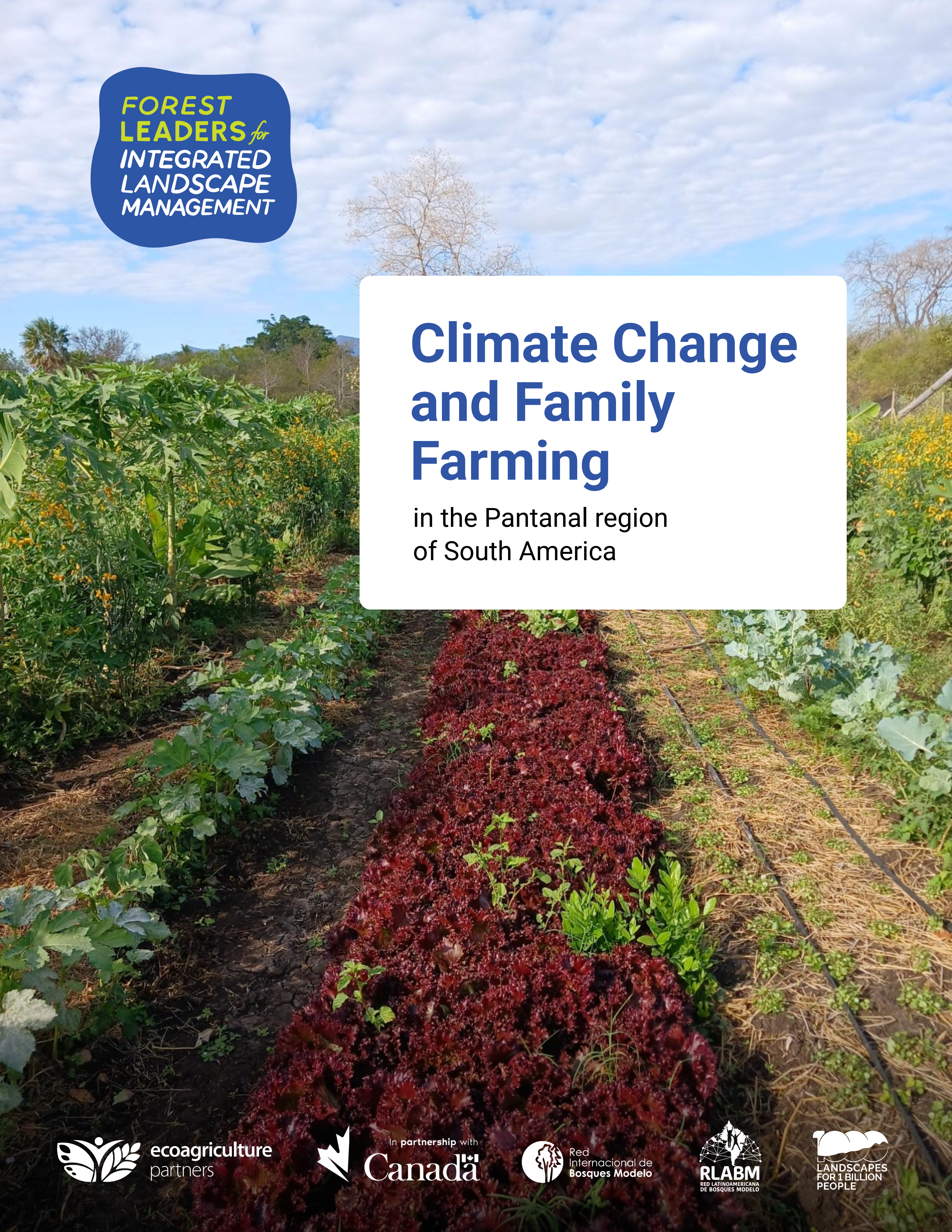
FOREST LEADERS *for* INTEGRATED LANDSCAPE MANAGEMENT



Climate Change and Family Farming

in the Pantanal region of South America

ecoagriculture partners

In partnership with Canada

Red Internacional de Bosques Modelo

RLABM RED LATINOAMERICANA DE BOSQUES MODELO

1000 LANDSCAPES FOR 1 BILLION PEOPLE

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Preface

Over the past three years, the ***Landscape Leaders for Landscape Management and Finance*** project has been collaborating with landscape leaders and their partners in Model Forest Networks (MFNs) in Latin America and Brazil to strengthen leaders' capacities to improve landscape resilience through the practice of inclusive *Integrated Landscape Management* (ILM) linked with *Integrated Landscape Finance* (ILF). One critical component of this multi-year project has been conducting **collaborative research** by research fellows with model landscapes in the **Latin American Model Forest Network** focused on and aligned with their research needs and priorities and then synthesizing and sharing these applied learnings.

Five research fellows were selected early in the *Landscape Leaders for Landscape Management and Finance* project. The fellows were selected based on their academic backgrounds and experience, aligned research interests, and previous leadership in the *Latin American Model Forest Network*. Together with members of the *Latin American Model Forest Network*, the research fellows collaboratively created a shared research agenda based on the needs and interests of the Model Forests in the network. The priority research topics identified include systems of sustainable governance; youth leadership and effective transitions to effective youth leadership; Indigenous partnerships and strengthening Indigenous engagement; and climate resilience and adaptations for resilience. Cross-cutting topics spanning these priorities were gender-responsive strategies and integrated landscape management and finance. All the fellows' research projects have synergies and high alignment with one or more of these topics.

Based on the research agenda, the fellows were then guided through a community-of-practice and mentorship model in designing and implementing each of their own collaborative and action-oriented research projects. They also had the opportunity to disseminate and share their research project findings at a broad array of events. This report, authored by a research fellow, is a proud accomplishment and outputs of collaborative research projects, advancing the needs and goals of the Latin American Model Forest across Latin America. We celebrate this achievement, the applied learnings and guidance it offers, and welcome next steps.

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Abstract

Climate change is generating both gradual and rapid environmental transformations, creating impacts and uncertainties that require continuous adaptation, particularly for family farming in the Pantanal. This report analyzes the **climate-related impacts** perceived by rural communities and the **adaptation strategies** they have adopted, with the aim of identifying factors that strengthen socio-ecological resilience.

Sixteen semi-structured interviews were conducted with rural producers from the **Pantanal Model Landscape**. In addition, historical climate maps and projections of temperature and precipitation for 2070 were developed to highlight trends and anomalies and to support communication and public decision-making. Farmers reported significant changes in rainfall patterns, increasing temperatures, more frequent fires, and growing conflicts with wildlife, all of which directly affect agricultural production and family well-being. In response, communities have intensified the use of wells and irrigation systems, diversified production, implemented Agroforestry Systems, and engaged in integrated landscape management initiatives. These strategies have been locally developed and, in some cases, supported by public policies and socio-environmental projects.

The findings highlight the importance of strengthening agroecological practices, fostering community-based innovation, and aligning adaptive public policies to enhance the resilience of family farming systems in the Pantanal.

Keywords:

socio-ecological resilience

agroecology

adaptation

integrated landscape management

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Introduction

Climate change affects a wide range of socio-ecological processes, from the functioning of natural ecosystems to social well-being, health, and the economic sector, involving gradual transformations over time, increasing uncertainty, and driving changes and adaptations. One of the main effects of global warming already being experienced is the **alteration of hydrological regimes**, which has triggered environmental disasters and significant economic losses (Marengo et al. 2021a; Tavares et al. 2023).

The Pantanal has been one of the biomes most intensely impacted in recent years by changes in hydrological regimes (Silva et al. 2024; Thielen et al. 2021). Since 2019, the biome has faced **severe drought conditions**, with consistently low precipitation levels year after year, increasingly record-high temperatures, low relative humidity, extremely low river water levels, and unprecedented wildfires (Marengo et al. 2021b; Silva et al. 2024; Thielen et al. 2021). An analysis by *MapBiomas*, based on land cover and land use maps in Brazil (1985–2024), indicates a **75 percent reduction** in the area annually flooded in the Pantanal biome (MapBiomas 2024).

Changes in rainfall regimes interfere with the flood and dry cycles of the Pantanal, exposing vegetation to fire and threatening the resilience of fauna and flora during the dry season (Marengo et al. 2021b; Silva et al. 2024). The increased frequency and intensity of wildfires have negative consequences for biodiversity, ecosystem processes, and ecosystem services, as well as causing significant **economic losses** (Pivello et al. 2021; Thielen et al. 2021). In 2020 alone, between January and September, approximately **40,000 km² were burned**, representing nearly one-third of the entire biome (Libonati et al. 2020). In addition, low air humidity combined with high temperatures and smoke compromises **air quality** and can lead to serious health consequences for the population (Lorenz et al. 2024).

Recent extreme climate events have intensified concerns about the future of the Pantanal biome, particularly regarding traditional land use practices and the incorporation of sustainable economic activities (Berlinck et al. 2021; Tomas et al. 2019).

Cattle ranching is the main economic activity in the Brazilian Pantanal and has been practiced in the region for over two centuries (Ribeiro 2015). This sector has been heavily impacted by droughts and wildfires, as reduced pasture availability has altered required management practices and increased production costs, ultimately leading to a reduction in meat supply (Vazquez et al. 2021).

Crop farming is not predominant in the Pantanal due to unfavorable conditions for most large-scale industrialized crops. Consequently the region produces food primarily through family farming practiced by smallholders, riverine populations, and traditional communities, ensuring food security and income generation for families (Vazquez et al. 2021; Borsato et al. 2011; Souza et al. 2022). However, drought conditions have also affected food production due to rainfall unpredictability, high temperatures, and heatwaves (Vazquez et al. 2021).

Record of the impacts of the forest fires that occurred in 2023 in the municipality of Corumbá, Mato Grosso do Sul, Brazil, highlighting the dense layer of smoke that covered the city for several days.

Given this scenario, it is essential to highlight actions aimed at **strengthening the climate resilience** of Pantanal communities. Socio-ecological climate resilience is defined as *the capacity of a socio-ecological system to absorb disturbances and maintain its ecological functions and processes without shifting to an alternative state* (Folke 2006; Folke et al. 2010). This concept particularly emphasizes the adaptive and transformative capacity of the **social component** of the system (Nikinmaa et al. 2020).

Studies on **resilience** generally seek to identify activities associated with greater adaptive capacity in the face of climate change and are fundamental to normative planning theory and decision-making processes aimed at sustainably meeting human well-being and societal needs without compromising ecosystem services and functions (Wilkinson 2012). Furthermore, studies addressing climate change impacts on **agriculture** tend to focus on specific crops, particularly commodities, while relatively few have examined impacts on family farming systems (Tanure 2020, 2023).

According to data from the *Brazilian Agricultural Census* (IBGE 2017), **family farming** is present in 77 percent of agricultural establishments in Brazil, occupying 23 percent of the total agricultural area, corresponding to 80.89 million hectares. The same census indicates that family farming accounts for 23 percent of national agricultural production and employs 10.1 million people, representing 67 percent of the total workforce in agricultural establishments. In addition to its economic role, family farming is closely linked to the transmission of cultural memories and practices, the maintenance and reproduction of **traditional knowledge**, and the continuity of less environmentally impactful agricultural practices aligned with environmental conservation and regenerative agriculture (IBGE 2017; Tanure 2020, 2023).

Figure 1: Integrated Landscape Management (ILM)

Source: 1000 Landscapes for 1 Million People, *An Introduction to Integrated Landscape Management*.

Small-scale rural producers are among the groups most vulnerable to climate change, as they generally have lower income levels, depend directly on environmental resources for income generation, have lower levels of formal education, and limited access to basic services (Peiter et al. 2011). In this context, **integrated landscape management** (ILM) has emerged as an important pathway for strengthening community adaptive capacity. Increased social cohesion and participatory governance can enhance communities' ability to adapt to projected climate change impacts (Hügel & Davies 2020; IPCC 2023). The term *integrated landscape management* refers to actions and policies aimed at territorial management initiatives at a scale that encompasses the entire landscape, involving **multiple stakeholders** such as traditional communities, farms, smallholders, private companies, and government sectors (McGonigle et al. 2020). The central objective of ILM is *the participatory strengthening of ecosystem processes and functions, food production, livelihoods, and local governance within a previously defined landscape* (Milder et al. 2014; McGonigle et al. 2020).

The Pantanal Model Landscape emerged as an initiative that brings together diverse actors for decision-making and governance actions aimed at the region's economic and sustainable development (Ecoa 2021). Within the Pantanal Model Landscape, the groups most vulnerable to climate change are riverine communities and small-scale rural producers. Subsistence activities among these groups include family farming, fishing, hunting, cattle grazing, and natural resource harvesting (Ecoa 2021). Due to the strong environmental dependence of these groups for food security and income generation under climate change, a participatory assessment of impacts and adaptive capacity is essential, as well as a more detailed and context-specific understanding of the socio-ecological dynamics of the Pantanal Model Landscape. These communities are directly exposed to climate variability and possess in-depth knowledge of the climatic challenges of their territory. Therefore, community participation and local knowledge can enhance legitimacy, increase engagement, accelerate behavioral change, raise risk perception, influence decision-making, and highlight community members as agents of change (Mercer et al. 2008; IPCC 2023).

Aerial view of the São Gabriel Agrarian Reform Settlement, in Ladário, Mato Grosso do Sul, Brazil, an area that is part of the Pantanal Model Landscape, during the rainy season.

General Objective

Considering the significant environmental and socioeconomic losses associated with climate change and the urgent need for context-specific information to support climate resilience actions in the Pantanal, this study aims to analyze the impacts of climate change in the territory of the **Pantanal Model Landscape**, with a focus on **family farming**. The study integrates climate projections, local perceptions, and adaptation strategies to support socio-ecological resilience actions.

Specific Objectives

a. To develop a **regional climate overview** to support the understanding of climate change impacts and to guide local adaptation strategies.

b. To analyze **local perceptions of climate change**, its impacts, and adaptation strategies among communities engaged in family farming.

c. To identify elements that enhance or constrain **socio-ecological resilience** within the Pantanal Model Landscape territory.

Aerial view of an **agroforestry system** in the **Pantanal Model Landscape**, demonstrating the structural stability and vegetation persistence of the system during the dry season, in contrast to the surrounding drought-affected landscape.

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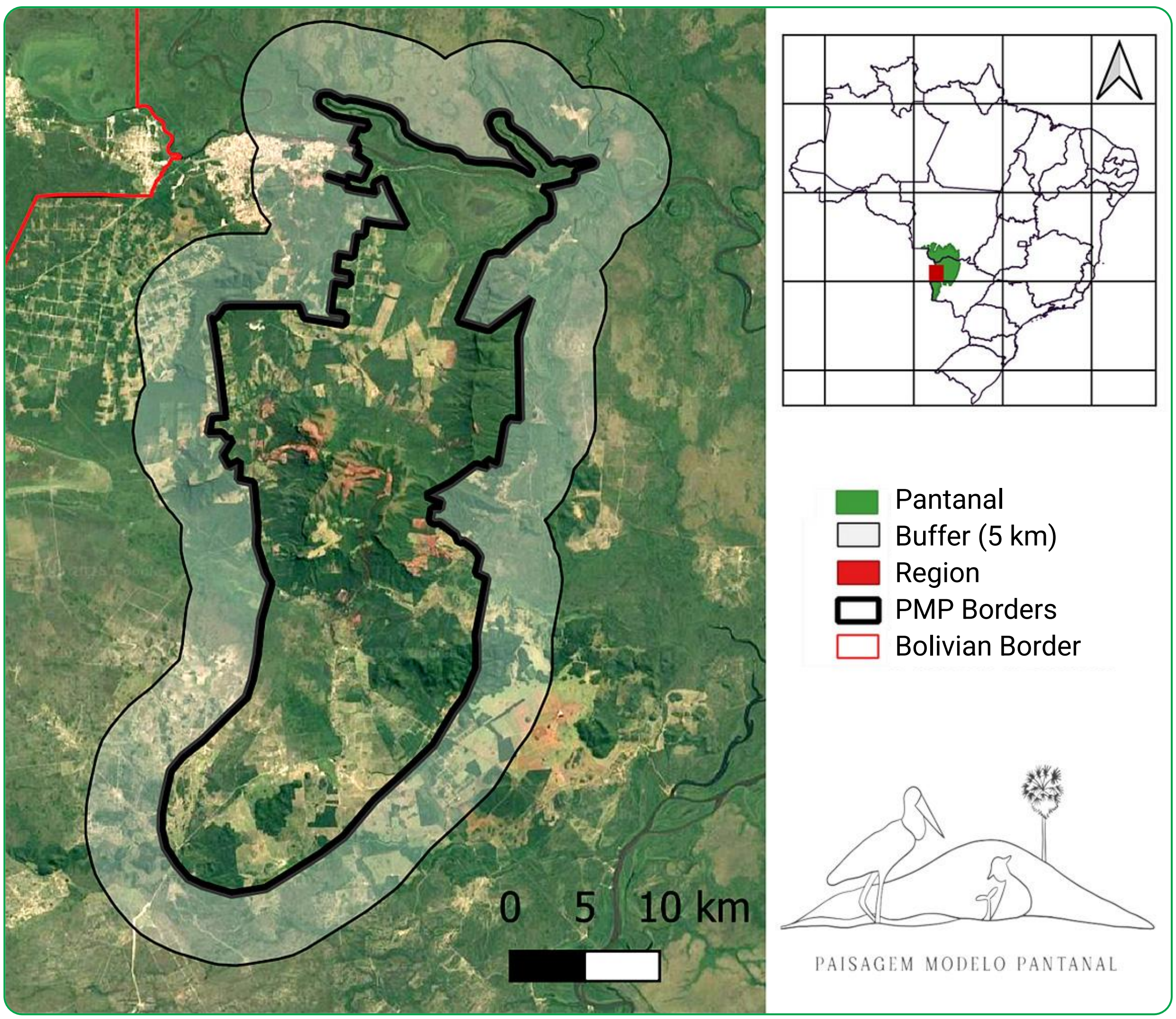
Materials and Methods

The Pantanal is one of the largest, most diverse, and continuous floodplains in the world, covering approximately 140,000 km² and located in the center of South America in the Upper Paraguay Basin (Harris et al. 2005; Tomas et al. 2019). The landscape consists of a mosaic of floodable and non-floodable areas with grasslands, forest formations, open woodlands, and temporary or permanently flooded zones that host a high diversity of fauna and flora species (Tomas et al. 2019).

The climate is classified as **tropical savanna** (Aw) according to Köppen, with rainfall concentrated in the summer from November to March and a dry season from April to October. Absolute maximum temperatures can reach 40°C from October to January, while minimum temperatures may drop to around 0°C in June and July (EMBRAPA 1997). The annual averages for precipitation and temperature are approximately 1,180 mm and 25.5°C, respectively (Soriano 1999).

The study was conducted in the territory of the **Pantanal Model Landscape** (PMP), a territorial governance platform based on the integrated management of landscapes, encompassing approximately 76,000 hectares across the municipalities of Corumbá and Ladário, located on the western edge of the Pantanal, in Mato Grosso do Sul, Brazil (figure 2; Ecoa 2021). The PMP serves as a space for coordination among diverse social actors, fostering local development through integrative, inclusive, and adaptive strategies (Ecoa 2021).

Figure 2: Geographical location of the Pantanal Model Landscape.



The research adopted a **community-based** and **participatory approach**, aligned with ILM principles, emphasizing dialogue, knowledge co-production, and engagement with local actors. **Semi-structured interviews** were conducted with family farmers from the São Gabriel Agrarian Reform Settlement and from the Baía Negra Environmental Protection Area (APA), which are directly embedded within the PMP territory. Interviews were conducted in person, lasted an average of 30 minutes, and followed a semi-structured guide with 18 questions addressing perceived climate changes, impacts on livelihoods, and local adaptation strategies. All procedures complied with the ethical principles established by the Brazilian General Data Protection Law (Law No. 13.709/2018), ensuring confidentiality and anonymity through coded identifiers. A total of sixteen interviews were audio-recorded, transcribed, and analyzed using Dedoose software (version 9.0.54; SocioCultural Research Consultants, LLC, Los Angeles, CA), supporting the qualitative analysis of narratives related to climate perception, adaptation, and resilience at the landscape level.

The **maps of maximum temperature and precipitation** were produced using QGIS software, based on the SIRGAS 2000 / WGS 84 coordinate reference system (EPSG:4326). Historical data from the 1961–1990 period and climate projections for 2070 com RCP4.5, were obtained from the Regional Eta Model coupled with MIROC5, provided by the National Institute for Space Research (INPE/CPTEC). The analyzed variables included mean annual maximum temperature (°C) and total annual precipitation (mm), with a spatial focus on the Pantanal biome, as defined by the TerraBrasilis/INPE (2024) platform. Climate anomalies were calculated as the difference between the projected 2070 scenario and the historical reference period, representing the expected variation in temperature and precipitation across the Pantanal Model Landscape (PMP).

Access road to the *Baía Negra* Environmental Protection Area (APA), in Ladário, Mato Grosso do Sul, Brazil, an area that is part of the Pantanal Model Landscape, during the **dry season**

Access road to the *Baía Negra* Environmental Protection Area (APA), in Ladário, Mato Grosso do Sul, Brazil, an area that is part of the Pantanal Model Landscape, during the **rainy season**

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Results

This section presents an overview of the main results concerning family farming in the Pantanal, Brazil, with a focus on **local perception, main impacts, adaptation strategies, and climate dynamics**. Specifically, the study examined how farmers perceive changing climatic conditions and how these changes affect livelihoods, food, and income production. It also analyzed the adaptation strategies implemented, including emergent, policy-supported, and iterative approaches, alongside the development of historical maps and climate projections for 2070 to contextualize these observations.

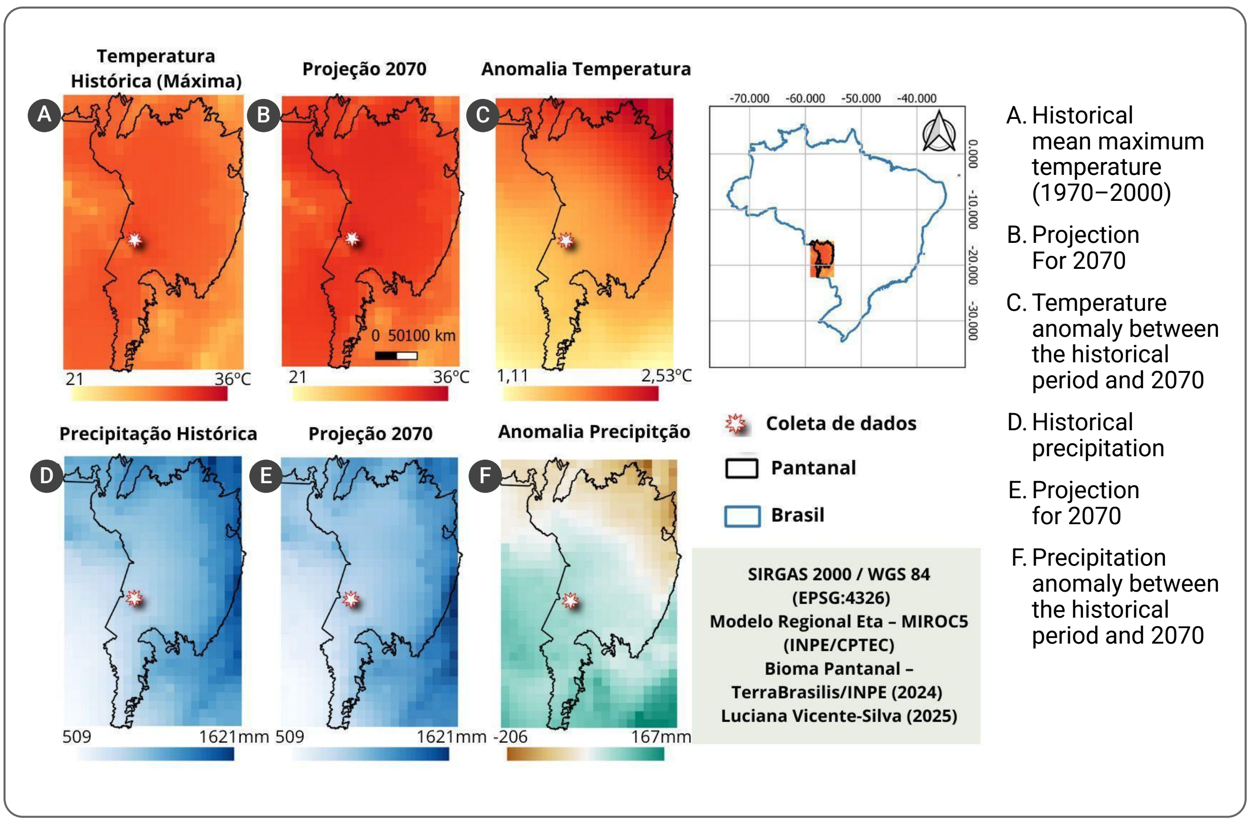
Climate maps, projections for 2070, and anomalies in the Pantanal

The climate maps were developed based on historical meteorological data and climate projections derived from regionalized models for 2070. These visual representations aim to contextualize the patterns and trends of temperature and precipitation changes across the Pantanal biome.

The climate maps reveal a clear **warming trend** and a redistribution of rainfall patterns in the Pantanal biome. Historically, maximum temperatures are already high in the region, especially in the northern portion (Figure 3A), but projections for 2070 (Figure 3B) indicate a generalized intensification, with anomalies reaching up to +2.53 °C in the north (Figure 3C). This pattern suggests that the Pantanal will experience a significant increase in **thermal stress**, particularly in areas of higher altitude and open vegetation.

Regarding **precipitation**, the historical pattern shows greater rainfall in the northern part of the biome (Figure 3D). However, the 2070 projection (Figure 3E) points to a North–South inversion trend, with substantial reductions of up to −200 mm in the North and slight increases in the southern portion, especially near Porto Murtinho and Corumbá (Figure 3F). These contrasting trends highlight potential shifts in water availability, which could intensify **drought events** in the north and increase variability in **flood cycles** in the south, dynamics that align with farmers' perceptions of irregular rainfall and growing water scarcity.

Figure 3. Maximum temperature and precipitation in the Pantanal biome



Semi-structured Conversational Interviews

Sixteen semi-structured interviews were conducted with family farmers. Of these, 30 percent involved the joint participation of couples, 23 percent were carried out exclusively with men, and 37 percent solely with women, aged between 24 and 75 years. Regarding their productive profile, 85 percent of respondents sell food as a source of income, while 15 percent prioritize production for self-consumption. The interviews lasted, on average, between 25 and 45 minutes. Based on semi-structured conversational interviews exploring farmers' perceptions of climate change impacts and adaptation strategies, three key themes emerged: **irregular rainfall**; a generalized **decline in agricultural production**; and **water** as the central element guiding adaptation efforts.

Local perceptions of climate change

All farmers reported perceivable changes in climate, particularly **increases in temperature** and reductions and **irregularity of rainfall**, factors they associate directly with agricultural production, livestock management, and livelihoods (table 1). Farmers' perceptions were strongly influenced by recent extreme events, especially the intense wildfires and heatwaves recorded in the Pantanal in 2020 and 2023.

Beyond extreme events, farmers also described gradual **environmental instability** observed over the past three to five years, based on everyday and long-term observation of local ecosystems. This experiential knowledge was expressed in statements such as: *"It got worse when this river drought started," "Before, streams used to reach the doorstep, but now, for about five or six years, there has been no water," "The bay dried up and never filled again, all the fish died,"* and *"In recent years, about five years now, things have changed a lot here. But it's the drought, right? Lack of rain."*

These perceptions demonstrate a strong experiential awareness of climatic instability, grounded in both extreme events and everyday environmental observation. These accounts demonstrate that farmers' awareness of climate change is not limited to dramatic events but is also grounded in continuous and sensitive observation of environmental changes affecting water availability, vegetation, and ecosystem dynamics.

Table 1: Farmers' perceptions of climate change in the Pantanal

1	Comparison with past climatic conditions
2	Feeling of environmental insecurity
3	Unpredictability of rainfall
4	Streams dried up
5	Ponds dried up
6	Bays dried up
7	Higher temperatures
8	Reduced rainfall

Reported impacts on agricultural production and livelihoods

The impacts reported by farmers reflect how these perceived climatic changes translate into concrete challenges for agricultural and livestock systems. The main impacts include the abandonment of previously viable crops such as corn and beans, increased incidence of agricultural pests and animal diseases, higher water demand, rising production costs, animal intoxication, and increased animal and plant mortality.

Two impacts deserve particular emphasis due to their relevance to the Pantanal context: the increasing occurrence of **wildfires** and the intensification of **conflicts with wildlife**. Wildfires were described as recurrent, increasingly frequent, and severe threats, causing direct losses to production systems and natural resources. Conflicts with wildlife were linked to intensified droughts and fires, which reduce the availability of food and water in natural environments and force animals to seek resources in productive areas. Reported cases include predation of calves and domestic dogs by jaguars (*Panthera onca*); consumption of fruits, leaves, and seeds by deer, monkeys, and birds such as parakeets (*Psittacara leucophthalmus*), chachalacas (*Ortalis canicollis*), and parrots (*Amazona aestiva*); as well as predation of roots and fruits by peccaries (*Tayassu pecari*).

Wildfires also affected complementary livelihood activities, particularly **beekeeping**. Farmers reported the abandonment of *Apis mellifera* hives used for honey production and sales, as smoke alters bees' natural behavior, reduces honey production and quality, and often causes colonies to abandon hives in search of safer locations.

Overall, **production losses** were widely reported, with reductions estimated between 40 percent and 90 percent over the last five years. These losses highlight the growing vulnerability of family farming systems in the Pantanal to climate change, revealing impacts that directly affect household income and compromise families' ability to remain in their territories.

Table 2: Reported impacts of climate change on family farming in the Pantanal

1	Reduction in production
2	Increase in animal diseases and intoxication
3	Higher mortality of plants and animals
4	Increase in insect attacks
5	Conflicts with wild animals
6	Wildfires
7	Increase in production costs
8	Abandonment of previously viable species
9	Increase in water demand
10	Intensification of care and management practices

Policy-supported, iterative, and emergent adaptations

Adaptation strategies identified among family farmers in the Pantanal can be grouped into three interrelated categories, *policy-supported, iterative, and emergent*, which together reflect different degrees of institutional involvement, organization, and adaptive capacity. *Policy-supported* adaptations are those promoted or facilitated by public programs and institutions, often focused on providing infrastructure and technical assistance. *Iterative* adaptations emerge through collaborative projects that combine local knowledge with external support, emphasizing experimentation, learning, and landscape restoration. Finally, *emergent* adaptations arise from farmers' immediate responses to climatic and economic pressures, expressing both creativity and structural vulnerability. These three dimensions coexist and interact, illustrating how adaptation in the Pantanal is a dynamic and multilevel process shaped by the intersection of policy, collective action, and local ingenuity (table 3).

Policy-supported adaptations

Adaptations supported by public policies mainly included actions related to **water access** and strengthening **agricultural production**. Initiatives mentioned included the installation of cisterns and community wells, generally financed by municipalities or state and federal programs. Many also emphasized the importance of emergency water deliveries by potable water trucks, considered essential for reducing water insecurity and sustaining the livelihoods of many families. Courses on **organic production** offered by institutions such as Embrapa and UFMS were also reported, but they still reach only a limited number of families, reducing their impact on scale. **Technical assistance** was highlighted as being available and important for encouraging the use of technologies such as shading nets, irrigation, and soil management. However, the insufficient number of professionals limits coverage and restricts families' access. However, interviewees highlighted that the effectiveness of these measures is often undermined by institutional and operational shortcomings: cistern maintenance is inadequate, gaps in local governance persist, funding is episodic, and the coverage of technical services remains insufficient.

Iterative adaptations

Iterative adaptations, generally linked to **sustainable development** and **environmental restoration projects** and often implemented by NGOs and research foundations, were considered particularly relevant because they generate direct results for the families involved. Within this context, the **integrated landscape management** (ILM) approach, exemplified by the *Pantanal Model Landscape* initiative and supported by national and international funding, was highlighted. Actions implemented included the use of solar pumps for irrigation, the establishment of **Agroforestry Systems** (AFS) accompanied by training courses on their design and management, the production of native seedlings for reforestation, remunerated reforestation initiatives in conservation units, pasture restoration, as well as strengthening of community governance through associations, meetings, and conflict-resolution mechanisms.

In addition, the structuring of **community fire brigades**, including the provision of equipment and specialized training for wildfire prevention and response, has been an important strategy to enhance local adaptive capacity in the face of increasing fire risks. Despite the relevance of these initiatives and their transformative potential, their reach remains limited, as they are still in early stages of implementation and involve only a limited number of families.

Emergent adaptations

Emergent adaptations, developed in response to families' immediate needs, revealed both the ingenuity and vulnerability of the local context. The use of **artesian wells** was cited as the most important measure to cope with drought. However, many farmers reported a significant reduction in water availability during critical periods, particularly in shallow wells of up to 10 meters, a phenomenon not observed until about five years ago. Vegetable production is seasonal, concentrated between May and August when temperatures are milder. Limited resources constrain investment in more efficient systems for year-round production, since high temperatures and low water availability restrict agricultural output.

Cattle management also requires adaptation to climatic seasonality. During the dry season, producers who cannot afford additional feed or pasture restoration move their animals to legal reserve areas, conservation units, or bay margins, a practice that ensures survival but generates social conflicts and additional environmental pressures. Other strategies mentioned included fencing gardens with mesh and electric shocks to prevent animal invasions; substituting more sensitive species with varieties more resistant to heat, such as goats, guinea fowls, sweet potatoes, and cowpeas; as well as the traditional practice of itinerant cultivation, in which gardens or fields are relocated to another site each planting cycle, thereby preserving soil fertility, reducing pest attacks, and ensuring continued production.

Adaptation strategy in the *Pantanal Model Landscape*: intensified use of **irrigation systems** to support crop establishment and reduce water stress

Adaptation strategy in the *Pantanal Model Landscape*: use of **solar panels** to reduce electricity costs for pumping water from wells

Table 3: Types of adaptation strategies adopted by family farmers in the Pantanal and their main characteristics

Type of adaptation	Examples and main actions	Characteristics and challenges
Policy supported	• Installation of cisterns and community wells • Courses on organic production • Delivery of drinking water by potable water trucks • Technical assistance promoting shading nets, irrigation, and soil management (Embrapa, UFMS)	• Funded by municipal, state, or federal programs • Recurrent problems with maintenance and collective management (e.g., electricity costs for pumps) • Limited outreach due to insufficient technical staff
Iterative	• Integrated landscape management (ILM) projects such as the Pantanal Model Landscape • Installation of solar pumps for irrigation • Implementation of Agroforestry Systems (AFS) with training • Production of native seedlings and remunerated reforestation • Pasture restoration • Strengthening of community governance (associations, meetings, conflict resolution) • Community fire brigades	• Supported by national and international funding • Generate direct benefits and promote environmental restoration • Limited coverage; still in early stages of implementation
Emergent	• Use of artesian wells (up to 10 m) to face drought • Seasonal vegetable production (May–August) • Movement of cattle to reserve areas or bay margins during dry periods • Fencing of gardens with mesh or electric shocks • Substitution of species for heat-resistant varieties (goats, guinea fowls, sweet potatoes, cowpeas) • Itinerant cultivation (rotating gardens or fields each cycle)	• Developed in response to immediate needs • Reflect both ingenuity and vulnerability • Limited by environmental constraints • May cause social conflicts and ecological pressures

4

Discussion

This study integrates **climate projections, spatial analysis, and local knowledge** to examine how global climatic trends materialize in the everyday realities of family farming systems in the Pantanal. By combining biophysical data with farmers' perceptions and adaptive responses, the project reveals not only the ecological transformations underway but also their socio-economic and governance implications.

The findings highlight that climate change in the Pantanal is not an abstract future risk, but a lived and ongoing process that reshapes production systems, livelihoods, and territorial dynamics. In this sense, the project contributes to **bridging scientific evidence and local experience**, offering a grounded basis for resilience-building strategies and territorially informed public policies.

Climate maps, projections for 2070, and anomalies in the Pantanal

Our analysis of historical maps and projections for 2070 indicate **consistent warming** in the Pantanal, accompanied by a **redistribution of rainfall patterns**. These trends have been widely documented in recent studies and are perceived by local communities (Marengo et al. 2021b; Silva et al. 2024). The anomaly maps show temperature increases of up to +2.53°C in northern areas and +1.62°C in the study area, reinforcing a possible pattern of thermal intensification and a greater occurrence of extreme events such as heatwaves and wildfires, phenomena already reported by farming families.

Projected precipitation for 2070 indicates substantial reductions in the northern Pantanal and moderate increases in the south. The decrease in rainfall in the northern portion of the biome is particularly concerning because this region contains the **headwaters** and **recharge areas** responsible for much of the water input that sustains the Pantanal floodplain; prolonged droughts in this area compromise the flood pulse and reduce downstream flow (Lázaro et al. 2020). The trend of **declining rainfall** is already reflected in shorter and more unstable hydrological cycles, as demonstrated by the 2019–2020 megadrought and by recent studies reporting reduced river discharge, contraction of flooded areas, and persistent hydrological deficits (Thielen et al. 2021; Marengo et al. 2021b; MapBiomas 2024). The intensification of drought in the Pantanal is associated with a combination of factors, including the expansion of dikes and drainage canals, land-use changes and replacement of native vegetation in headwater areas, as well as reduced evapotranspiration and global warming that lead to diminished rainfall in the region (MapBiomas 2024; Marengo et al. 2021b; Ernst et al. 2025).

Rice Bay (*Baia do Arroz*) during the rainy season in July 2017

Rice Bay (*Baia do Arroz*) in November 2025, after not receiving sufficient river water to remain full since 2020

This climatic context provides a foundation for farmers' perceptions, who, as shown in the results, report **prolonged droughts, irregular rainfall, the disappearance of lagoons and streams, and rising temperatures**. These transformations are consistent with what is expected under continued warming and hydrological redistribution (Harris et al. 2005; Berlinck et al. 2021). Furthermore, recent studies using remote sensing data confirm the reduction of water surface coverage in the Pantanal over recent decades), reinforcing local observations (Justino et al. 2025; MapBiomas 2024).

Local perceptions of climate change

Our results reveal that farmers' perceptions and environmental knowledge are closely linked to local ecological dynamics, highlighting everyday experience in the Pantanal as a sensitive indicator of environmental change (Peiter et al. 2011). Farmers interpret declines in agricultural production, loss of watercourses, and increased disease incidence in plants and animals as expressions of water stress, intensified climate extremes, and ecological imbalance. These interpretations are consistent with recent assessments pointing to growing socio-environmental vulnerability in the Pantanal (Tomas et al. 2019; Marengo et al. 2021b; Ernst et al. 2025).

Frequent mentions of production losses and environmental instability indicate that climate change is perceived not as an isolated event but as an **ongoing process** reshaping ecological and productive dynamics. In this sense, local perceptions emerge as an essential component not only for understanding current transformations but also for guiding territorially grounded adaptation policies capable of strengthening community resilience.

Reported impacts on agricultural production and livelihoods

Field observations show that the reported impacts do not occur in isolation; rather, they form a **negative feedback cycle** that progressively weakens family-based production systems. Declining agricultural productivity is accompanied by increased disease incidence and toxic exposure in animals, plant mortality, and more frequent insect attacks, which become more prevalent under hotter and drier conditions (Skendžić et al. 2021; Godde et al. 2021). At the same time, the shortening of the rainy season and habitat degradation intensify conflicts with wild animals entering productive areas in search of food and water (Calhoun et al. 2025). These factors increase production costs and demand constant adaptation from already fragile systems.

Impacts of prolonged drought and soil degradation on agricultural production, highlighting reduced crop vigor and increased soil exposure

This set of pressures results not only in economic losses but also in a significant rise in production costs, driven by greater need for inputs, irrigation, animal replacement, and emergency pest-control strategies. In several cases, farmers have abandoned previously viable species, replacing them with crops less sensitive to water stress or with lower-risk activities. The growing demand for water, combined with rainfall irregularity, intensifies management and care tasks, increasing the workload, particularly for women, who already carry out much of the productive and domestic labor (Moreira et al. 2025).

Frequent mentions of production losses indicate a potential **decline in food security and family income**, impacts similar to those observed in other agricultural regions under strong climatic pressure, such as Brazil's semi-arid Northeast (Mesquita et al. 2016; Costa et al. 2021). In the Pantanal, however, these effects are exacerbated by the biome's unique ecology, including altered flood cycles, conflicts with wildlife, and damage caused by forest fires, events that have intensified in recent decades (Berlinck et al. 2021; Libonati et al. 2020).

Adaptive Strategies: Public Policies, Iterative Actions, and Emerging Responses

The adaptation strategies supported by **government programs** identified in the interviews, such as the installation of cisterns and community wells, organic production courses, and technical assistance for irrigation and soil management, reflect a pattern widely described in the literature on adaptation in rural and socio-environmentally vulnerable areas. Several studies indicate that policies aimed at **access to water** and **productive strengthening** constitute fundamental pillars of adaptation in contexts of climate change, especially in regions subject to prolonged droughts (Tomas et al. 2019; Marengo et al. 2021b). However, the results show that the effectiveness of these initiatives is significantly limited by institutional and operational weaknesses. Recurring problems with cistern maintenance, gaps in local governance, energy costs associated with wells, and insufficient technical assistance are obstacles mentioned both by participants and in analyses that discuss the barriers to the consolidation of lasting adaptations in rural territories (Biesbroek et al. 2013).

Natural vegetation in São Gabriel Agrarian Reform Settlement, in Ladário, Mato Grosso do Sul, Brazil, during the dry season.

These difficulties illustrate what the literature describes as the **"mismatch" between policy design and implementation**: although programs formally exist, their effectiveness in the daily lives of communities is conditioned by municipal capacity, resource availability, continuity of funding, and social participation. Thus, the evidence reinforces the argument that, without improvements in institutional capacity and without more robust community management mechanisms, one-off measures tend not to translate into sustainable long-term responses.

Undergraduate students in Biology from the Federal University of Mato Grosso do Sul (UFMS) involved in field research activities

Iterative adaptations observed in projects such as the *Pantanal Model Landscape* and in *integrated landscape management* practices represent a form of active resilience grounded in social learning, aligning with critical perspectives on resilience in socio-ecological systems (Cretney 2014; Folke et al. 2010; Nikinmaa et al. 2020). The introduction of solar pumps, agroforestry systems, pasture-restoration practices, native seedling production, and the strengthening of community governance illustrate how interventions supported by technical assistance and institutional partnerships can promote structural transformations in local territories. These initiatives enhance local autonomy, reinforce collective organization, and stimulate productive diversification. Although their current coverage remains limited, such actions hold substantial transformative potential because they strengthen core dimensions of resilience, diversity, connectivity, learning, and adaptive capacity (Folke 2006; Wilkinson 2012).

Emerging adaptations, such as the intensified use of artesian wells, the seasonal cultivation of vegetables, the movement of cattle to reserve areas or bay margins during prolonged droughts, the fencing of home gardens with mesh or electric systems, and the substitution of traditional species for more heat-resistant varieties (e.g., goats, guinea fowls, sweet potatoes, cowpeas), reveal both the practical ingenuity and the structural vulnerability of rural families facing increasingly severe dry seasons.

These strategies reflect a form of "*resilience under pressure, common in socio-ecological contexts where adaptive capacity is constrained by limited financial, technological, and institutional support*" (Cretney 2014; Peiter et al. 2011). While they provide **essential short-term relief**, some of these practices, such as relocating cattle to bay margins or reserve zones, can generate social conflicts, exacerbate ecological degradation, and increase future exposure to climate risks.

Socio-ecological Resilience in the Pantanal Model Landscape

The socio-ecological resilience of family farming in the Pantanal is shaped by the interaction between **local adaptive strategies** and the intensification of **environmental pressures**. On the one hand, strategies such as crop diversification, the adoption of species more resistant to heat and drought, the implementation of agroforestry systems, and the use of sustainable technologies, such as solar-powered pumps and efficient irrigation systems, enhance farmers' capacity to absorb climatic impacts. In addition, local ecological knowledge, articulated with social learning processes, such as integrated resource management promoted by community-based initiatives like the Pantanal Model Landscape, contributes to increased autonomy, improved resource management capacity, and the reorganization of productive practices in the face of hydrological uncertainty. These findings are consistent with core resilience principles related to diversity, connectivity, and iterative adaptation (Folke et al. 2010; Nikinmaa et al. 2020).

At the same time, several **structural factors** continue to weaken this resilience. Intensifying droughts, rising temperatures, rainfall irregularity, and the reduction of flooded areas, trends widely documented for the Pantanal, have led to production losses, increased pest outbreaks, plant mortality, and escalating conflicts with wildlife (Marengo et al. 2021b; Lázaro et al. 2020). These climatic pressures intersect with **institutional limitations**, including inadequate maintenance of cisterns, insufficient technical assistance, high energy costs for water extraction, and discontinuities in public programs, collectively undermining adaptive capacity. **Social vulnerabilities**, such as geographic isolation, increased dependence on external inputs, low educational levels, limited access to information, constraints on the adoption of innovative practices, and the disproportionate burden of labor carried by women, further constrain resilience (UNDP 2012; Castro & Cerezini 2024).

Some short-term adaptation strategies, such as transferring livestock to the edges of bays and/or protected areas during severe droughts or increasing reliance on artesian wells, provide immediate relief but can generate new vulnerabilities and trigger social conflicts. Thus, socio-ecological resilience in the Pantanal Model Landscape, despite promising local innovations, remains constrained by **persistent structural limitations** that highlight the need for **sustained investments** in territorial governance, water security, ecological restoration, and institutional capacity to support long-term adaptation (Folke et al. 2010; IPCC 2023).

5

Conclusion

The results indicate that family farming in the Pantanal is experiencing **severe impacts from climate change**, ranging from extreme droughts and the loss of aquatic ecosystems to recurrent wildfires and a sharp decline in agricultural production.

Local perceptions demonstrate strong **environmental sensitivity and in-depth knowledge of the territory**, aligning closely with projected climate trends for the biome. The observed adaptation strategies reveal a mosaic of responses, ranging from improvised and emergency actions to more promising iterative processes supported by institutions and grounded in ecological restoration and integrated landscape management.

However, these initiatives have not yet reached a scale sufficient to transform the current vulnerability scenario. Strengthening continuous **public policies**, expanding **investments** in sustainable management, and supporting **integrated landscape projects** are fundamental pathways to promote socio-ecological resilience and ensure dignified conditions for the permanence of Pantanal families in their territories, especially in the face of a hotter, drier, and more unpredictable climatic future.

Forest fire recorded in 2025 within the *Pantanal Model Landscape* territory, highlighting the impacts of fire on native vegetation

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