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Performance of Management Interventions to the Impacts of *Prosopis juliflora* in Arid and Semiarid Regions of the Middle Awash Valley, Ethiopia

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ABSTRACT

The objective of this paper is to provide up-to-date empirical information on the expansion of *P. juliflora*, its environmental and livelihood impacts, and the performance of past and current management strategies in the Middle Awash Valley (MAV), Ethiopia. This study was based on data collected using focus group discussion, key informant interviews, and field observation. The results show that *P. juliflora* has expanded rapidly and invaded valuable grazing and croplands, and settlement areas. The rapid expansion of *P. juliflora* in the study area is attributed to climate change (increased temperature and declined rainfall), its ecological competition, spreading of seeds by wild animals and pastoral (mobile livestock) livelihood system, and recent occurrences of flood and drought-induced pasture scarcity that has forced livestock to eat more *P. juliflora* seed pods. Also, delays in the use of land cleared for farming activity have created good opportunities for Prosopis expansion. The perception and views of people on the benefits of *P. juliflora* and management options vary according to livelihood systems and stakeholder types (e.g., environmental managers and pastoralists). The attempted management strategies to eradicate *P. juliflora* (cutting, burning, and bulldozering or converting into economic utilization by making charcoal, fodder, and furniture) failed to achieve the intended outcomes. These management interventions failed due to many reasons. Some of these were the rapid rate of *P. juliflora* expansion triggered by the recurrent drought, severe scarcity of pasture that forced livestock to eat *P. juliflora*'s seed pods and travel into new areas, inadequate technologies to aid utilization and eradication, inability to collect sufficient quantity of pods to produce fodder for livestock, and absence of sufficient and satisfactory markets for the end-product (fodder). The results generally imply the need for urgent policy and management interventions. This study also highlights important issues that should be considered in introducing and implementing management strategies in the future.

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1. Introduction

Prosopis juliflora (*P. juliflora*) is one of the invasive plant species that was deliberately introduced in many arid and semi-arid lands of Africa and Asia to combat desertification, rehabilitate degraded lands, supply firewood, and fodder for livestock. It is a woody shrub tree that has long roots, grows in dense thickets with long thorns that can injure animals and humans, and is hard to handle or walk through due to sharp thorns [1]. *P. juliflora* is an invasive plant that can grow in different ecological zones and can grow on soils from sand to clay and from saline to alkaline soil types, at an altitude below 200 to above 1500 m above sea level, and in areas with mean annual rainfall between 50 mm and 1500 mm [4]. *P. juliflora* (mesquite) is one of 44 species in the *Prosopis* genus and has been widely introduced in Ethiopia and other African countries [2]. The presence of *Prosopis pallida* (*P. pallida*) is also reported in the region [3]. The rapid growth rates, ability to coppice after damage, and long and branched root systems make *P. juliflora an* effective invader of the arid and semi-arid lands. The plant is well suited to extreme climate conditions such as very high temperature and scant rainfall and grows in infertile soils [2]. In some countries, like Ethiopia, certain characteristics of the pastoral livelihood systems of arid and semi-arid regions may also contribute to the rapid spread of *P. juliflora* [4]. This is because most livestock such as goats, camels, donkeys, and cattle eat *P. juliflora's* seed pods, particularly during dry seasons and drought times when pasture becomes scarce in the region. During these times, pastoralists travel to different locations searching for pasture and water for their livestock, thereby spreading *P. juliflora* into new areas [5]. A study by Shiferaw *et al*. [2] found an average of 2833, 1642, and 760 *P. juliflora's* seeds per kilogram of the dung of cattle, camels, and goats, respectively. P. juliflora will likely continue to expand under increasingly drier environmental conditions and increasing distances required for livestock mobility [6]).

Available evidence indicates that *P. juliflora* has many detrimental effects on biodiversity, ecosystem services, and human livelihoods and is one of the key drivers of some environmental changes in the arid and semi-areas [1]. It largely kills off indigenous plant species, alters ecosystem services such as water supply and hydrological functioning [7], and degrades grazing potential [4]. The livelihood of communities in many arid and semi-arid lands, including Sudan [8], South Africa [9], Eritrea [10], Kenya [11], India [12], and Ethiopia [4, 13] are negatively affected by varieties of *P. juliflora*. On the other hand, according to some studies *P. juliflora* provides some ecological and economic advantages. These include carbon sequestration, preventing soil erosion, and flood risks [1]. Although it was reported that this *Prosopis* variety introduced in sub-Saharan Africa was one with non-palatable pods with a bitter, astringent taste [14], there is empirical evidence from Ethiopia and Kenya that indicate *P. juliflora* pods are used to feed livestock [2-4]. In Kenya, attempts were made to produce flour from *Prosopis* pods mixed with other cereal crops (e.g., wheat flour) to produce different locally-acceptable food items [3]. According to Maundu *et al*. [11], in some areas of Kenya, *P. juliflora* serves as a major source of income for pastoral households. In Ethiopia, it is used for charcoal and fuelwood, and fencing purposes [5]. There is also evidence that *P. juliflora* can support the establishment of large-scale businesses. In this instance, South Africa is producing organic medicines from the pods of *P. juliflora* [15]. *P. juliflora* is also used as a bio-energy source to produce carbon-free energy in India [12]. These economic utilizations are considered as management options and strategies in many articles [1, 16-18]).

However, the benefits of *P. juliflora* for ecological services and economical utilization are generally seen as outweighed by its disadvantages, both in the perceptions of local people and experts, and within policy in many countries [1, 18]. As a result, many attempts have been made to eradicate or at least manage the spread of *P. juliflora* through cutting, burning, chemical applications, and biological control [1, 4, 5]. The practices of management strategies (both eradication and economical utilization) have had different success and failure histories in various parts of the world [1]. Some of these management strategies, such as fodder, bio-energy, and medicine production, require knowledge, skill, capital, and technology, while some others, like charcoal production, can be implemented using local knowledge and technologies.

In Ethiopia, *P. juliflora* was introduced in the 1970s through collaborative actions of governments and international development organizations [19]. Rehabilitation of degraded soils, firewood, and fodder supply and combating desertification in the semi-arid regions (SARs) were the major objectives for the introduction of *P. juliflora* to Ethiopia. Between its introduction and 2006, *P. juliflora* invaded about 700,000 ha of land, and more than 70% of the invasion was observed in the Afar region of Ethiopia [20]. A study by Shiferaw *et al*. [21] reported that *P. juliflora* had invaded about 1.17 million hectares of land in 35 years. The Middle Awash Valley (MAV) of the Afar National Regional State is one of the most widely invaded and deeply affected parts of Ethiopia, in which the plant has invaded over 3605 km^2 of land [22]. The average annual expansion rate was 3.48 km^2 during 1973-2004, and the invaded area was expected to have increased by over 30% by 2020 [23]. In this part of Ethiopia, management measures that focus on eradication and economical utilization have been practiced over the last few decades. However, until now, there is little evidence of whether the introduced management strategies were successful or not.

The information and recommendations from previous studies (e.g., Wakie *et al*. [24], Ilukor *et al*. [18], and Berhane *et al*. [25]) on *P. juliflora* management options are mixed as to whether it should focus on economic utilization or eradication. This may be because different commentators have different interests and value *Prosopis* differently. Some studies (e.g., Tilahun *et al*. [22] and Berhanu and Tesfaye [26]) recommend actions to stop the expansion of *P. juliflora* and eradicate it from invaded areas to rehabilitate and preserve rangelands for the pastoral communities. Others (e.g., Tessema [27], Wakie *et al*. [24], Ilukor *et al*. [18], and Berhane *et al*. [25]) suggested management actions through utilization. However, none of these studies have attempted to assess and evaluate the implementation and performance of existing management strategies. There is an absence of clear scientific information that helps policymakers to tackle the problem. For these reasons, and other factors such as availability of limited resources, poor capacity, and lack of technologies, there have been no appreciable actions taken to tackle the negative impacts and/or promote the benefits from *P. juliflora.* There is a need for further studies to generate additional knowledge and information that will help stakeholders navigate the dilemmas and debates on the different management strategies of *P. juliflora*.

Moreover, the impacts of *P. juliflora* on different stakeholders and social groups (women, men, children, elders and youth, pastoral and agro-pastoral communities) and their perception of different management strategies were not captured by previous studies. The current conditions of the different strategies introduced into Ethiopia to manage *P. juliflora* were not assessed. Our study, therefore, investigated the expansion, impacts, and management practices of *P. juliflora* in the face of climate change. It investigated the impact of *P. juliflora* on different social groups (male, female, elders, youth, and children) and livelihood systems (pastoral, agro-pastoral, and urban) in the Middle Awash Valley, Ethiopia. Furthermore, it explored the local community's perception, different local stakeholders, experts, and government bodies on the past, current, and planned management strategies to reduce the impact of *P. juliflora*. In this paper, we report on some of the main findings of this work in the hope that we can make one step toward addressing this information gap.

2. Methodology

2.1. Description of the Study Area

The study was conducted in the Middle Awash Valley (MAV) in the Central Rift Valley system of Ethiopia. Awash Fentale and Amibara *woreda* (administrative districts) of the Afar National Regional State (AfNRS) were our case study sites. The study districts are contiguous and located between 8°46′ and 9°51′ N and 39°40′ and 40°40′ E (Figure **1**). The size of these *woredas* is 1,046.41 km^2 and 2,007.05 km^2, respectively. The topographic feature of the area is generally flat with a maximum altitude of 1000 m a.s.l. The Awash River and its tributaries (Bulga, Kebena, and Kesem) drain the study area.

The climate of the area is generally warm and dry. We analyzed the climate condition of the study area using rainfall, temperature, and evapotranspiration data for the 1980-2014 period, obtained from Worer Agricultural Research Center meteorology station. The mean monthly temperature of the study area varied between 24.3°C (in December) and 32°C (in June). The mean annual temperature was estimated at 27.9°C. The mean monthly rainfall and evapotranspiration range from 4.9 mm (in December) to125 mm (in August) and from 200.1 mm (in December) and 294.9 mm (in June), respectively. The mean annual rainfall and evapotranspiration were estimated at 573.4 mm and 2801.1 mm. Precipitation is generally scant, irregular, and unpredictable and seems to have a bimodal pattern with rainy seasons in February-April and July-August (Figures **2a** & **2b**). In addition, the rainfall for 20 out of 35 years was below the long-term mean (Figure **2b**). This area is known for its frequent drought and flood episodes, affecting the natural ecosystem and human livelihood strategies [28].

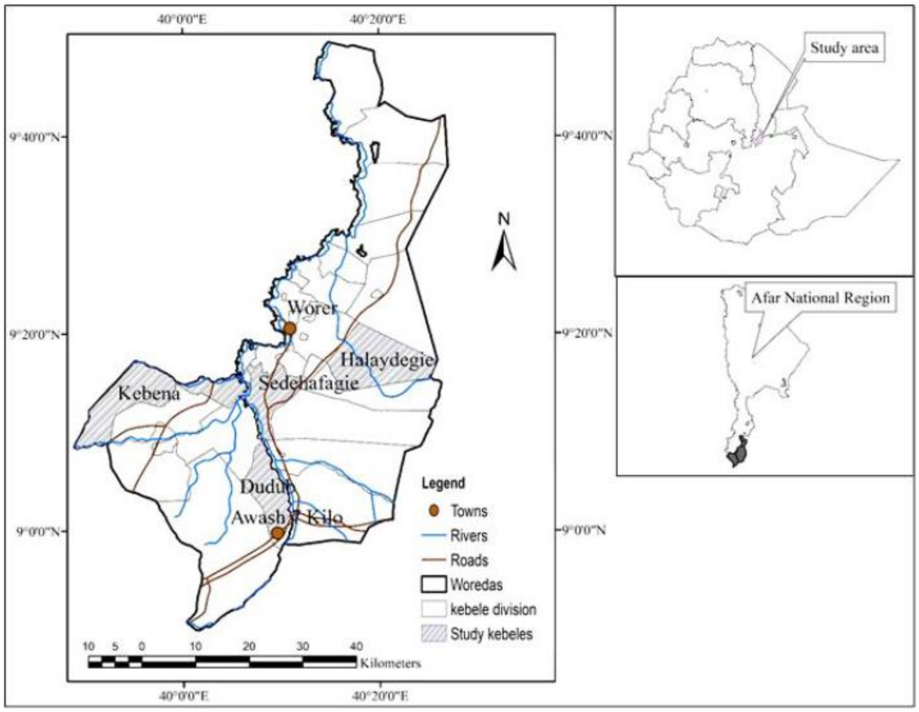

Figure 1: Location of the study area.

The natural climatic-climax vegetation cover of the study area includes varieties of grasses, forbs, and woody vegetation dominated by *African Acacia*. The Acacia species that grow widely in the study area are *Keselto* (*Acacia nilotica*)*, Adado* (*Acacia senegal*), Maka'arto (*Acacia mellifera)*, *Mederto* (*Cordia* spp.), and *Ehebto* (*Acacia tortilis*) [4]. These tree varieties are largely used for firewood, charcoal making, house construction, and forage purposes for livestock. *Denkito (Eragrostis cylindriflore), ayti-adoita (Terapogon cenchriformis), melif (Andropogon canaliculatus*) are major grass varieties preferred by livestock in the area. The AfNRS is a host to 81 mammal species and over 640 bird species, of which six are endemic [5]. However, the indigenous biodiversity and biomass production of the region is affected by recurrent drought hazards, invasion of *P. juliflora,* and the expansion of state and private commercial agricultural land investments [28, 4].

The main sources of the population's livelihoods are pastoralism and, for some, irrigation-based agro-pastoralism forms a recent activity introduced by the Government of Ethiopia through its resettlement program [29]. The common types of livestock in the area included cattle, camels, goats, and sheep. The major types of agricultural crops grown in the region included cotton, maize, sugarcane, and vegetables. There are relatively few people in urban areas (e.g., Awash Sebat Kilo, Awash Arba, and Worer), whose livelihoods include non-agricultural activities such as trading, service occupations, and the public sector.

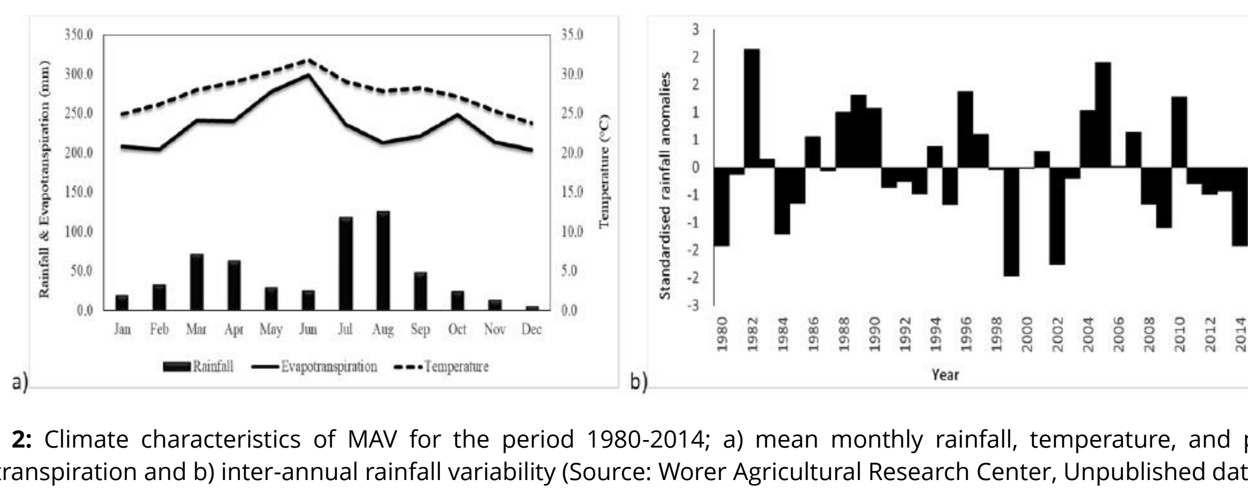

Figure 2: Climate characteristics of MAV for the period 1980-2014; a) mean monthly rainfall, temperature, and potential evapotranspiration and b) inter-annual rainfall variability (Source: Worer Agricultural Research Center, Unpublished data).

2.2. Sources of Data and Methods of the Study

This study was based on empirical data collected from five selected sites in the Awash Fentale and Amibara *woredas* (Figure **1**). Data were collected from 87 participants using key informant interviews (KII) and focus group discussions (FGDs) in 2017 and 2018. We also made field observations in different periods to observe *P. juliflora* performance and variability between wet and dry seasons.

A multi-stage sampling approach was used to select study sites, where in the first stage, *kebeles* (subunits of *woreda/* district) invaded by *P. juliflora* were selected with the help of local experts. In the second stage, the *kebele* populations were stratified into three livelihood classifications that included pastoral, agro-pastoral, and urban classes. Furthermore, sampling was designed to have a balanced representation of the various type of settlement patterns (villagised, traditional settlement, and urban) (Table **1**).

Table 1: Characteristics of the study sites/*kebeles*.

***Kebele*/Village Name**	***Woreda*/ District**	**Latitude**	**Longitude**	**Livelihood Type**	**Settlement Condition**
Kebena	Awash Fentale	09° 24′ 16″	40° 19′ 39″	Agro-pastoral	Villagised
Dudub	Awash Fentale	09°04′59″:	40°10′00″	Pastoral	Traditional
Awash 7 Kilo	Awash Fentale	09° 02′ 49.3″	40° 09′ 06.1″	Urban	Urban
Halaydegie	Amibara	09° 28″ 18″	40° 29′ 81″	Pastoral	Traditional
Sedehafagie	Amibara	09° 14′ 16″	40° 08′ 5.7″	Agro-pastoral	Urban

We conducted one FGD in each of the rural Kebena, Dudub, Halaydegie, and Sedhafagie *kebeles*. Each FGD contained eight participants selected from different social groups (male, female, elder and youth). We selected participants with the help of local development agents. Discussions were made to explore their observations and perceptions on the extent and mechanisms of *P. juliflora* spread and its impacts on ecosystems and peoples' livelihoods. We also explored how *P. juliflora* affected the different social groups, stratified by their livelihood system, age, and gender. In addition, discussions involved the current and planned management strategies, implementation processes, advantages and disadvantages of each management type, their current condition, and challenges for success.

We conducted 57 Key Informant Interviews (KIIs) with selected experts who have knowledge on *P. juliflora* at the government offices (pastoral and agricultural offices, water development and land administration offices), elders, Awash National Park (ANP), non-governmental organizations (NGOs) (e.g., FARM-Africa and FAO), Worer Agricultural Research Center (WARC), Kesem Sugar Factory (KSF) and Awash Basin Authority (ABA) (Table **2**). The discussions with these experts focused on the positive and negative impacts of *P. juliflora* on the ecosystem and the socio-economic activities. The interviews also addressed past, current, and planned *P. juliflora* management strategies, with an emphasis on the types of management technologies, implementation, community participation, preferences, and utilization and effectiveness. Participants were also asked to explain their observations on the contribution of current development interventions (e.g., large-scale sugarcane plantation, the Kesem Sugar Factory, and resettlement programs) to the expansion and management of *P. juliflora*. Furthermore, discussions were made on the role of current and future climate change and variability (e.g., occurrences of drought) for *P. juliflora* expansion and the importance of implementation of management strategies for climate change mitigation action. We used various indicators to differentiate climate variability and climate change for the participants. Inter-annual rainfall variability and the occurrence of drought and flood events are used to describe climate variability. At the same time, temperature rise, increasing water loss through evapotranspiration due to temperature rise, decrease in rainfall amount, and the likely increase in drought and flood events were used to describe climate change [29-30].

As mentioned, we also analyzed the climate data to understand how the climate has changed over the past three decades in the study area and the implications of this on *Prosopis* expansion rates. Thus, trends of climate changes were detected using linear regression, and the inter-annual variability was assessed using the Standardized Rainfall Anomaly method.

Table 2: Descriptions of Key Informant Interviewees used in this study.

Description of Interviewees	Number of People Interviewed
Elders and community leaders in the four rural *kebeles*	12
Kebele administrators in the four rural *kebeles*	8
Agricultural extension workers and natural resource management experts in the four rural *kebeles*	8
Agricultural and Pastoral Development Office Leaders of the Awash Fentale and Amibara *woredas*	2
Natural resources management experts at Awash Fentale and Amibara *Woreda* Agricultural and Pastoral Offices	5
Extension service core process leaders at Awash Fentale and Amibara *Woreda* Agricultural and Pastoral Offices	2
Disaster risk management core process leaders at Awash Fentale and Amibara *Woreda* Agricultural and Pastoral Offices	2
Water resource management experts at Awash Fentale and Amibara *Woreda* Water Offices	2
Land Administration experts at Awash Fentale and Amibara *Woredas* Administration Offices	2
Agricultural and natural resources management experts at Worer Research Center and Semera University	3
Natural resources management and development experts working in different NGOs offices	3
Natural resource management and irrigation water management experts in Awash Basin Authority	3
Sugarcane plantation irrigation agronomy expert in Kesem Sugar Factory	1
The head and natural resource management expert in Awash National Park	2
Mayor and Urban Sanitation work expert of Awash 7 Kilo	2
Total	57

The qualitative data gathered through focus group discussions and key informant interviews were organized into themes and analyzed in order to reveal the differing perceptions on the impacts of *P. juliflora* and on management strategies. Electronic records and notes taken from focus group discussions and interviews were transcribed and analyzed in terms of discursive patterns and narratives.

3. Results and Discussions

3.1. Perception of the Expansion of *P. juliflora*

Table **3** summarizes the introduction and expansion of *P. juliflora* in the study area. *P. juliflora* is an exotic plant and was first observed in '*mesno*' (irrigation) sites around Worer town of Amibara *woreda*, Middle Awash Valley (MAV). All informants explained that *P. juliflora* was introduced by a non-local expert researcher who used to work for Awash Basin Authority (ABA) in the early 1970s. Discussants in Dudub and Sedhafagie *kebeles* indicated that researchers once promoted the species, and pastoralists were encouraged to plant it in their villages. The purpose of this plantation was to enhance the vegetation cover of the area and thereby withstand desertification, protect soil from erosion and provide pods for use as fodder for livestock. According to our informants, in the 1980s and 1990s that *P. juliflora* began to invade other *kebeles* of the Amibara and neighboring Awash Fentale *woreda*. The reported dispersal mechanisms were primarily through livestock, which came to these sites to feed on the residue of cotton plantation crops in dry seasons. By then, some livestock such as goats, camels, and donkeys used to eat the pod (containing the seed of the plant) of *P. juliflora* and transported the seed to other areas. In addition to spreading, livestock facilitated the germination rate as the seed is easily split from the pod and gets wet when it passes through the digestive system and is excreted with dung on the ground. A participant in the FGDs indicated that "… *if you put the seed on the ground here to grow, it cannot be grown, but if camels spent one night here, new P. juliflora would grow in the next few weeks or months*" (a male Elder in Dudub *Kebele*). Thus, livestock and the practice of transhumance (pastoral livelihood system) play a leading role in spreading *P. juliflora* in the study area. In the same way, 2 of the 4 focus groups (Sedhafagie and Kebena) stated that wild animals such as warthogs, deer, rabbits, apes, monkeys, and rodents had spread the seed of *P. juliflora*, but over short distances. Thus, livestock was primarily responsible for spreading *P. juliflora* pods/ seeds to wider areas in the Middle Awash Valley of Ethiopia.

Table 3: Summary on the expansion of *P. juliflora* in Awash Fentale and Amibara *woredas.*

Indicators	Description
Introduction of *P. juliflora*	*P. juliflora* was introduced by non-local expert researcher in the 1970s
First plantation site	"*Gudeb* site" along irrigation cannels in Worer area in Amibara *woreda*
Agents for *P. juliflora's* seed dispersal	Livestock, wild animals, channel and flood water flow
Other conditions facilitating the spread of *P. juliflora's* seed	Transhumance livestock rearing system, development intervention (e.g., road and railway constructions), clearance of natural vegetation and delays to the use of cleared lands for sugarcane plantation in Awash Fentale *woreda*
Current coverage	All the five *kebeles* in Awash Fentale and 16 out of 19 *kebeles* in Amibara

The other main mechanisms of *P*. *juliflora* dispersal were the transportation of the pods/seed by channeled water and in times of flood and due to human development activities undertaken in the region (Table **3**). For instance, discussants in Dudub and Kebena *kebeles* indicated that land clearance for large- scale irrigation farming, resettlement, road and building construction all aggravated the expansion of *P. juliflora* trees. As a consequence, dense stands of *P. juliflora* were found along roads, the Awash River and its streams and irrigation canals.

According to informants from the *woreda* agricultural and pastoral office, 16 out of 19 rural *kebeles* in Amibara *woreda* and all the five *kebeles* in Awash Fentale *woreda* were invaded by *P. juliflora* (Table **3**). This makes up about over 80% of the study *woredas* to be invaded by *P. juliflora*. There is a very high prospect of future spread as the increasing drought and climate change have created favorable conditions for its growth. The seeds can germinate under considerable moisture stress and temperatures that range between 20 and 40^0 C [26]. This also applies to the native African Acacias. However, *P. juliflora* has a more effective water consumption capacity from deeper and wider sources due to its long and lateral roots expansion [21]. This makes other local species less competitive in accessing available soil moisture. Thus, the present, ongoing and future climate change is expected to aggravate the expansion of *P. juliflora*.

3.1.1. The Nexus between Climate Change and P. juliflora Expansion

Current and future climate change and variability would likely create a more suitable environment for the expansion of *P. juliflora* in the Middle Awash Valley. Discussions with all FGDs and interviews with experts at all levels made clear that over time the rainfall amount has become less and the frequency and severity of drought has increased over the last twenty years. This perception of local people was confirmed by our empirical climatic data (Figures **3a** & **3b**). Although not statistically significant, the trend result for annual rainfall shows a decreasing change at a rate of 14.2 mm/decade for the period 1980-2014. In contrast, temperature and potential evapotranspiration amounts show statistically significant increasing trends (at $p<0.05$ level), at rates of 0.37°C/decade and 114.3 mm/decade, respectively. There was a big gap between the rainfall and potential evapotranspiration amounts, with temperature rise the most significant variable to explain this difference, leading to greater soil moisture deficit (Figure **2a**). Climate models have projected a further rise in temperature and uncertain rainfall change for the MAV [30]. Evidences from this study and elsewhere (e.g., Berhanu and Tesfaye [21]) indicate that *P. juliflora* is growing and expanding very well under the increasingly drier climate and more frequent drought-like conditions, whereas other indigenous plant and grass species are diminished to a large extent. In this regard, it is possible to say *P. juliflora* may continue to expand in the changing climate as it can grow under high temperature and severe moisture stress. Similarly, Kyuma *et al*. [31] reported that rapid expansion of *P. juliflora* is correlated negatively with a decrease in mean monthly rainfall amount and positively with a rise in temperature in the drier parts of Kenya. The very long (30 meters) and laterally extended (up to 30 meters) roots of *P. juliflora* enable it to extract water from distant sources. In addition to this, the occurrences of frequent droughts and climate change induced pasture scarcity forced livestock to eat the pods of *P. juliflora* as confirmed by local community at all our FGDs. Livestock mobility was also very high at times of drought and migration and was made over long distances (to the neighbouring Amhara and Oromia National Regional States of Ethiopia). The role of livestock and increasing mobility during drought times in search of pasture and water is also reported for the spread of *P. juliflora* in the drylands of Eritrea [10], Kenya [11] and South Africa [9]. Collectively, these hydrometeorological and social factors facilitate the spread of *P. juliflora*.

On the other hand, natural resource management experts in Amibara *woreda,* the ABA and researchers at Worer Agricultural Research Center discussed the capacity of *P. juliflora* to sequester carbon (and contribute to climate change mitigation efforts). There are also other studies e.g., Ilukor *et al*. [18] and Birhane *et al*. [25] which investigated the carbon sequestration potential of *P. juliflora*. These studies found higher carbon storage potential in highly *P. juliflora* invaded areas compared to less or non-invaded sites. According to the later study, the total carbon stock of the entire *P. juliflora* species community were about 40% higher at highly invaded area than at less invaded area [25]. *P. juliflora's* carbon sequestration potential was understood by natural resource managers and research groups, and for this reason some of them (e.g., researchers from Worer Agricultural Research Center) argued to maintain it in marginal lands that could not be used for grazing and farming activities. Key informants from research centers and NGOs also suggested finding ways to generate economic benefit through global carbon trade finances. Moreover, *P. juliflora* has very good potential to enhance available nitrogen and phosphorus (largely derived from soil carbon) that are useful to enhance vegetation biomass and soil fertility in the study area [18]. However, none of these environmental roles or the potential economic benefits to be obtained from the carbon trade was discussed by the community members (e.g., pastoralist and agro-pastoralist) in any of the FGDs.

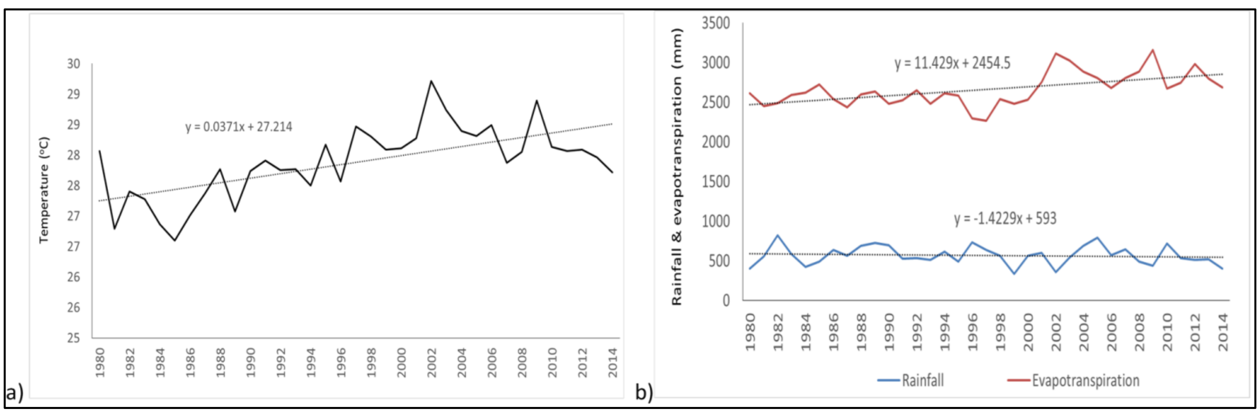

Figure 3: Trends of a) mean annual temperature and b) total rainfall and evapotranspiration amounts for Worer station.

3.2. Impacts of *P. juliflora* on the Ecosystem and Socio-Economic Activities

P. juliflora has multiple positive and negative impacts on ecological, livelihood strategies and other socio-economic systems in the arid and semi-arid areas. Local communities (both pastoralists and agro-pastoralist) argue that negative impacts significantly outweighed the positive impacts. However, the perceptions, views and aspiration of the local community, researchers and experts who are working on natural resource management differed in characterizing the impacts of *P. juliflora* on ecological and socio-economic systems.

3.2.1. Positive Ecological Impacts

Some agricultural and environmental researchers and experts working in *Woreda* Agricultural and Pastoral offices have reported that *P. juliflora* is useful for soil salinity treatment, soil erosion control, shading from sunlight and to serve as a wind break. According to them, *P. juliflora* can reduce the level of soil salinity if *P. juliflora* is growing on a saline farm field for two to three years, as it can reduce the level of the water table using its longer root system and very high-water consumption ability. We observed that the Worer Agricultural Research Center, Kesem Sugar Factory and some private agricultural investors have used *P. juliflora* to treat saline farmlands. *P. juliflora* is also acknowledged for its carbon sequestration and soil nutrient improvement potentials as discussed above and also reported by other studies in Ethiopia (e.g., Ilukor *et al*. [18] and Birhane *et al*. [25]) and other parts of east Africa (e.g., Maundu *et al*. [11] and Kyuma *et al*. [31]) and southern (e.g., Shackleton *et al*. [1] and Ndhlovu *et* *al*. [9]) Africa. Furthermore, it formed dense forest cover in some areas and made the area green and served as a home for flocks of birds and other wild animals in the study area. Our key informants and discussants in Sedhafagie and Kebena *kebeles* reported that the number of lions and warthogs is increased over time due to the formation of dense *P. juliflora* cover in their areas. Also, a few natural resource management experts reported the advantage of *P. juliflora* to reduce the prevalence of flood hazards and soil erosion caused by wind.

Whereas most of these ecological benefits were understood and acknowledged by some agricultural and environmental management experts of the *woreda* agricultural and pastoral offices, Semera University, and Worer Agricultural Research Center, local communities have little perception and acknowledgment of most of these ecological services except for the plant's use as shade and wind break. The lack of acknowledgment of some of *P. juliflora's* ecological services could be due to the fact that the negative ecological impacts (e.g., invading their rangelands, villages, and water points) have more significant impacts on their day-to-day life than the positive ecological impacts. As understood from the FGDs, the ecological services obtained from *P. juliflora* do not affect their day-to-day lives, and they seemed to focus on immediate negative impacts or immediate benefits of *P. juliflora.* However, it is expected that the ecological benefits of *P. juliflora* (e.g., wind breaks and control for soil erosion) are relatively high in degraded areas.

3.2.2. Positive Socio-Economic Benefits

P. juliflora was used for domestic energy (firewood), constructing byres and fencing houses (Figure **4a**) and farmlands, for shade (Figure **4b**), and to some extent as house construction material. The local communities also used the pods of this tree to feed their livestock in periods of severe shortages of feed, such as in dry and drought periods. However, focus group participants generally did not prioritize these benefits. Instead, they emphasized that this tree is of poor quality for domestic energy and construction and has a greater tendency to cause physical injuries to humans and livestock than indigenous tree species. Fences and houses constructed using *P. juliflora* byre are considered less durable as its wood is not as hardy as native alternatives and is attacked by termites. However, as local native plants are rarely available, local people are forced to use *P. juliflora* for the aforementioned purposes.

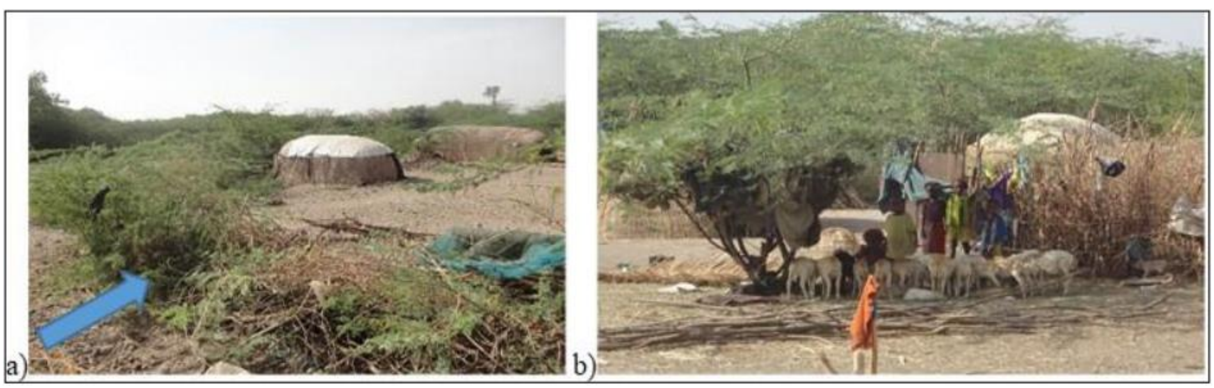

Figure 4: Use of *P. juliflora* for a) fencing and b) shade from sunlight.

In the study sites, attempts have been made to generate income from *P. juliflora* by producing charcoal and forage from its pods for livestock. In fact, some local people have generated income from charcoal production in the past. For example, Amibara *woreda* licensed five unions consisting of 20-30 pastoralists in Serkemo, Sedehafagie, Halaydegie, and Bedula-alie *kebeles*. These unions have generated a reasonable income by producing and selling charcoal at market centers of Adama and Addis Ababa. According to agricultural extension expert informants, some unions earned up to one million Ethiopian Birr (equivalent to USD 36363.64) per year from sales of charcoal. Some other unions also attempted to generate income by producing fodder from *P. juliflora* pods with financial and technical support from international NGOs such as FARM-Africa and FAO. However, all of these activities were not functional during our study period for various reasons. For example, charcoal production was prohibited by the regional government as a result of the indiscriminate cutting of all types of native plants and the reported contribution of the activity to conflicts among pastoral communities and clans. Fodder production was stopped due to the absence of demand, low market price, technology failure, and the health risk associated with *P.*

juliflora pod collection. As a consequence, the use of *P. juliflora* as a source of livelihood and income generation through the above-mentioned uses had been mostly abandoned in the study area.

In contrast to the experience in our study area, *P. juliflora* is considered a major income source for households in many African countries, including some drylands of Kenya [11]. According to Choge *et al*. [3], in Kenya, about US$1.5 million per year is generated from the sale of *P. juliflora's* pods for fodder and charcoal products. The sale of *P. juliflora* products, mainly charcoal, offers supplementary sources of income in other African countries, for example in Eritrea (Bokrezion [10]), Nigeria (Borokini and Babalola [32]), Sudan (Suliman *et al*. [33]) and South Africa (Wise *et al*. [15] and Shackleton *et al*. [17]). In addition, *P. juliflora* pod has been used to produce organic medicine in South Africa, and this medicine has the value of stabilizing human blood sugar levels [17]. Wise *et al*. [15] reported one company generating about USD100000 profit from medicinal sales.

3.2.3. Negative Impacts

The negative impacts of *P. juliflora* are not the same across space (administrative *woreda*) and livelihood systems (pastoral, agro-pastoral, and urban), institutions (development and conservation), and social groups (elders, women, children, and youths). Our informants confirmed that *P. juliflora* caused a number of negative impacts on indigenous biodiversity and ecosystem services. According to key informants and focus group discussants, *P. juliflora* has not only rapidly infested their rangeland but also reduced the presence of important native plant species. Most of the major native tree and plant species noted earlier in the paper have declined in abundance. The tree varieties are largely used for firewood, charcoal making, construction, and forage purposes in the study area. Other native plants have been used for different services, including firewood, forage, traditional medicine, and toothpicks. FGD participants and experts reported that *P. juliflora* reduced soil moisture, depleted the underground water table, and invaded and dried up surface water sources (e.g., ponds). It also blocked access to all surface water sources and blocked irrigation water movement and management practices (canal clearance and maintenance), invaded flood protection dikes, and disrupted maintenance of irrigation canals and flood protection dikes (Figures **5a-f**). As a consequence, ecologically productive grazing and fertile cultivable lands became un-usable when invaded by *P. juliflora.* Accordingly, about 600,000 ha (making up 25%) of the grassland cover was converted into *P. juliflora* cover and or bare land between 1986 and 2017 [21]. The multiple ecological damages caused by *P. juliflora* are also reported for other parts of the Afar region [4, 5, 23], Eritrea [10], Kenya [3, 11], Nigeria [32], South Africa [9, 17] and Sudan [8].

P. juliflora impacted different social groups differently. Participants at all our focus group discussions indicated that the effects of *P. juliflora* is relatively higher on women as they are vulnerable to physical injury by *P. juliflora's* thorns during firewood collection. Its invasion also increases their work as they are forced to travel longer distances and spend long hours collecting wood and grass for house construction. Elders also said they face physical injury while walking at night due to problems with their vision, and children were vulnerable to injury by *P. juliflora's* thorns as they commonly walk on bare feet. *P. juliflora* has narrowed and diminished play areas for children and causes health complications if young children eat the pods of *P. juliflora*. Children are also forced to travel a longer distance to look after goats and calves. Similarly, male youths and adults must travel longer distances to find pasture for their livestock and, in consequence, also face conflicts with members of other communities.

Informants at all our study sites indicated that the development of dense *P. juliflora* cover had increased the risk to humans and livestock from dangerous animals (such as lions, leopards, and snakes). It also invaded settlement areas and caused the displacement of homes at all the study *kebeles*.

Information collected from our four FGDs and all key informants confirmed that *P. juliflora* negatively affected livestock well-being, number, and productivity in the study area. The records indicated that the hard thorns of *P. juliflora* cause physical injuries to livestock. *P. juliflora* also causes *Armico* (physical distortion of the face of animals) and permanent impairment in the ability to digest cellulose when they ate the pods at the time of pasture scarcity. *P. juiflora* causes severe pasture shortage and reduced access to water and block movements, thus exposing them to predators. Livestock is forced to travel to new areas and long distances to find pasture. Almost all our informants agreed that the number and productivity of livestock is significantly reduced over time due to the negative effects of *P. juliflora*.

Agro-pastoralists in Sedhafagie and Kebena *kebeles* have also been affected by *P. juliflora* as this tree has rapidly invaded their farmlands, blocking access to water and host wild animals (e.g., warthog, flocks of birds and rodents). These people spent a lot of their time, income, and labor to clear *P. juliflora* (Figure **5b**) and protect wild animals from damaging their croplands. Consequently, the food security condition and other livelihood strategies of pastoral and agro-pastoral communities were negatively influenced, and this increased their vulnerability to multiple climatic (e.g., drought) and non-climate risks, e.g., food insecurity, conflict, and poverty.

Figure 5: Impacts of *P. juliflora* on a) human health, b) incur cost to remove from farmland, c) invaded irrigation cropland, d) narrowing irrigation ditch and block water access, e) incur cost to clear from road and f) narrowing roads.

P. juliflora also negatively impacted urban and semi-urban areas and the urban community in different ways. For instance, it serves as a cover for criminal activities such as robbery and theft and reduces the quality of the environment in the towns. Thick *P. juliflora* growth is used commonly as dumping sites for wastes/garbage, and the thick *P. juliflora* growth also traps refuse. It creates major problems for urban water distribution by bending pipelines and blocking water movements. Development projects and institutions like Kesem Sugar Factory and Awash River Basin Authority also suffered from *P. juliflora* in many ways. For example, *P. juliflora* negatively affected these institutions by rapidly invading farmlands prepared for a sugarcane plantation, blocking the movement of farm machinery and cars by puncturing their tyres and invading roads (Figure **5e**), thereby increasing the workload and cost for clearance and weeding activities. For Awash Basin Authority, the dense vegetation cover has also created a problem for land surveying and evaluation studies.

Most of these negative consequences of *P. juliflora* on socio-economic and livestock resources that we found in our study area were also experienced in the other arid and semi-arid parts of Africa. For example, physical injury by *P. juliflora's* thorns both on humans and livestock, the effects on farmlands and rangelands, the blocking of access to water sources, and reduced services from the natural forest are all reported in Kenya [3, 11]), Sudan [33], and South Africa [15, 17]. The large amount of money needed for *P. juliflora* management is also reported for South Africa, which is estimated at about USD35.5 million per year [1].

3.3. Management Strategies and Practices

Multiple *P. juliflora* management strategies have been introduced and attempted in the Middle Awash Valley over the last 20 years (Table **4**). Previously attempted management interventions were aimed to promote both eradication (e.g., cutting and uprooting) and economic utilizations (e.g., production of charcoal, fodder, and furniture). Technologies and strategies targeted to eradicate *P. juliflora* were removal using simple manual cutting and burning (Figure **6a**), cutting and uprooting (Figure **6c**), cutting and burning the root part by adding dry animal manure or motor oil (Figure **6b**), clearing by bulldozers (Figure **5e**), removal by weeding and establishing area enclosure sites. It is important to note that these management strategies are quite different in terms of the extent of application across the study area, their effectiveness, and the challenges encountered in applying the technology. For example, all our informants confirmed that the simple manual cutting and burning (Figure **6a**) method has been widely applied through the Productive Safety Net Program (PSNP) and through individual efforts to remove *P. juliflora* from settlement areas, roads, and water points. However, all our informants perceived it as tiring, risky, less effective due to the high coppicing capacity of the tree, and not workable over large areas. If coordinated among land owners or government agencies, controlled burns can work over large areas. The local community and experts well understand it as an ineffective method. Removal by manual cutting and uprooting (Figure **6c**) has been applied at selected sites (e.g., farmlands). It is perceived as an effective method but considered again as tiring, risky, and not workable over large areas. An attempt was also made to remove *P. juliflora* by cutting and burning the root part by adding animal manure or motor oil (Figure **6b**) in the Halaydegie and Sedehafagie *kebeles*. It is applied as an experiment by very few individuals, and it is perceived as an effective method if rigorously implemented. However, it is perceived as difficult and expensive to be applied over larger areas too. KSF, ARB, and private agricultural investors have been using bulldozers (Figure **5e**) to clear *P. juliflora* from irrigation farmlands and roads. Some NGOs also used this to prepare land for area enclosure for the community. This method was perceived as effective in many ways (e.g., it can be applied over large areas in a short period, easily uproots big trees, and has no risk of injury). But bulldozers are not easily accessible, are costly, and not affordable to the local community. The use of clearing bulldozers can also add to soil compaction as well. This method is also criticized for its damage to other indigenous plant varieties as it is difficult to remove P. juliflora alongside other small size indigenous plants selectively. Weeding is mentioned as a strategy to remove newly emerging/ growing *P. juliflora* from farmlands in Sadahafagie and area enclosure sites in Halaydegie rangeland *kebeles*. Our informants perceived that this method is effective in managing the expansion of *P. juliflora* into new areas as it is easy to apply and less risky. However, this method is not viable to apply in the current highly invaded areas and less practical to apply over large areas because of the labor requirements. Furthermore, area enclosure sites (protected area) were established in Andido and Halaydegie *kebeles* in Amibara *woreda* by the Agricultural and Pastoral Office together with community unions to clear and manage *P. juliflora* (Figure **6e**). There were three delineated area enclosure sites in Amibara *woreda*: Halaydegie (12 km^2), Andido (12 km^2), and Kurkura (20 km^2). The objective was to restore the degraded indigenous plant biodiversity due to *Prosopis* invention and to use the area as a source of pasture for livestock by implementing cut and carry methods. This management activity was carried out by community-based Traditional Rangeland Management Councils (TRMC), facilitated by clan leaders and elders. This method appeared to reduce the Prosopis tree and regenerate the rangeland significantly. However, it needs a huge initial capital to clear and uproot *P. juliflora* from invaded areas, and it is mainly used in areas that have good potential for grazing. In addition to this, controlled burning and herbicides are less expensive and effective methods that can be used to control the expansion of *P. juliflora* over large areas.

Different strategies were attempted previously, and some new strategies are planned to convert *P. juliflora* into economic utilization (Table **4**). Some of the past attempts are charcoal making and fodder furniture productions. Biofuel and dry biomass production are the planned strategies. The previous three economic utilization strategies (e.g., charcoal making, fodder, and furniture production) were introduced and supported by some international NGOs projects such as FARM-Africa and FAO. Participants in the FGDs and key informants indicated that community unions that were established in *P. juliflora* invaded *kebeles* to make and sell charcoal in 2010 and 2011. However, this activity was prevented by Afar Regional government after two years as it created conflicts between beneficiaries and negatively affected indigenous trees due to non-selective utilization. Currently, this strategy is not functional, and most people do not have an interest in this strategy for the aforementioned reasons. Participants in Sadahafagie *kebele* also indicated that charcoal making had a long-term impact on soil, grass, and seed stocks of indigenous plants at charcoal production sites, and there was a risk of physical injury by its hard thorn. Community unions were also established in Sadahafagie *kebele* to produce fodder from the seed pods of *P. juliflora*. According to our key informants from Amibara *Woreda* Agricultural Office, these unions did not continue fodder production for a number of reasons that include a mismatch between the nature of pods and the crusher/grinder, the tiresome work of pod collection, lack of market for products, lack of experience and support, and the risk associated with its thorn and wild animals. The local community is interested in fodder production from *P. juliflora* only if they have access to appropriate and manageable technologies as well as good market access. In contrast to our study area, charcoal making and fodder production are considered effective means to generate income for many households in the arid parts of Kenya [3, 11].

Table 4: Descriptions of current and planned *P. juliflora* management strategies in MAV.

Major Focus	Specific Management Strategies	Current Condition
Removal	Simple manual cutting and burning (Figure **6a**)	Functional in many sites
	Manual cutting and uprooting (Figure **6c**)	Functional at selected sites
	Cutting and burning the root part by adding animal manure or motor oil (Figure **6b**)	Functional at few sites
	Clearing by bulldozers (Figure **5e**)	Functional at selected sites
	Removal small *prosopis* by weeding	Functional at selected areas
	Establish area enclosure sites	Functional in Amibara *woreda*
Economic utilization	Charcoal production	Failed or prevented by local government
	Fodder production	Failed
	Furniture production	Previous attempt failed, but there is a new plan
	Production of biofuel (Figure **6d**)	Under construction but no tangible information
	Production dry biomass energy by Dire Dawa National Cement Factory	Planned
Ecosystem function	Saline soil treatment,	Functional along farmlands
	Erosion protection by serving as wind break	Functional
	Landscape greening and carbon sequestration	Functional, but need additional empirical evidence
	Serve as a shelter for some wild animals (e.g., snake, lion, warthog, etc)	Functional

On the other hand, community unions were established at Sedehafagie and Werer towns to produce different furniture from *P. juliflora*. However, this attempt failed and is not functional. Currently, there is a plan to start lumber and furniture production from *P. juliflora* as part of the Ethiopian Climate Resilient Green Economy (CRGE) strategy. The government has constructed workshop rooms near Worer town and delivered machinery to community unions. These unions could not start their activities due to a lack of required facilities, e.g., training, financial and planning for production and marketing. Although there is no tangible evidence, our key informants in Amibara indicated that the government has planned to generate electricity (137 MW) using *P. juliflora* as a bio-energy source. Workshop rooms were under construction near Melkasedie town (Amibara *woreda*), and machinery was purchased to support job creation for local people. However, it had not yet started production, and it was not clear how the larger community would participate and benefit from this project. In addition to this, Dire Dawa National Cement Factory made an agreement with the Afar National Regional State to produce dry biomass for use as energy in its factory instead of importing coal. This factory received a license from Afar National Regional State. The agreement included clearing *P. juliflora* by uprooting and leveling the ground for other uses by the local community, e.g., grazing land and irrigation farming. The agreement also included the plantation of *P. juliflora* on marginal lands (e.g., saline lands).

The perception and preferences for different management options and strategies differed between stakeholders and livelihood systems. For example, individuals in the pastoral communities (e.g., Halaydegie) preferred that *P. juliflora* land cover be converted into rangeland and farmland by creating water access for irrigation works. Survey participants who lived close to roads and towns (e.g., Dudub *kebele*) preferred the development of large-scale economic utilization (e.g., bio-fuel factories) to secure job opportunities. Key informants from environmental, agricultural, and research offices perceived the combination of eradication and economic and systematic ecological utilization as feasible adaptation options to tackle negative impacts and exploit the benefits of *P. juliflora*. They have suggested the following hybrid management strategies:

Figure 6: Some management strategies a) cutting, b) cutting and burning, c) cutting and uprooting, d) planned bio-fuel manufacturing factory, and e) area enclosure at Halaydegie.

1) Apply targeted eradication on valuable lands and leave marginal lands for *P. juliflora* to use for carbon sequestration and as a source of wood for domestic energy.

2) Convert *P. juliflora* into large-scale economic utilization such as biofuel plantations and dry mass production. This would generate carbon-free energy and allow *P. juliflora* to provide other ecological services such as carbon sequestration and landscape greening.

3) Introduce different technologies such as bulldozers that enable the community to rapidly remove and uproot P. juliflora and reduce risks from valuable lands (e.g., farmlands, settlement areas, and grazing lands).

4) Use *P. juliflora* to treat soil salinity, soil erosion control, and as a windbreak in villages and along irrigation farmlands.

5) It is highly invasive, so it will always have to be controlled as it moves into productive fields and wildland landscapes.

Furthermore, agricultural experts and environmentalists indicated that total eradication might not be a viable solution as it would bring other negative environmental consequences like wind erosion, flood risk, and shortage of wood for domestic energy. They also indicated that total eradication means missing the multiple ecological advantages of *P. juliflora,* such as carbon sequestration, salinity treatment, landscape greening, and land cover/shading.

3.4. Why Applied Management Strategies were not Effective?

We have explored the possible reasons that have made the attempted management strategies less effective. Major factors contributing to the failure and unsuccessful achievement of past and current management interventions are generally attributed to the highly invasive nature of *P. julifora*, the livelihood conditions of the communities, environmental factors including climate variability, technological incompatibility, and lack of management commitment from both the government and community sides.

The rapid expansion rate and durability (such as its ability to coppice) of *P. juliflora* are major factors that negatively affected the success of management strategies that focused on eradication (e.g., cutting and burning), which have been widely implemented for more than two decades. When cut down above the ground, *P. juliflora* has very high and rapid coppicing capacities. One *P. juliflora* tree can regenerate about 20-30 shoots from its stump. It is also rapidly growing and forms thick forest cover from the primary tree (Figure **7**).

Figure 7: The coppicing of *P. juliflora*.

Other environmental drivers, including climate variability, could not be controlled by local people and triggered the expansion of *P. juliflora*. There were different types of wild animals (e.g., warthogs, rodents, monkeys, apes, and birds) and natural events like runoff that caused the spread of *P. juliflora* seeds. Wild animals spread *P. juliflora* into farmlands and cleared lands from nearby *P. juliflora* cover by eating the pod and excreting wastes on non-infested lands. The local people cannot control these spreading agents. On the other hand, as discussed, *P. juliflora* has a high drought-resistant capacity, as a result of which, the occurrence of frequent and prolonged drought hazards largely complicated the efforts made on *P. juliflora* management. For example, in some of the study sites (e.g., Dudub and Halaydegie *kebeles),* the attempt to convert *P. juliflora* land cover into pasture and cropland using rain-fed and rainwater harvesting systems failed due to the occurrence of prolonged drought between 2014 and 2016. The cleared lands in these *kebeles* were reinvaded and rendered inaccessible by thick *P. juliflora* trees. Furthermore, at times of drought, livestock eats the pods of *P. juliflora* associated with scarcity of pasture, and the rate of migration into other areas is also increased. All these had accelerated the expansion of *P. juliflora*.

The pastoral livelihood system (the practice of transhumance) is another attribute that negatively impacted the success of some management efforts in many ways. Both pastoralist and agro-pastoralist communities practiced migration (transhumance) during wet and dry seasons and drought periods in our study area. In addition to spreading the seed of *P. juliflora* into non infested areas and over long distances, pastoralists and agro-pastoralist were unable to consistently eradicate *P. juliflora* in a given area due to their constant migration. Accordingly, areas that have not been grazed for some months have been rapidly invaded by *P. juliflora*, resulting in thick *P. juliflora* cover. Since the *P. juliflora* invasion was too severe to manage, pastoralists have left the infested area intact and migrated to other areas that were free from *P. juliflora*. This again leads to further expansion of *P. juliflora.*

The inadequacy of technologies to aid utilization and eradication also negatively affected the management of *P. juliflora*. As discussed by KII participants, some of the introduced technologies were incompatible with the intended outcomes. For example, the attempt to produce different furniture from *P. juliflora* wood and fodder from its pod partly failed due to inappropriate technologies, risks during raw material collection, and unsatisfactory economic returns. The type of mill used to produce fodder from *P. juliflora* pods was unable to grind them because of their sticky nature. In addition, it was too difficult to collect a sufficient quantity of pods per unit of time and area as the number of pods per tree is not sufficient. Pod collectors have also experienced physical injuries by the strong and poisonous *P. juliflora* thorns, and there was also a risk associated with the attack from wild animals. The pods collected in these situations were sold at a low price (Ethiopian Birr 0.40/ kilogram), making the activity even less attractive. Furthermore, there was no sufficient and satisfactory market for the end product (fodder). On the other hand, some technologies like bulldozers used to clear *P. juliflora* were not easily accessible and were expensive for the local communities. Furthermore, those *kebeles* that have used grease (or burnt motor oil) to kill the root system of *P. juliflora* by burning could not find enough of this material to apply it over a large *P. juliflora* infested area.

In addition, the effort made to manage (and reduce expansion) was insignificant as compared to the rate of *P. juliflora* expansion during the last two decades. For example, most of the eradication works (e.g., cutting and uprooting) were implemented by human labor only for 45 days per year through the PSNP. This work also focused on clearing *P. juliflora* from some important sites (roads, villages, and water points) but was not implemented over larger and dense *Prosopis* cover areas.

Our informants from government and NGO offices confirmed the absence of continuous support for the sustainable implementation of management strategies. For example, there were no or only weak mechanisms to transfer resource management projects and experiences from NGOs to government management systems when NGOs' projects were phased out. Evidence for these failures was that the furniture and fodder production projects introduced by one NGO ultimately failed when the *Prosopis* management projects were phased out. In addition, support and effort made by the Federal Government of Ethiopia and Afar National Regional State to support *P. juliflora* management were not sufficient, or only ad-hoc, and not consistent. In fact, the Federal Government has recognized the problem of *P. juliflora* only recently. It has developed a management guideline called "National Strategy on *Prosopis juliflora* management" [34]. The Afar National Regional State also has issued a policy that supports the management of *P. juliflora*. However, there was limited financial, and resource supports provided to the community and *woreda* to implement some of the proposed management strategies.

4. Conclusion

P. juliflora was deliberately introduced in the MAV to tackle desertification and soil erosion and benefit the pastoral community with firewood and fodder for their livestock. *P. juliflora* has the potential to sequester carbon, enhance soil nutrients and treat saline soils. In this regard, most of the initial assumptions were met as it has made the landscape green, served as a windbreak, and provided shade. *P. juliflora* was also partly used to feed livestock at times of pasture scarcity. However, it is observed that the initial assumptions have resulted in trade-offs that have damaged ecosystems and pastoralists' livelihood systems. Current evidence indicates that the negative impacts of *P. juliflora* outweigh its positive consequences. The thorns and seeds of *P. juliflora* have caused livestock severe physical injury and internal health complications. *Prosopis* thorn has also caused injury to human skin. The rapid expansion of *P. juliflora* largely reduced the availability of indigenous tree and grass species that caused a severe scarcity of pasture for livestock and wild animals. As a result, livestock number, composition, and productivity have declined over time in our study area. The expansion and dense growth of *P. juliflora* trees block roads and water access for livestock and human use. It also creates a problem for crop farming by invading farmland and hosting crop-damaging wild animals. These impacts from *P. juliflora* have negative implications on food security, access to natural resources, and livelihood systems for the pastoral and agro-pastoral communities in the MAV. With more expansion of the projected *P. juliflora,* the vulnerability of pastoral communities to climatic and non-climatic risks (e.g., food insecurity, conflict, and poverty) is likely to happen in the future. Some social groups, such as women, elders, children, and pastoralists depending only on livestock rearing, were disproportionately affected by *P. juliflora*. The attempted management strategies to eradicate *P. juliflora* (cutting, burning, and bulldozering or converting into economic utilization by making charcoal, fodder, and furniture) failed to achieve the intended outcomes. One of the main reasons is the rapid rate of *P. juliflora* expansion triggered by the recurrent drought development and a severe scarcity of pasture that forced livestock to eat *P. juliflora's* seed pods and travel into new areas and long distances. In addition to these, the inadequacy of technologies to aid utilization and eradication has also negatively affected the management of *P. juliflora*. Moreover, it was too difficult and tiring to collect a sufficient quantity of pods per unit of time and area as the number of pods per tree is insufficient. The absence of sufficient and satisfactory markets for the end-product (fodder) and the development of regulations prohibiting charcoal production are other factors that have made economic utilization unsuccessful. Current evidence indicates that the expansion and impacts of *P. juliflora* are beyond the capacity of the existing management strategies and efforts made by local people.

The results generally imply the need for urgent policy and management interventions. These should focus on clearing and controlling the further expansion of the tree into valuable lands and creating opportunities to convert *P. juliflora* into economic benefits. Considering the present available technology, it is difficult and may not even be possible to remove *P. juliflora* completely from the landscape. Thus, it is advisable to develop hybrid methods which comprise both its utilization in some less productive areas and removal from valuable lands (croplands, rangelands, water points, and settlement areas). Any management strategies that focus on economic utilization should benefit the larger community to avoid possible conflicts.

Furthermore, any recommended management strategies and policy developments need to consider the views of different stakeholders and social groups e.g., women, elders, children, and pastoralists. Lastly, the introduction of management strategies should be based on carefully evaluating its short, medium, and long-term impacts on the environment and sustainable socio-economic development to avoid further unintended consequences. In this regard, a combination of multiple management strategies that include eradication and economic and environmental functions can be applied to minimize negative consequences and benefit from its advantages. One of the strategies can be to apply targeted eradication on valuable lands and leave marginal lands for *P. juliflora* to use for carbon sequestration and as a source of wood for domestic energy. Another management strategy is to convert P. juliflora into large-scale economic utilization such as bio-fuel and dry mass production in densely invaded areas. This can be used to generate energy (e.g., ethanol) and allow *P. juliflora* to provide other ecological services such as carbon sequestration and landscape greening. The introduction of different technologies (e.g., furniture, charcoal, and fodder production) can enable the larger community to generate income from *P. juliflora*.

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Declarations

Authors' Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, analysis and interpretation, and first draft writing were performed by Mekonnen Adnew Degefu and Mohammed Assen. Roger Few and Mark Tebboth performed manuscript structuring, second draft writing, and critical revision. All authors read and approved the final manuscript.

Conflicts of Interest/Competing Interests

The authors have no relevant financial interests to disclose.

Availability of Data and Material

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code Availability

Not applicable to this paper.

Ethics Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Ethiopian national and Addis Ababa University research guidelines.

Consent to Participate

Informed consent was obtained from all individual participants included in the study including to publish photographs.

Consent for Publication

The submission is the independent work of the authors. It has not been submitted and not published or accepted for publication, and is not under consideration for publication, in another journal or book. The submission has been approved by all relevant authors, and all persons entitled to authorship have been so named. All authors have seen and agreed to the submitted version of the manuscript.

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