

Climate Change and Resilience of Terrestrial Ecosystems: Case of The Androy Region, Madagascar

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Abstract

This study examined the impacts of climate change on the resilience of terrestrial ecosystems in the Androy Region, southern Madagascar. A mixed-methods research design was employed, integrating climatic data analysis, household surveys, key informant interviews, field observations, and document review to assess ecosystem responses and community adaptation strategies. The findings revealed that declining rainfall, rising temperatures, and recurrent droughts have accelerated land degradation, reduced vegetation cover, intensified food insecurity, and weakened ecosystem resilience. The study also identified socioeconomic and institutional constraints, including limited agricultural resources, inadequate infrastructure, and gender inequality, as factors reducing adaptive capacity. Nevertheless, ecosystem restoration, sustainable land management, and community-based natural resource management emerged as important resilience strategies. The study concludes that integrated ecosystem restoration, climate adaptation, and strengthened institutional support are essential for enhancing ecosystem resilience and promoting sustainable development in the Androy Region.

Keywords: *climate; resilience; ecosystems; Androy; Madagascar.*

Introduction

Climate change has become one of the most significant threats to terrestrial ecosystems worldwide, particularly in arid and semi-arid regions where ecological processes are highly sensitive to climatic variability (Aragón et al., 2021; de Jong et al., 2011). Rising temperatures, declining and erratic precipitation, prolonged droughts, and the increasing frequency of extreme climatic events have accelerated land degradation, biodiversity loss, and the disruption of ecosystem services that sustain human well-being (IPCC, 2023; UNEP, 2022). These environmental changes are especially pronounced in developing countries, where ecological vulnerability is compounded by socioeconomic constraints, weak institutional capacity, and a heavy dependence on natural resources for rural livelihoods (World Bank, 2021). Consequently, strengthening ecosystem resilience has become a central objective of global environmental policies and sustainable development initiatives, particularly in regions facing recurrent climate-related shocks.

Madagascar is internationally recognized as one of the world's biodiversity hotspots, hosting exceptional levels of endemic flora and fauna. However, this unique natural heritage is increasingly threatened by climate change and human-induced environmental degradation (Seddon et al., 2020; Eymynorane et al., 2026). The southern part of the country has experienced recurrent droughts, increasing temperatures, irregular rainfall patterns, and severe land degradation over recent decades, resulting in declining agricultural productivity, food insecurity, biodiversity loss, and ecosystem degradation (IPCC, 2023; World Bank, 2021). These environmental pressures have been further intensified by anthropogenic activities, including deforestation, uncontrolled bushfires, overgrazing, and unsustainable exploitation of natural resources, which collectively reduce the ecological capacity of landscapes to recover from climatic disturbances (FAO, 2022; UNEP, 2022).

Among the regions of southern Madagascar, Androy represents one of the country's most climate-vulnerable territories. Characterized by a semi-arid climate, low annual rainfall,

high evapotranspiration, and recurrent episodes of *kéré* (chronic drought-induced food crises), the region has become increasingly susceptible to environmental degradation and humanitarian emergencies (World Bank, 2021; Amnesty International, 2025). The deterioration of terrestrial ecosystems—including the loss of vegetation cover, soil erosion, declining soil fertility, and reduced biodiversity—has substantially affected ecosystem services that support agriculture, livestock production, and rural livelihoods. These changes have contributed to chronic food insecurity, increasing poverty, forced migration, and heightened social vulnerability among local communities (IOM, 2021; Andriamaro, 2022).

The concept of ecosystem resilience provides an appropriate framework for understanding how terrestrial ecosystems respond to climatic and anthropogenic disturbances. Ecological resilience refers to the capacity of ecosystems to absorb disturbances, reorganize, adapt, and recover while maintaining their essential structures, functions, and ecological processes (Holling, 1973). Recent resilience research has expanded this concept by emphasizing adaptive capacity, ecological transformation, and the interactions between environmental, institutional, and social systems (IPCC, 2023). In climate-sensitive regions such as Androy, ecosystem resilience depends not only on biophysical characteristics but also on governance arrangements, sustainable land management practices, community participation, and local adaptation strategies.

Previous studies have extensively documented the impacts of climate change on drought occurrence, agricultural productivity, food security, biodiversity conservation, and migration in southern Madagascar (World Bank, 2021; FAO, 2021; Andriamaro, 2022; Amnesty International, 2025). Other research has examined the relationships between poverty, environmental degradation, and climate-induced migration (Andrianandrasana et al., 2025; Mutabazi et al., 2026). Although these studies provide valuable insights into individual dimensions of climate vulnerability, they have generally examined climatic hazards, ecosystem degradation, and community adaptation as separate phenomena. Consequently, limited empirical evidence exists regarding how climatic variability, ecological degradation, and human responses interact to influence the resilience of terrestrial ecosystems in the Androy region. Moreover, relatively few studies have adopted an integrated systems perspective that simultaneously considers climatic drivers, ecosystem dynamics, socioeconomic vulnerability, and local resilience strategies.

Addressing this knowledge gap is particularly important because effective climate adaptation requires a comprehensive understanding of both ecological processes and human-environment interactions. Ecosystem resilience is shaped not only by climatic conditions but also by land-use practices, institutional support, community-based natural resource management, and ecological restoration initiatives. Understanding these interrelationships can provide a stronger scientific basis for designing sustainable adaptation policies that simultaneously conserve biodiversity, restore degraded landscapes, and enhance the adaptive capacity of rural communities.

This study therefore aims to analyze the impacts of climate change on the resilience of terrestrial ecosystems in the Androy Region of southern Madagascar. Specifically, it examines recent climatic trends, evaluates their effects on vegetation cover, soils, biodiversity, and ecosystem services, identifies the natural and anthropogenic factors influencing ecosystem resilience, and assesses the contribution of local adaptation and sustainable natural resource management practices to ecological recovery. By integrating climatic, ecological, and socioeconomic dimensions within a single analytical framework, this study contributes to the growing body of knowledge on climate resilience in tropical semi-arid ecosystems. Its findings are expected to provide evidence-based recommendations for ecological restoration, climate adaptation planning, sustainable land management, and community-based conservation policies in Madagascar and other climate-vulnerable dryland regions.

Methodology

This study employed a mixed-methods research design to examine the impacts of climate change on the resilience of terrestrial ecosystems in the Androy Region of southern Madagascar. Integrating quantitative and qualitative approaches enabled a comprehensive assessment of climatic trends, ecosystem degradation, and local adaptation strategies. The quantitative component focused on analyzing changes in climatic variables, including temperature, precipitation, drought frequency, and indicators of ecosystem degradation, whereas the qualitative component explored local perceptions of climate change, resilience practices, and sustainable natural resource management.

The study was conducted in the five districts of the Androy Region—Ambovombe-Androy, Bekily, Beloha, Tsihombe, and Antanimora Sud—which are characterized by a semi-arid climate, recurrent droughts, irregular rainfall, and fragile terrestrial ecosystems. These districts were purposively selected because they have experienced severe climate-related environmental degradation and represent the major ecological and socioeconomic conditions of southern Madagascar.

The target population comprised rural households, local government officials, technical officers responsible for environmental management, representatives of non-governmental organizations, and community leaders involved in natural resource management and climate adaptation. A stratified sampling technique was applied to ensure adequate representation of the five districts, while purposive sampling was used to select key informants with extensive experience in climate change adaptation and ecosystem management. A total of 250 households participated in the questionnaire survey, representing approximately 50 households from each district. In addition, 30 key informants were interviewed, including 10 local government officials, 8 environmental and agricultural technical officers, 7 representatives of non-governmental organizations, and 5 community leaders actively engaged in environmental conservation and climate resilience initiatives. Furthermore, five focus group discussions, each consisting of 8–10 participants, were organized to validate community-level observations and adaptation practices.

Primary data were collected between May and August 2025 through structured household questionnaires, semi-structured interviews, focus group discussions, and direct field observations. The household questionnaire gathered information on perceived climatic changes, ecosystem degradation, agricultural production, livelihood vulnerability, and adaptation strategies. Semi-structured interviews generated detailed information regarding environmental governance, conservation initiatives, ecosystem restoration, and institutional responses to climate change. Field observations were conducted to document evidence of vegetation degradation, soil erosion, water scarcity, and land-use changes across the study sites.

Secondary data were obtained from scientific publications, reports produced by the Malagasy Ministry of Environment and Sustainable Development, the General Directorate of Meteorology, the Food and Agriculture Organization (FAO), the Intergovernmental Panel on Climate Change (IPCC), the World Bank, and other national and international institutions. Climatic records covering precipitation and temperature trends were used to complement field observations and support the interpretation of environmental changes.

The principal research instruments included structured questionnaires, interview guides, focus group discussion guides, observation checklists, handheld Global Positioning System (GPS) receivers for recording observation sites, and digital cameras for field documentation. Geographic Information Systems (GIS) and remote sensing techniques were employed to examine changes in vegetation cover, land use, and land degradation. Satellite imagery from the Landsat 8 Operational Land Imager (OLI) and Sentinel-2 missions was analyzed to assess temporal changes in vegetation conditions and landscape degradation within the study area.

Quantitative data were coded and analyzed using IBM SPSS Statistics version 27 and Microsoft Excel 2021. Descriptive statistics, including frequencies, percentages, means, and trend analyses, were used to summarize climatic variables and environmental indicators. Tables and graphs were generated to illustrate long-term changes in rainfall, temperature, drought frequency, and other ecosystem characteristics. Qualitative data obtained from interviews, focus group discussions, and field observations were analyzed using thematic content analysis. Interview transcripts were systematically coded to identify recurring themes related to ecosystem degradation, climate vulnerability, adaptation practices, and resilience-building strategies. The integration of quantitative and qualitative findings through data triangulation enhanced the credibility and reliability of the results by enabling cross-validation across multiple data sources.

Participation in the study was voluntary, and informed consent was obtained from all respondents before data collection. Participants were assured that the information collected would remain confidential, used exclusively for academic purposes, and reported anonymously in accordance with accepted research ethics.

Results and Discussion

Results

Irregular rainfall

Tabel 1. Evolution of average annual rainfall in the Androy Region

Period	Average annual rainfall (mm/year)	Variation (%)
1990-2000	620 mm	Reference (0%)
2001-2010	580 mm	-6.5%
2011-2020	530 mm	-14.5%
2021-2025	500 mm	-19.4%

Source : Authors

The observed trends highlight a sustained downward trend in rainfall in the Androy region. This situation is a major indicator of the territory's environmental vulnerability. The scarcity of rain leads to a reduction in water availability for households, livestock, and crops.

The rise in temperatures in the Androy region

Table 2. Link between climate and environmental changes (2018-2025)

Year	Average temperature (°C)	Annual precipitation (mm)	Frequency of droughts	Food insecurity (%)	Childhood malnutrition (%)
2018	26.5	450	1	70	40
2019	27.0	430	2	75	42
2020	27.5	420	2	80	45
2021	28.0	400	3	85	47
2022	28.5	380	3	90	50
2023	29.0	370	4	95	52
2024	29.5	360	4	95	55
2025	30.0	350	5	95	55

Source : Authors

The results show a direct link between climate change and the increase in migration observed in the Androy region. When temperatures rise, rainfall decreases, droughts become more frequent, and food insecurity worsens, households gradually lose their livelihoods. Faced with this situation, migration becomes a strategy for adaptation and survival.

The increased frequency of droughts

Table 3. Irregular rainfall and chronic drought (Androy, 2015–2025)

Year	Rainfall situation	Rainfall anomaly	Drought intensity / Kéré	Observed impacts
2015	Severe deficit	-30 to -50%	Severe drought	Beginning of a food crisis, agricultural losses
2016	Very low rainfall	-40 to -60%	Severe Kere	Famine, internal migration
2017	Weak and irregular	-20 to -45%	Chronic drought	Persistent food insecurity
2018	Short showers	-25%	Moderate to severe drought	Decline in cassava/maize production
2019	Irregular rainfall	-30%	Chronic drought	Soil degradation, rural migration
2020	Water deficit	-35 to -50%	Kéré moderate	High water stress, affected livestock
2021	Prolonged drought	-40%	Severe Kere	Humanitarian crisis,
2022	Very light rain	-30 to -55%	Severe Kere	Expansion of famine-affected areas
2023	Late and light rains	-25 to -40%	Chronic drought	Persistent food insecurity
2024	Extreme irregularity	-20 to -45%	Kéré recurring	Increased migration to urban areas
2025	Unstable start to the season	-30%	Persistent drought	High vulnerability, ongoing migration

Source : Authors

Data analysis confirms that the Androy region is facing a sustained climate change phenomenon, characterized by reduced rainfall and increased interannual variability. This trend directly affects agricultural and pastoral production systems, which constitute the main source of livelihood for local populations.

The recurring drought episodes observed between 2015 and 2025 reflect a decrease in the resilience of rural households. Successive rainfall deficits lead to reduced harvests, increased livestock mortality, and a progressive degradation of natural resources.

Land degradation

Table 4. Structural Vulnerability Factors

Categories	Indicators	Levels	Effects
Economic	Cultivated land	5%	Low production
Social	Education Level	30%	Few alternatives
Social	Gender inequalities	40%	Female vulnerabilities
Institutional	infrastructure	25%	Isolations
Institutional	Public intervention	20%	Low resilience

Source: Authors

The results show that the vulnerability of the Antandroy population stems from a combination of interdependent economic, social, and institutional factors. Low agricultural production (5% of land cultivated) reduces income and food security. At the same time, low

levels of education (30%) limit opportunities for economic diversification, while gender inequalities (40%) exacerbate the precarious situation of women.

Discussion

The findings demonstrate that climate change has substantially reduced the resilience of terrestrial ecosystems in the Androy Region through the combined effects of declining rainfall, increasing temperatures, recurrent droughts, and accelerating land degradation. Rather than acting independently, these climatic stressors interact to reduce ecosystem productivity, alter ecological processes, and undermine the capacity of local communities to adapt to environmental change. The progressive decline in rainfall observed during the study period reflects increasing climatic instability in southern Madagascar and highlights the growing vulnerability of semi-arid ecosystems to prolonged water deficits (Reynolds et al., 2007). Reduced precipitation directly limits soil moisture availability, suppresses natural vegetation regeneration, and decreases agricultural productivity, thereby weakening ecosystem functions and the provision of essential ecosystem services.

These findings are consistent with the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2023), which identifies increasing rainfall variability and prolonged droughts as major drivers of ecosystem degradation in tropical drylands. Similar observations have been reported by the World Bank (2021), which documented that southern Madagascar has experienced persistent rainfall deficits that have intensified desertification, reduced agricultural yields, and increased dependence on humanitarian assistance. The results also support the conclusions of FAO (2021), which emphasizes that declining precipitation significantly accelerates soil degradation, reduces vegetation cover, and limits the regenerative capacity of dryland ecosystems.

The study further reveals a continuous increase in mean annual temperature accompanied by declining rainfall and increasing drought frequency. Higher temperatures intensify evapotranspiration, reduce soil water availability, and increase physiological stress on vegetation, thereby limiting ecosystem recovery following climatic disturbances. Rising temperatures also contribute to declining agricultural productivity through increased crop water demand and reduced pasture availability for livestock. These interacting processes create a feedback mechanism in which environmental degradation further decreases ecosystem resilience while simultaneously increasing the vulnerability of rural livelihoods.

Comparable trends have been documented in other semi-arid regions of sub-Saharan Africa, where warming temperatures have accelerated land degradation and reduced ecosystem productivity (Aragón et al., 2021; IPCC, 2023). In southern Madagascar, climate-induced environmental degradation has been associated with declining food production, increasing livestock mortality, and reduced household income, all of which reinforce multidimensional poverty (Andriamaro, 2022; Emynorane et al., 2025). Consequently, ecosystem degradation should not be viewed solely as an ecological issue but also as a major socioeconomic challenge affecting sustainable rural development.

The repeated occurrence of droughts between 2015 and 2025 illustrates the cumulative impacts of climate variability on ecosystem resilience. Chronic drought reduces vegetation recovery, alters species composition, and accelerates soil erosion, thereby increasing the susceptibility of ecosystems to further disturbances. At the household level, prolonged drought diminishes agricultural production, reduces livestock assets, and intensifies food insecurity, forcing communities to adopt coping strategies such as temporary migration, livelihood diversification, or increased dependence on natural resources. Similar relationships between drought, ecosystem degradation, and human mobility have been reported by Black et al. (2011) and more recently by Amnesty International (2025), which documented that recurrent drought has become a significant driver of climate-induced displacement among Antandroy communities.

An important contribution of this study lies in demonstrating that ecosystem resilience is determined not only by climatic variables but also by structural socioeconomic and institutional conditions. The findings indicate that limited cultivated land, low educational attainment, gender inequalities, inadequate infrastructure, and weak institutional support collectively constrain the adaptive capacity of local communities. These factors reduce opportunities for livelihood diversification and limit access to information, financial resources, and adaptation technologies required to respond effectively to climatic shocks. Similar conclusions have been reached by Andrianandrasana et al. (2025), who emphasized that poverty, environmental degradation, and climate-induced migration are mutually reinforcing processes in Madagascar. Likewise, Mutabazi et al. (2026) argued that strengthening community resilience requires integrated interventions addressing both environmental restoration and socioeconomic vulnerability.

The results also highlight the importance of ecosystem-based adaptation as a practical strategy for enhancing resilience under changing climatic conditions. Sustainable land management practices, including ecological restoration, reforestation, agroforestry, soil and water conservation, and community-based natural resource management, can improve ecosystem recovery while simultaneously supporting rural livelihoods. These approaches increase vegetation cover, reduce soil erosion, improve water retention, and enhance biodiversity conservation, thereby strengthening the capacity of ecosystems to withstand future climatic disturbances. Such nature-based solutions have increasingly been recognized as cost-effective adaptation measures that generate both ecological and socioeconomic benefits (UNEP, 2022; IPCC, 2023).

From a policy perspective, the findings suggest that climate adaptation strategies in the Androy Region should extend beyond emergency humanitarian responses and prioritize long-term investments in ecosystem restoration and sustainable land management. Strengthening local institutions, expanding climate information services, improving rural infrastructure, promoting climate-smart agriculture, and supporting community participation in natural resource governance are essential for enhancing both ecosystem resilience and human well-being (Eric et al., 2025; UN Convention to Combat Desertification, 2022). Because ecological degradation and socioeconomic vulnerability are closely interconnected, effective climate adaptation policies should adopt an integrated landscape approach that simultaneously addresses biodiversity conservation, sustainable livelihoods, and environmental governance.

Overall, this study contributes to the growing body of knowledge on climate change and ecosystem resilience by providing an integrated analysis of climatic, ecological, and socioeconomic dimensions within one of Madagascar's most climate-vulnerable regions. Unlike previous studies that primarily examined drought, food insecurity, or migration separately, the present research demonstrates how climatic change, ecosystem degradation, and structural vulnerability interact to shape the resilience of terrestrial ecosystems. This integrated perspective provides a stronger scientific basis for designing evidence-based policies aimed at promoting ecological restoration, strengthening community resilience, and advancing sustainable development in dryland regions facing increasing climate risks.

Conclusion

This study demonstrated that climate change has significantly reduced the resilience of terrestrial ecosystems in the Androy Region through the interaction of declining rainfall, rising temperatures, recurrent droughts, and structural socioeconomic vulnerabilities. The findings highlight that ecosystem resilience depends not only on ecological conditions but also on effective governance and community adaptive capacity. Strengthening resilience therefore requires integrated strategies that combine ecosystem restoration, climate-smart land management, community participation, and institutional support to promote

sustainable environmental conservation and improve the long-term livelihoods of vulnerable populations.

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