

Research Article

Climate Change and Prosopis Juliflora: Impact on Rangelands in the Afar Region, Ethiopia: A Review

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Abstract

This literature review examines the dual impact of climate change and the invasive species *Prosopis juliflora* on rangelands in the Afar Region of Ethiopia. Climate change has intensified environmental stressors in this arid region, leading to increased temperatures and erratic rainfall patterns, which threaten the productivity of rangelands. Concurrently, *Prosopis juliflora*, an invasive species introduced for reforestation, has spread aggressively across these rangelands, exacerbating land degradation. The review synthesizes current research on the ecological and socio-economic effects of *Prosopis juliflora* invasion, including its impact on soil properties, water resources, and livestock productivity. It also explores how climate change may enhance the spread of *Prosopis juliflora*, creating a feedback loop that further degrades rangeland ecosystems. Despite existing management strategies, such as mechanical removal and chemical treatments, their effectiveness has been limited. The review identifies significant research gaps and emphasizes the need for integrated management approaches that address both climate change and invasive species. Sustainable strategies are crucial for mitigating the combined threats to the Afar Region's rangelands and supporting the livelihoods of local pastoral communities.

Keywords

Prosopis Juliflora, Rangeland, Climate Change, Livestock

1. Introduction

The Afar Region of Ethiopia, located in the northeastern part of the country, is characterized by its arid and semi-arid landscapes, making it one of the most challenging environments for agricultural activities. The region's economy is heavily dependent on pastoralism, with rangelands serving as the primary source of grazing for livestock, which are the backbone of the livelihoods of the Afar people. However, these rangelands are under increasing pressure due to two major environmental stressors: climate change and the invasion of *Prosopis juliflora*.

1.1. Overview of Climate Change and Its Global Impact on Ecosystems

Climate change is a global phenomenon that has far-reaching impacts on ecosystems, biodiversity, and human livelihoods. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events are disrupting natural habitats and altering the distribution of species [16]. In arid and semi-arid regions, such as the Afar Region, the impacts of climate change are particularly pronounced, leading to increased desertification, reduced water availability, and the degradation of rangelands [11].

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1.2. Significance of Rangelands in the Afar Region, Ethiopia

Rangelands in the Afar Region are critical for sustaining the pastoral way of life. They provide the necessary forage for livestock, which are a vital source of food, income, and cultural identity for the Afar people. However, the productivity of these rangelands is highly sensitive to environmental changes. As climate change intensifies, the region is experiencing more frequent and severe droughts, leading to a decline in vegetation cover and a reduction in the carrying capacity of the land [23]. This has significant implications for the food security and economic stability of the pastoral communities.

1.3. Introduction to *Prosopis juliflora* and Its Invasive Nature

Prosopis juliflora is a fast-growing, thorny shrub or small tree native to Central and South America. It was introduced to Ethiopia in the 1970s as part of efforts to combat desertification and provide fuelwood [9]. *Prosopis juliflora* has become the most damaging weed in pastoral and agro-pastoral communities due to its infestation of pastureland, causing irreversible displacement of native pasture grasses and other natural tree species [1]. In Ethiopia, the area invaded by *Prosopis juliflora* is estimated to be 1.5 million ha, with an annual invasion rate of around 50,000 ha; of this, around 700,000 ha are located in the Afar Region [21]. However, the species quickly became invasive, spreading rapidly across the rangelands of the Afar Region. Its deep root system and high drought tolerance give it a competitive advantage over native vegetation, allowing it to dominate large areas of land [5].

The invasion of *Prosopis juliflora* has had profound ecological and socio-economic consequences. The species forms dense thickets that are impenetrable to both humans and livestock, reducing the availability of grazing land and water resources [31]. Additionally, *Prosopis juliflora* alters soil properties, making it difficult for native plants to regenerate, further degrading the rangelands [24].

1.4. The Need for This Review

Given the intertwined nature of climate change and *Prosopis juliflora* invasion, it is crucial to understand how these factors collectively impact the rangelands of the Afar Region. This review aims to synthesize the existing literature on the subject, providing insights into the mechanisms by which climate change and *Prosopis juliflora* exacerbate rangeland degradation. The review also highlights the socio-economic implications for pastoral communities and explores potential management and mitigation strategies. By doing so, it seeks to inform policy and decision-making processes aimed at preserving the ecological integrity of the region and ensuring the sustainability of pastoral livelihoods.

2. Study Area, Materials, and Methods

2.1. Study Area

The study focuses on the Afar Region in northeastern Ethiopia, an area characterized by its arid and semi-arid climate. The Afar Region encompasses a range of landscapes including lowlands, plateaus, and rift valleys, with temperatures often exceeding 40 °C and annual rainfall averaging less than 300 mm. The region's rangelands are critical for pastoralist communities who depend on them for grazing livestock. The introduction of *Prosopis juliflora* has significantly altered these rangelands, impacting soil health, water availability, and biodiversity.

2.2. Materials

A comprehensive review of existing research articles, books, and reports on climate change impacts, *Prosopis juliflora* invasion, and rangeland management was conducted. Sources included peer-reviewed journals, government and NGO reports, and academic theses. Historical and projected climate data for the Afar Region were obtained from the Intergovernmental Panel on Climate Change (IPCC) reports and local meteorological stations. Data on the distribution and impacts of *Prosopis juliflora*, as well as its effects on rangeland soil properties, water resources, and livestock productivity, were gathered from relevant research studies and field surveys.

2.3. Methods

A systematic review approach was used to collate and analyze existing literature on climate change and *Prosopis juliflora* impacts. Key databases such as Google Scholar, JSTOR, and PubMed were searched using relevant keywords. Articles were selected based on their relevance, quality, and recency. The Qualitative analysis was employed to synthesize findings from various studies. The impact of *Prosopis juliflora* on rangeland ecosystems was assessed by comparing pre- and post-invasion conditions, focusing on soil health, vegetation cover, and biodiversity. The socio-economic effects on pastoral communities were evaluated by reviewing case studies and reports that document changes in livestock productivity, income, and food security. The review identified research gaps by examining the scope and limitations of existing studies, and by highlighting areas where further research is needed.

3. Climate Change in the Afar Region

3.1. Overview of Climate Patterns in the Afar Region

The Afar Region, located in northeastern Ethiopia, is characterized by an arid and semi-arid climate with extreme tem-

peratures and low, highly variable rainfall. The region is part of the Rift Valley, which contributes to its unique geological and climatic conditions. Traditionally, the area has experienced two main seasons: a hot, dry season and a short, sporadic rainy season, with average annual rainfall ranging between 150 to 500 mm [11]. However, these patterns have become increasingly erratic due to climate change.

3.2. Evidence of Climate Change in the Afar Region

Recent studies indicate significant shifts in the climate of the Afar Region, consistent with broader trends observed across the Horn of Africa. These changes include increasing temperatures, with average temperatures rising by 1.3 °C to 2.1 °C over the last century [16]. Additionally, the region has experienced changes in precipitation patterns, with a trend toward more erratic rainfall and a reduction in the length of the rainy season [12]. This has led to prolonged drought periods, which are becoming more frequent and severe.

3.3. Impact of Climate Change on Rangelands

The rangelands of the Afar Region are particularly vulnerable to climate change due to their dependence on seasonal rainfall for vegetation growth. According to the study of [25], in Ethiopia, especially arid and semi-arid areas, degradation of rangeland is majorly due to climate change impact, which is associated with the variability of rainfall and temperature. As rainfall becomes more unpredictable and droughts more frequent, the productivity of these rangelands has declined significantly. This has resulted in reduced vegetation cover, loss of soil moisture, and increased desertification [37]. Furthermore, climate change has been shown to disrupt rangelands in a variety of ways, including changes in water resources, rangeland productivity, land use systems, and rangeland-based livelihoods, as well as the spread of invasive species [25, 22]. The degradation of rangelands has direct implications for the pastoral communities that rely on these lands for grazing their livestock.

3.4. Socioeconomic Implications of Climate Change

Climate change in the Afar Region not only impacts the environment but also has profound socioeconomic consequences. The pastoralist communities in Afar are highly dependent on livestock, which are in turn reliant on the availability of rangelands. As climate change reduces the productivity of these lands, the livelihoods of pastoralists are increasingly threatened. Food insecurity, loss of income, and increased competition for dwindling resources have become prevalent issues [36]. Moreover, the changing climate has exacerbated conflicts over land and water resources, further destabilizing the region [19].

3.5. Future Climate Projections for the Afar Region

Climate models predict that the Afar Region will continue to experience significant climatic changes in the coming decades. According to projections by the IPCC, temperatures in the region could increase by up to 3.1 °C by the end of the 21st century, with a corresponding decrease in rainfall and an increase in the frequency of extreme weather events such as droughts and floods [16]. These changes will likely exacerbate the challenges faced by the rangelands and the communities that depend on them, making sustainable management and adaptation strategies more critical than ever.

Given the pressing need to address the challenges posed by *Prosopis juliflora* in Ethiopia, it is crucial to explore the potential invasion dynamics of this species under various climate change scenarios. Understanding these dynamics is essential for informed decision-making and effective management of this invasive plant. In a study by [33], the current and future (2050 and 2070) climatic suitability for *Prosopis juliflora* in Ethiopia was analyzed under two climate scenarios: RCP4.5 and RCP8.5. The results reveal that under the current climate, 94.8% of the country is unsuitable for the establishment and spread of *Prosopis juliflora*, while only 0.4% (4.56 million hectares) is highly suitable.

However, the situation is expected to change dramatically by 2050. The study projects that under the RCP4.5 and RCP8.5 scenarios, the area highly suitable for *Prosopis juliflora* could increase by 55.6% and 63.6%, respectively. Similarly, the moderately suitable area is anticipated to grow by 33.3% and 42.9%. Looking further ahead to 2070, the projections indicate an even more alarming expansion, with the highly suitable area increasing by 73.3% (3.43 million hectares) and 80.0% (3.65 million hectares) under the RCP4.5 and RCP8.5 scenarios, respectively.

This projected expansion poses a significant threat, as *Prosopis juliflora* has already caused considerable damage to rangelands across various regions of Ethiopia. If its spread continues unchecked, the environmental and economic impacts could be devastating, further endangering the livelihoods of local communities. Addressing this issue promptly is vital to prevent worsening conditions and to safeguard the country's natural resources and the well-being of its people.

3.6. Adaptation and Resilience Strategies

Given the ongoing and projected impacts of climate change, there is a growing need for adaptation and resilience-building strategies in the Afar Region. Efforts to improve water management, such as the development of water harvesting and storage systems, have been implemented to help communities cope with reduced rainfall and prolonged

droughts [34]. Additionally, initiatives to promote the use of drought-resistant crops and alternative livelihoods are being explored as ways to reduce dependency on traditional pastoralism and increase resilience to climate change [20].

4. Invasion of *Prosopis Juliflora*

Prosopis juliflora, commonly known as mesquite, is a leguminous tree or shrub native to South America, Central America, and the Caribbean. It was introduced to Ethiopia in the 1970s as part of a reforestation and soil conservation effort, aimed at combating desertification and providing fuelwood and fodder [9]. However, what was intended to be a beneficial species for environmental management has since become one of the most aggressive invasive species in the Afar Region and other parts of Ethiopia.

4.1. Ecological Characteristics of *Prosopis Juliflora*

The success of *Prosopis juliflora* as an invasive species can be attributed to its ecological characteristics. It is highly tolerant of arid and semi-arid conditions, making it particularly suited to the Afar Region's harsh environment. *Prosopis juliflora* has a deep root system that allows it to access water from deep underground sources, enabling it to survive and thrive even in drought conditions [5]. Additionally, the tree is a prolific seed producer, and its seeds can remain viable in the soil for many years, ensuring continuous regeneration even after attempts at eradication [31].

The species' ability to fix atmospheric nitrogen gives it a competitive advantage over native flora, particularly in nutrient-poor soils. This ability not only enhances its growth but also alters soil nutrient dynamics, often making the environment less favorable for indigenous plant species [2]. Furthermore, the dense thickets formed by *Prosopis juliflora* reduce the availability of light and space for other vegetation, leading to the displacement of native plant communities.

4.2. Spread and Impact on Biodiversity

The spread of *Prosopis juliflora* in the Afar Region has been rapid and extensive, facilitated by several factors. Livestock, particularly camels, play a significant role in dispersing *Prosopis juliflora* seeds, as they consume the pods and later excrete the seeds in different locations [9]. Additionally, the tree's seeds are dispersed by water, particularly during flash floods that are common in the region, further aiding its expansion [15].

The invasion of *Prosopis juliflora* has had severe consequences for biodiversity in the Afar Region. Native plant species, which are vital for maintaining the ecological balance of rangelands, are being outcompeted and replaced by *Prosopis juliflora*. This replacement results in the loss of habitat for many wildlife species that depend on native flora [31]. The decline in biodiversity has cascading effects on the entire ecosystem, including soil degradation, changes in hydrological cycles, and reduced ecosystem services.

4.3. Socioeconomic Impacts

The invasion of *Prosopis juliflora* is not only an ecological problem but also a significant socioeconomic challenge. The Afar Region is predominantly inhabited by pastoralist communities whose livelihoods depend on the availability of rangelands for grazing their livestock. As *Prosopis juliflora* spreads, it encroaches on these grazing lands, reducing the area available for livestock and leading to a decline in livestock productivity [23]. The dense thickets formed by *Prosopis juliflora* also create physical barriers that restrict the movement of both people and animals, further complicating traditional grazing practices.

Moreover, the presence of *Prosopis juliflora* has been associated with an increase in conflicts among pastoralist communities, as they compete for the increasingly scarce grazing lands [24]. The reduction in livestock productivity, coupled with the loss of access to traditional grazing areas, has led to increased food insecurity and poverty in the region. The tree's invasion also impacts water resources, as its deep root system depletes groundwater levels, further exacerbating the challenges faced by pastoralist communities [29].

4.4. Attempts at Control and Eradication

Various methods have been employed in an attempt to control the spread of *Prosopis juliflora*, but with limited success. Mechanical removal, which involves cutting down the trees and uprooting the stumps, has been one of the most commonly used methods. However, this approach is labor-intensive, costly, and often ineffective in the long term, as the trees can regenerate from the remaining root systems [2]. Chemical control using herbicides has also been attempted, but concerns about environmental pollution and the impact on non-target species have limited its widespread use [29].

Biological control, involving the introduction of natural enemies such as insects that feed on *Prosopis juliflora*, has been explored in some regions. However, the complexity of the Afar Region's ecosystem and the potential for unintended consequences has made this approach challenging [15]. Overall, the control of *Prosopis juliflora* requires a combination of methods and sustained effort, along with community involvement and awareness programs to prevent further spread.

Generally, the invasion of *Prosopis juliflora* in the Afar Region presents a complex challenge with far-reaching ecological and socioeconomic impacts. The species' resilience and adaptability have made it a formidable invasive species, difficult to control once established. Addressing the *Prosopis juliflora* invasion requires an integrated approach that combines ecological management with strategies to support the livelihoods of affected communities. As climate change continues to alter the region's environment, the need for effective management of invasive species like *Prosopis juliflora* becomes even more critical.

5. Impact of *Prosopis Juliflora* on Rangelands

5.1. Effects on Soil Properties and Water Availability

The invasion of *Prosopis juliflora* has significantly altered the soil properties and hydrological balance of rangelands in the Afar Region. This species is known for its deep-rooting system, which enables it to access water from deep underground, effectively lowering the water table and making water less available for native plants and grasses [24]. This change in water availability can lead to the desiccation of soil, reducing its fertility and making it less suitable for agriculture and grazing.

Moreover, *Prosopis juliflora* tends to increase soil salinity. As it depletes water from the soil, salts are drawn to the surface, leading to soil salinization, which further inhibits the growth of native vegetation [31]. The accumulation of leaf litter from *Prosopis juliflora* can also alter the soil pH and nutrient composition, making the environment more conducive to its own growth while suppressing native species. This alteration in soil chemistry can lead to a monoculture of *Prosopis juliflora*, where other plants struggle to survive.

5.2. Influence on Grazing Patterns and Livestock Productivity

The spread of *Prosopis juliflora* has led to significant reductions in the availability of pastureland for grazing. As *Prosopis juliflora* colonizes rangelands, it forms dense thickets that are often impenetrable, reducing the area available for grazing [23]. The presence of these dense thickets not only limits access to grazing land but also lowers the quality of available forage. The thorny nature of *Prosopis juliflora* makes it difficult for livestock to graze, and the plant itself provides little nutritional value to animals [9].

Prosopis juliflora is a significant threat to rangelands, leading to reduced grazing land for livestock. Its aggressive growth is attributed to its resilience in saline soils, rapid growth rate, nitrogen-fixing ability, and deep-rooting system, along with its capacity to remain dormant in the soil for extended periods and germinate when conditions are favorable. These characteristics make it a formidable competitor, often outcompeting and displacing native grass species that cannot withstand such competition [8, 6]. In areas affected by *Prosopis juliflora*, natural pastures have been severely degraded, and native tree species have been displaced, resulting in fewer, lower-quality grazing sites, particularly in rangelands. [26] Have documented a negative correlation between the increase in *Prosopis juliflora* invasion and the availability of fodder and feed on grazing lands. The reduction in grazing land directly impacts livestock, leading to a significant decline in both livestock numbers and their productivity. Stud-

ies by [28] in the Gebiresu zone especially in the Amibara district revealed that between 1997 and 2011, camel and cattle populations declined by 20% and 36%, respectively, due to bush encroachment, including the invasion by *Prosopis juliflora*. Additional research highlights the adverse effects of *Prosopis juliflora* on livestock productivity, as the loss of grazing areas and palatable grass species has led to a notable decrease in livestock output [30, 10].

Livestock are forced to travel greater distances to find suitable grazing areas, which increases their energy expenditure and reduces overall productivity [2]. This situation is particularly detrimental to pastoralist communities who rely on livestock for their livelihoods. The decrease in livestock productivity has led to economic hardships, including reduced milk and meat production, which are vital sources of income and nutrition for these communities [24].

5.3. Socioeconomic Implications for Pastoral Communities

The invasion of *Prosopis juliflora* has far-reaching socioeconomic impacts on the pastoralist communities of the Afar Region. The reduction in rangeland productivity has exacerbated food insecurity, as livestock, the primary source of food and income, are less productive [23]. Additionally, the spread of *Prosopis juliflora* has led to the displacement of pastoral communities. As traditional grazing lands become unusable, communities are forced to migrate in search of new grazing areas, leading to conflicts over resources and increased vulnerability to climate change impacts [31].

The invasion by *Prosopis juliflora* also reduces the size of farmlands, with its roots making plowing difficult. Additionally its impact on crop production, including competition for agricultural land, increased time and labor costs for clearing land [26]. Moreover, *Prosopis juliflora* has been associated with severe health issues in animals [1, 3]. It causes toxicity, reduces stocking rates, and can lead to death in livestock due to the tannin content in its leaves, especially with prolonged feeding. The thorns can injure the eyes and hooves of livestock, causing further harm. The high sugar content in the pods can disrupt rumen bacterial activity, leading to permanent digestive issues and dental problems, such as disfiguration and tooth decay, which impair the animals' ability to graze effectively [38, 13].

Furthermore, the economic burden of managing *Prosopis juliflora* adds to the challenges faced by these communities. Efforts to clear the invasive species are labor-intensive and costly, often requiring external assistance. The need to continually manage *Prosopis juliflora* diverts resources from other critical activities, such as livestock management and water resource development, further entrenching poverty in the region [14].

In some cases, communities have attempted to derive economic benefits from *Prosopis juliflora* by using its wood for fuel or charcoal production [5]. However, these activities are

not sustainable long-term solutions, as they do not address the underlying ecological issues and may even encourage the further spread of the species.

6. Interplay Between Climate Change and Prosopis Juliflora

The interaction between climate change and the invasion of *Prosopis juliflora* in the Afar Region of Ethiopia presents a complex challenge that exacerbates the degradation of rangelands. Both factors are not only interlinked but also reinforce each other in ways that amplify their individual impacts on the ecosystem.

6.1. Climate Change as a Driver of Prosopis Juliflora Spread

Climate change has led to significant shifts in temperature, precipitation patterns, and the frequency of extreme weather events in the Afar Region. These changes create conditions that favor the spread of *Prosopis juliflora*, an invasive species that thrives in arid and semi-arid environments. With rising temperatures and prolonged dry spells, the native vegetation becomes stressed, creating ecological niches that *Prosopis juliflora* can easily exploit [15].

Moreover, *Prosopis juliflora* has a deep root system and high drought tolerance, which allows it to out-compete native species under changing climatic conditions. This adaptability enables the species to colonize areas that were previously less susceptible to invasion, thereby expanding its range and density in the region [9]. The altered climate, characterized by more frequent droughts, reduces the resilience of native plants, further facilitating the dominance of *Prosopis juliflora* [31].

6.2. Prosopis juliflora and Its Impact on Climate Change Adaptation

The invasion of *Prosopis juliflora* has significant implications for the adaptation of rangelands to climate change. As *Prosopis juliflora* spreads, it alters the composition of the soil by increasing salinity and reducing water availability for other plants [2]. This degradation of soil quality diminishes the capacity of the land to support diverse plant species, which is crucial for maintaining ecosystem resilience in the face of climate change.

Additionally, *Prosopis juliflora* disrupts the hydrological cycle by consuming large amounts of water, leading to reduced groundwater recharge and lower water tables [24]. This further exacerbates water scarcity in the region, making it harder for native vegetation to survive and recover from climatic stresses. As a result, the ability of the rangelands to adapt to climate change is significantly impaired, with long-term consequences for ecosystem health and pastoral liveli-

hoods.

6.3. Feedback Loops and Synergistic Effects

The relationship between climate change and *Prosopis juliflora* creates a feedback loop that accelerates the degradation of rangelands. As *Prosopis juliflora* spreads, it displaces native vegetation, leading to a reduction in biodiversity and altering the structure of the ecosystem. This loss of biodiversity reduces the overall resilience of the ecosystem to climate change, making it more vulnerable to extreme weather events and prolonged droughts [14]. In turn, the degraded rangelands are less capable of supporting the pastoralist communities that depend on them, leading to increased pressure on the remaining resources. This pressure can result in overgrazing, which further degrades the land and creates even more favorable conditions for the spread of *Prosopis juliflora* [23]. The synergistic effects of climate change and *Prosopis juliflora* invasion thus create a vicious cycle of environmental degradation that is difficult to break without targeted intervention.

6.4. Regional Implications and Broader Impact

The interplay between climate change and *Prosopis juliflora* not only affects the Afar Region but also has broader implications for similar arid and semi-arid ecosystems in Ethiopia and beyond. Understanding this relationship is crucial for developing effective management strategies that can be applied to other regions facing similar challenges [4].

For instance, the knowledge gained from studying the dynamics in the Afar Region can inform adaptive management practices in other parts of Ethiopia where *Prosopis juliflora* is also spreading. These practices might include the restoration of native vegetation, the introduction of drought-resistant plant species, and the implementation of sustainable land management techniques that enhance ecosystem resilience.

7. Management and Mitigation Strategies

The management and mitigation of *Prosopis juliflora* invasion in the Afar Region of Ethiopia require a multi-faceted approach that addresses both the biological challenges posed by the species and the socio-economic impacts on local communities [7, 27]. Effective management strategies are crucial for restoring rangeland productivity, preserving biodiversity, and securing the livelihoods of pastoralists who depend on these ecosystems. This section discusses the various strategies employed to control *Prosopis juliflora*, the challenges associated with these efforts, and the role of integrated approaches in mitigating the combined effects of climate change and invasive species.

7.1. Mechanical Control

Mechanical control involves the physical removal of *Prosopis juliflora* through methods such as uprooting, cutting, and slashing. This approach is often labor-intensive and requires significant resources, making it a costly option for large-scale application. Despite its effectiveness in removing the above-ground biomass of the plant, mechanical control often fails to address the deep-rooted systems of *Prosopis juliflora*, which can regenerate and spread even after removal [23, 17]. In addition, the cleared land is prone to re-invasion if not properly managed or restored with native vegetation.

7.2. Chemical Control

Chemical control involves the use of herbicides to target and kill *Prosopis juliflora*. Herbicides such as glyphosate have been used to suppress the growth and spread of the species. However, chemical control poses environmental risks, including the potential contamination of water sources and the unintended impact on non-target species [29]. Moreover, the application of herbicides can be expensive and requires technical expertise, limiting its use in resource-constrained areas like the Afar Region. Additionally, there is the risk of developing herbicide resistance, which can further complicate management efforts.

7.3. Biological Control

Biological control involves the introduction of natural enemies, such as insects or pathogens, to suppress the growth and reproduction of *Prosopis juliflora*. This method is considered environmentally friendly and sustainable, as it leverages the ecological interactions between species to control invasive populations. For example, the use of seed-feeding beetles has shown some promise in reducing the seed production of *Prosopis juliflora* [14, 18]. However, biological control can be slow to take effect, and there is always a risk that the introduced species could become invasive themselves or negatively impact non-target organisms.

7.4. Integrated Management Approaches

Given the limitations of individual control methods, integrated management approaches are increasingly recognized as the most effective strategy for dealing with *Prosopis juliflora* invasion. Integrated approaches combine mechanical, chemical, and biological control methods with ecological restoration and community-based management practices. For example, after mechanical removal or chemical treatment, it is essential to restore the land with native grasses and shrubs to prevent re-invasion and enhance rangeland productivity [31].

Community involvement is also crucial in integrated management approaches. Local communities, particularly pastoralists, play a key role in managing rangelands, and their par-

ticipation is vital for the success of any control efforts. Training and awareness programs can empower communities to adopt sustainable land management practices and participate in the monitoring and control of *Prosopis juliflora*. Furthermore, the promotion of alternative livelihoods, such as the utilization of *Prosopis juliflora* for fuelwood, charcoal, or fodder, can help offset the economic impact of its invasion [24, 32].

7.5. Climate Change Adaptation Strategies

In addition to direct control methods, adaptation strategies that enhance the resilience of rangelands to climate change are essential for mitigating the impact of *Prosopis juliflora*. Climate change adaptation strategies include the introduction of drought-resistant native plant species, improved water management practices, and the development of sustainable grazing systems that prevent overgrazing and land degradation [35]. These strategies help to create more resilient ecosystems that are less susceptible to invasion by *Prosopis juliflora* and other invasive species.

7.6. Case Studies and Best Practices

Several case studies from the Afar Region and other parts of Ethiopia provide insights into successful management practices. For instance, the participatory rangeland management approach implemented in some areas of the Afar Region has demonstrated the effectiveness of involving local communities in rangeland rehabilitation and invasive species management [4]. Another example is the use of biological control in conjunction with community-led restoration projects in Kenya, which has shown promising results in reducing *Prosopis juliflora* cover and restoring native vegetation [31].

These examples highlight the importance of context-specific strategies that are tailored to the ecological, social, and economic conditions of the region. Best practices from these case studies can be adapted and scaled up to enhance the effectiveness of *Prosopis juliflora* management efforts across the Afar Region and beyond.

8. Conclusion

The impact of climate change and the invasion of *Prosopis juliflora* on the rangelands of the Afar Region in Ethiopia present a complex and pressing environmental challenge. The interplay between these two stressors has significant implications for both the ecosystem and the pastoral communities that depend on these lands for their livelihoods. The region is experiencing rising temperatures and altered precipitation patterns, which contribute to more frequent and severe droughts. These climatic changes exacerbate rangeland degradation by reducing vegetation cover, altering soil properties, and diminishing water availability. The resulting envi-

ronmental stress has heightened the vulnerability of the rangelands, leading to a decline in their productivity and resilience.

The invasive *Prosopis juliflora*, introduced as part of reforestation efforts, has become a highly aggressive species in the Afar Region. Its rapid growth and ability to thrive in arid conditions allow it to out-compete native flora, leading to significant ecological disruptions. The invasion has altered soil composition, depleted water resources, and reduced the availability of grazing land, thereby impacting livestock productivity and pastoral livelihoods. The socio-economic consequences are profound, with increased food insecurity and diminished income opportunities for local communities. The interaction between climate change and *Prosopis juliflora* creates a feedback loop that intensifies the challenges faced by the rangelands. Rising temperatures and altered precipitation patterns favor the spread of *Prosopis juliflora*, which further degrades the environment and reduces the land's resilience to climate variability. This interaction not only accelerates ecological degradation but also complicates management efforts.

The findings underscore the urgent need for integrated management strategies that address both climate change and invasive species simultaneously. Policymakers and rangeland managers must prioritize the development of adaptive management practices that can mitigate the effects of *Prosopis juliflora* while enhancing the resilience of rangelands to climate change. Implementing integrated approaches that combine ecological, social, and economic perspectives is essential for creating comprehensive solutions. Enhancing research and monitoring efforts is also critical to understanding the long-term impacts of these stressors and evaluating the effectiveness of management interventions. Furthermore, engaging local communities in the management process is crucial for the success of any intervention, ensuring that strategies are culturally and economically appropriate.

Addressing the dual threats of climate change and *Prosopis juliflora* invasion requires a multifaceted approach that integrates scientific knowledge, practical management strategies, and community involvement. By adopting a holistic and adaptive management framework, it is possible to mitigate the impacts on rangelands, support pastoral livelihoods, and foster a more resilient ecosystem in the Afar Region. The path forward should be guided by collaborative efforts and informed by ongoing research to ensure the sustainability of these vital rangeland resources.

9. Gaps in Research and Future Directions

While significant progress has been made in understanding the impact of climate change and *Prosopis juliflora* on the rangelands of the Afar Region, several critical gaps re-

main in the literature. These gaps present opportunities for further research that could enhance the effectiveness of management strategies and contribute to the sustainable use of rangelands.

9.1. Limited Long-Term Studies

One of the most significant gaps in the current body of research is the lack of long-term studies that examine the ongoing effects of *Prosopis juliflora* invasion and climate change on rangelands. Most studies are either short-term or cross-sectional, providing snapshots of conditions at specific points in time [23]. Longitudinal studies that track changes over decades are needed to fully understand the dynamics of rangeland degradation, shifts in vegetation patterns, and the socio-economic impacts on pastoral communities [5]. Such studies would also help in assessing the long-term effectiveness of different management interventions.

9.2. Inadequate Integration of Socio-Economic Factors

Although there is a growing recognition of the socio-economic impacts of *Prosopis juliflora* invasion, many studies still focus primarily on ecological and environmental aspects [31]. There is a need for more research that integrates socio-economic factors, particularly those that affect the livelihoods of pastoralists in the Afar Region. Understanding the social, cultural, and economic dimensions of rangeland management, including the roles of traditional knowledge and practices, is crucial for developing holistic management strategies [14]. Additionally, more research is needed to assess the cost-effectiveness and social acceptability of various control measures.

9.3. Insufficient Focus on Climate Change Adaptation

Research on climate change adaptation strategies in the Afar Region has been relatively limited, with most studies focusing on mitigation of *Prosopis juliflora* rather than adaptation to changing climate conditions [35]. There is a need for more comprehensive studies that explore how pastoral communities can adapt to both climate change and *Prosopis juliflora* invasion simultaneously. This includes investigating the potential for promoting drought-resistant native species, developing sustainable grazing practices, and enhancing water management techniques [29]. Research should also explore how climate change might alter the effectiveness of current and future management strategies for *Prosopis juliflora*.

9.4. Lack of Scalable and Integrated Management Approaches

Many of the management strategies proposed or imple-

mented for controlling *Prosopis juliflora* are not easily scalable or integrated with broader rangeland management practices [2]. There is a need for research that focuses on developing scalable solutions that can be implemented across large areas of rangelands, rather than small, localized projects. Additionally, integrated approaches that combine *Prosopis juliflora* control with climate change adaptation, soil conservation, and biodiversity restoration are crucial for achieving long-term sustainability [4]. Research should investigate the synergies and trade-offs between different management practices and how they can be effectively combined.

9.5. Underrepresentation of Indigenous Knowledge and Practices

Indigenous knowledge and practices related to rangeland management have been underrepresented in the literature, despite their potential to contribute to effective management strategies [11]. Pastoralist communities in the Afar Region have developed a range of strategies for coping with environmental variability, including climate change and invasive species. Research that documents and analyzes these practices could provide valuable insights into sustainable rangeland management. Furthermore, involving local communities in research and management efforts can enhance the relevance and effectiveness of interventions.

9.6. Future Directions for Research

To address these gaps, future research should focus on several key areas:

1. Longitudinal Studies: Conducting long-term studies to track the ecological, socio-economic, and climatic changes in rangelands over time.
2. Integrated Socio-Economic Research: Expanding research to include a deeper understanding of the socio-economic impacts of *Prosopis juliflora* and the ways in which communities can adapt to and manage these impacts.
3. Climate Change Adaptation: Developing and testing adaptation strategies that are tailored to the specific challenges posed by climate change and *Prosopis juliflora* in the Afar Region.
4. Scalable Management Approaches: Designing and implementing scalable, integrated management strategies that can be applied across the entire region.
5. Indigenous Knowledge: Incorporating indigenous knowledge and practices into research and management strategies, ensuring that local communities are active participants in the development and implementation of solutions.

In conclusion, while much has been learned about the challenges posed by climate change and *Prosopis juliflora* in the Afar Region, addressing the remaining gaps in research is essential for developing effective, sustainable solutions. By

focusing on long-term, integrated, and community-centered approaches, future research can contribute significantly to the preservation and restoration of rangelands in the region.

Abbreviations

RCP	Representative Concentration Pathway
IPCC	Intergovernmental Panel on Climate Change
°C	Degree Celsius
NGO	Non-Governmental Organization

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