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Analysis of the invasion rate, impacts and control measures of *Prosopis juliflora*: a case study of Amibara District, Eastern Ethiopia

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Abstract The tree *Prosopis juliflora*, introduced to Ethiopia in the 1970s to curb desertification, is imposing significant ecosystem and socioeconomic challenges. The objectives of this study are therefore to analyze the dynamics and associated impacts of the *P. juliflora* invasion over the period 1973–2004 and to evaluate the effectiveness of the management measures implemented to date. This required the analysis of Landsat images, field surveys, the use of structured questionnaires, and interviews. *P. juliflora* was found to invade new areas at an average rate of 3.48 km^2/annum over the period 1973–2004. The high germination nature of the seed, mechanisms of seed dispersal, and its wide-range ecological adaptability are the main drivers for the high invasion rate. By the year 2020, approximately 30.89 % of the study area is projected to be covered by *P. juliflora*. The expansion has affected human health, suppressed indigenous plants, and decreased livestock productivity. The management measures that have been implemented are not able to yield the desirable results because of the limited spatial scale, cost, and/or improper planning and implementation. Therefore, the formulation of a strategy for management approaches that include the engagement of the community and the limiting of the number of vector animals within the framework of the current villagization program remain important. Moreover, risk assessment should be completed in the future before an exotic species is introduced into a certain area.

Keywords *P. juliflora* invasion · Landsat · *P. juliflora* management · Exotic species

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Introduction

Invasive species are species of all taxonomic groups whose introduction and/or spread outside their natural past or present distribution threaten the environment such that the well-being of humans will ultimately be affected (Convention of Biological Diversity CBD 2010). This concern is reflected in Article 8(h) of the CB, which calls on its members to "prevent the introduction of, control or eradicate those species which threaten ecosystems, habitats or species." Such species are characterized by rapid reproduction and growth, high dispersal ability, phenotypic plasticity (ability to adapt physiologically to new conditions), and ability to survive on various food types and in a wide range of environmental conditions.

Invasion by alien (exotic) tree species is the most common type of invasion and has attracted increasing attention because of the associated economic costs (Pimentel et al. 2000) and because they reduce native biodiversity (Daehler and Strong 1994; Clavero and Garcia-Berthou 2005) or alter ecosystem functions (Vitousek 1990; Catford et al. 2009). The alien species are considered the second greatest agent of change to ecosystems after habitat change (Pejchar and Mooney 2009). The impacts on livelihoods are most likely more pronounced in developing nations because the majority of the populations in those countries consist of small-scale farmers who are dependent on natural resources for their survival (Stefan 2005).

Once an invasive species becomes firmly established, control can often be difficult, and eradication is usually impossible, if not merely too expensive (van Auken 2000; Cacho et al. 2008). *Prosopis* species have invaded over 4 million hectares in Africa (Witt 2010). A recent estimate shows that such invasions cost the world economy hundreds of billions of dollars each year (CBD 2010). Another earlier study estimated this cost to be as high as US$ 1.5 trillion annually (Pimentel 2001). However, to date, no cost-effective methods for containing and managing broad-scale mesquite (*Prosopis juliflora*) invasions have been found (van Auken 2000).

About 22 invasive alien species (IAS) have been identified in Ethiopia to date (McGinley 2007). *Prosopis juliflora* (Swartz) DC. (hereafter referred to as *P. juliflora*) is among these IAS that has become a widespread problem in the country. *P. juliflora* belongs to the family Fabaceae (Leguminosae), subfamily Mimosoideae, and genus *Prosopis* (Asfaw and Thulin 1989). It is native to North, South, and Central America and the Caribbean (Pasiecznik et al. 2001). It is a spiny, prickly, or armed shrub/tree that is fast growing and has the ability to develop extensive, deep root systems, sometimes exceeding 20–25 m (Jorn 2007). Mature *P. juliflora*, under favorable growing conditions, can develop into a tree with a height of 20 m and a diameter of over 1 m (Pasiecznik et al. 2001; Jorn 2007). The majority of *Prosopis* species are considered to be "conflict" species in that they confer benefits in terms of providing erosion control, shade, fuel wood, building materials, and pods for animal and human consumption in arid and semiarid regions, yet they are also considered to be invasive in that they have escaped cultivation and are having a negative impact on biodiversity, crop and pasture production, and water resources (Pasiecznik et al. 2001).

P. juliflora was introduced into high-quality pasturelands and irrigable areas, including the Awash River basin in the Afar National Regional State of East Ethiopia, during the 1970s as a measure to control desertification and the high dust wind in the area (Alemayehu 2006). The tree is widely considered to be a powerful invader and is becoming a problematic weed in Ethiopia, especially in the Afar State, invading large-scale farms, rangelands, and riverbanks (Kassahun 1999; Shiferaw et al. 2004). Both the local government and communities declared the invasion a top-priority problem and requested external support to prevent further expansion of the invasion and the restoration of invaded areas (FARM-Africa 2009).

However, in most developing countries, there is generally insufficient information regarding the invasion rate and impacts of *P. juliflora*, which arises from a lack of resources for conducting research and data collection (Witt 2010). Moreover, although a range of biological, mechanical, and chemical control measures exist (Zimmerman 1991; Bleton 2008), most of them are less applicable in the context of developing countries such as Ethiopia because they are either expensive or require a high skill level and/or because, even if the technologies were available, the policy and institutional environment and capacity are generally too weak to facilitate the implementation of such measures (Anagae et al. 2004).

In contrast, there are small-scale control and management measures being implemented by local communities either individually or collectively through cooperatives with limited support from governmental and nongovernmental organizations. However, to date, the rate of invasion and the current socioeconomic impacts of the plant are not well documented. Moreover, no systematic study has been conducted to identify management measures previously implemented by the community and to assess whether these measures have been effective.

Understanding the arrival, survival, and establishment and spread characteristics is a requirement for better understanding the colonization and ecosystem impacts the invasive species (Chapman 2012). Similarly, analyses and projections of land use and land cover (LULC) changes can provide a tool with which to assess such ecosystem changes and their environmental implications at various temporal and spatial scales (Lambin 1997). Remotely sensed data and the application of geographic information systems

(GIS) technologies provide an alternative means of rapidly assessing the dynamics and development of invasive species.

Therefore, the specific objectives of this study were (1) to analyze the invasion rate and future trends of *P. juliflora*, (2) to analyze its associated ecological and socioeconomic impacts, and (3) to identify and evaluate control measures that are being implemented to minimize its expansion.

Materials and methods

Description of the study site

The study was conducted in the Amibara District, which is located in the Afar Regional State in eastern Ethiopia at geographic coordinates of 09°13′–09°30′ N and 40°05′–40°25′ E (Fig. 1). The district covers a total land area of 2,941 km^2 and a home of 40,175 inhabitants, out of which the study area covers 527 km^2. Amibara district is where *P. juliflora* was presumed to be initially planted in the region, and the invasion has become seriously pronounced.

The study area has a physiography dominated by plains, with a slope range of 0–8 % and altitude range of 665–815 ma.s.l. The main soil types in the area include Eutric Fluvisols, Eutric Cambisols, and Vertic Cambisols (MoA 1997). The climate can generally be described as arid to semiarid, with maximum and minimum temperatures varying from 25 to 42 °C and 15.2 to 23.5 °C, respectively, and an average annual rainfall of 560 mm (Worer Agrometeorolog Section WAS 2008). May and June are the driest months, whereas July through September is the main rainy season, during which flash floods originating from the highlands recurrently overtop the Awash River bank and damage the surrounding area.

The cattle population of Afar State is approximately 1,620,147, with 131,832 of them found in Amibara District. Transhumance pastoralism is the major production system in the study area, where cattle, camel, goats, and sheep are the dominant animals being reared. Livestock are kept primarily for their products (milk, milk products, and meat) and income generation. Over 90 % of the population depends largely on the milk from cattle, sheep, goat, and camels as their staple food.

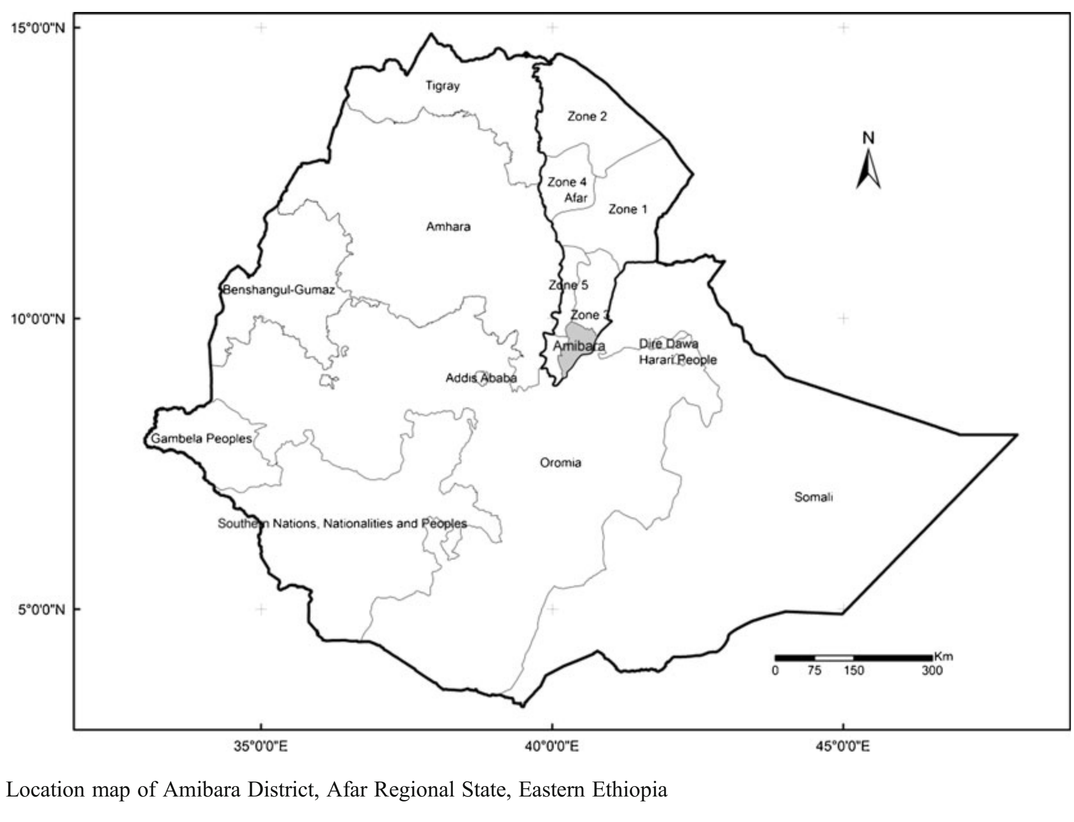

Fig. 1 Location map of Amibara District, Afar Regional State, Eastern Ethiopia

Methodology

Land use and land cover change analysis

Satellite image analysis This study employed multitemporal and multisensor Landsat images from the Landsat Multispectral Scanner of 1973, Landsat Thematic Mapper (TM) of 1987 and 1999, and Landsat Enhanced Thematic Mapper of 2004. The images, obtained from the Ethiopian Mapping Agency (EMA), were radiometrically and geometrically corrected, restored for missing scan lines, and geo-referenced. Earth Resources Data Analysis System Imagine version 8.6 and ArcGIS version 9.2 digital image processing software were used for the processing, analysis and integration of the spatial data.

The first delineation of the study area boundary was completed based on a topographic map (scale 1:50,000) supplied by EMA using ArcGIS 9.2. Then, the boundary was used to take a subset of the satellite images from the different study periods. Using prior knowledge of the study area, a ®reprocessed Spot Image from Google Earth (Fig. 2) and results from a field survey in 2008, with additional information from old maps obtained from the Awash Basin Authority (ABA) and Worer Agricultural Research Center (WARC), a classification scheme was developed for the study area (Table 1). The description of the scheme was based on the standard classes defined by the US Geological Survey and the study details and objectives (Thompson 1996; Mohan et al. 2011). Accordingly, six classes were identified and defined, namely, cropland, wetland, bare land, open acacia bushland, grassland, and area covered by *P. juliflora*. Global Positioning Systems (GPS; e-Trex Euro, Garmin) was used to obtain accurate locations of point data for each land use class.

Both unsupervised and supervised image classification techniques were tested using different classification algorithms. Finally, supervised classification with the maximum likelihood algorithm was used. After the classification process, postclassification

Fig. 2 Reprocessed 2007 Spot Image from Google Earth, outlining the primary land use and land cover classes including *P. juliflora* used in this study

Table 1 The description of the LULC classes used for change detection in Amibara District, Afar Regional State, Eastern Ethiopia

LULC classes	General description
Cropland	Areas of land ploughed/prepared for growing crops. This category includes areas currently under crop cultivation and land under preparation
Wetland	Areas with rivers, marshlands, and other water bodies
Bare land	Areas with essentially no vegetative cover, some very scattered acacia trees or nonvegetated areas, or areas with very little vegetative cover (excluding agricultural fields with no crop cover), where the substrate or soil exposure is clearly apparent
Open acacia bushland	Areas covered in the upper strata with some very scattered Acacia trees up to 20 m in height. The middle and under strata are formed by small Acacia trees, shrubs, and bush plants in which multiple stems and branches are produced from the base of the main stem
Grassland	Areas covered primarily with different grass species, which are used as a natural pasture, or with other small herbaceous plants. Usually, trees, shrubs and bushes are very scattered
P. juliflora land	Areas covered with the invasive species *P. juliflora*, which is an exotic species with dark evergreen leaves and closed canopy cover throughout the year, with an average tree count of more than 100 plants within a 15×15-m^2 area and stands forming a thicket with a minimum height of 3 m

filtering (3×3 filter) of the classified images was conducted to reduce the noise and classification error observed (Lillesand and Kiefer 1999).

The accuracy of the classified images was assessed based on the confusion or error matrix (Campbell 1987), which is a simple cross-tabulation of the mapped class label against that observed in the ground or reference data for a sample of cases. Thus, by interpreting the various false color combinations of images, by making interband comparisons and with the help of other ancillary data, approximately 150 GPS ground control points (18–25 samples for each class) were selected and used in this study.

The kappa coefficient of agreement (Cohen 1960) was one parameter used in these analyses of error/confusion error matrices. Accordingly, the LULC classification of this study yielded kappa coefficients of 75.80, 80.40, 80.52, and 81.05 % for the classification of images for the years 1973, 1987, 1999, and 2004, respectively. The overall accuracy of the LULC map for the four respective years was estimated to be 86.68, 90.71, 91.09, and 92.14 %.

Change detection based on land use/land cover classification The classified images were vectorized in ArcGIS and saved as shape files, from which areas of each LULC class were computed using the automated area computation function. The LULC change detection was assessed using the image differencing algorithm, which describes the total net change between the two time-series images. Then, based on the area computed from all the study years, the changes in area of each land use were computed as positive or negative, corresponding to an increase or decrease in area, respectively, within a class. Finally, the annual rate of change for each LULC class, including *P. juliflora*, was calculated for the periods 1973–1987, 1987–1999, 1999–2004, and 1973–2004 by dividing the change in area of each LULC during each period by the number of years corresponding to the study periods.

Socioeconomic survey and data analysis

Socioeconomic data on causes, impacts, and control measures of *P. juliflora* invasion were collected from both primary and secondary sources. The primary data were collected from structured interviews, focus group discussions, key informant interviews, and field surveys.

A total of six focus group discussions comprising six to eight members each (two to four clan leaders, two key informants, one women representative, and one youth representative) were conducted. There were also discussions with the management committee of the Charcoal Makers and Pod Collectors cooperatives, established by

FARM-Africa (a British-based nongovernmental organization) to promote *P. juliflora* control though the maximization of its utilization in each kebele (the smallest administrative unit of Ethiopia similar to a ward). The key informants included local elders, religious leaders, development agents, and experts from the district agricultural office, as well as staff members of FARM-Africa, ABA, WARC, Awash State Farm, and the local health center. The interview with the key informants focused on the invasion status, impacts, and management strategies of *P. juliflora* invasion.

The structured interview was administered to 120 household heads selected from a total of 1,502 households on the basis of stratified random sampling. This sample group represented the different kebeles from the three main occupation groups [pastoralists (n=72), agro-pastoralists (n=30), and charcoal makers (n=18)]. Among the 120 household heads who participated in the survey, 68 (56.7 %) were illiterate, 8 (6.7 %) were only able to read and write, 14 (11.7 %) had been to Koran school, 26 (21.7 %) had attended school up to grades 6, and 4 (3.3 %) had attended school beyond grade 6. Finally, the data that were obtained from the focus group discussions, key informant interviews, and field observations were analyzed using qualitative methods. The quantitative data collected through the household surveys were analyzed using simple descriptive statistics, such as percentages, frequencies, and means, in the Statistical Package for Social Science version 13.

Results and discussion

Land use/land cover change detection

Figure 3a–ds show the LULC maps for the years 1973, 1987, 1999, and 2004, for which the corresponding area extent and net change detection results for each LULC class are presented in Table 2. Moreover, the rate of change for each LULC and the conversions among the different LULCs were analyzed for the periods 1973–1987, 1987–1999, 1999–2004, and 1973–2004 (Table 2).

The cropland in 1973 covered an area of 44.22 km^2. This area almost tripled (109.58 km^2) by 1987 and further increased to 133.93 km^2 in 1999, from which it remained almost unchanged until 2004. Wetlands represented the smallest area proportion among the different LULC classes in all of the study years. In 1973, the wetland coverage was 24.08 km^2. The area had more than doubled (57.07 km^2) by 1987, decreased to 43.29 km^2 by 1999, and again slightly increased to 46.76 km^2 by 2004. The extent of bare land in 1973 was 71.06 km^2, and thereafter, it showed subsequent decrements to 44.74 km^2 in 1987, 37.39 km^2 in 1999, and 39.07 km^2 in 2004. The open acacia bushland had the second highest area coverage of all the other LULC classes, namely, 134.03 km^2, in 1973. However, this had sharply decreased to 57.58 km^2 by 1987, 48.47 km^2 by 1999, and 29.33 km^2 by 2004. Grassland was the most abundant and also the most dynamic LULC class in the study area in all study periods. However, the extent of grassland had significantly decreased from 254.56 km^2 in 1973 to 180.36 km^2 in 1987 and again exhibited slight decreases to 176.36 and 171.36 km^2 in 1999 and 2004, respectively. *P. juliflora* was detected for the first time in the 1987 image, where it covered a total area of 78.56 km^2; subsequent increases to 88.10 and 107.86 km^2 were observed in 1999 and 2004, respectively. This satellite image-based analysis for *P. juliflora* also provides indirect evidence that the tree was introduced in the period 1973–1987. Thus, this justifies the effectiveness of the use of medium-resolution remotely sensed data sources, such as Landsat, for monitoring the dynamics of invasive tree species in a rapid, inexpensive manner.

During 1973–1987, the *P. juliflora* coverage area exhibited the largest increase, increasing by 5.61 km^2/annum, followed by cropland (4.67 km^2/annum) and wetlands (2.38 km^2/annum). In contrast, the open acacia bushland and grassland areas showed decreases of the same orders of magnitude (5.46 and 5.30 km^2/annum, respectively), followed by bare land (1.88 km^2/annum). The period 1987–1999 was when a relatively lower net area change was observed across the different LULC classes compared with the other two study periods. Cropland and *P. juliflora* coverage areas increased by 2.03 and 0.79 km^2/annum, respectively, whereas the remaining LULC classes showed decreases in area ranging from 0.30 km^2/annum (grassland) to 1.15 km^2/annum (wetlands). In the period 1999–2004, *P. juliflora* again showed the highest increase in coverage area of 3.95 km^2/annum; in contrast, open acacia bushland area exhibited the largest decrease of 3.83 km^2/annum. During this period, the cropland area started to decrease slightly (0.08 km^2/annum), whereas the wetland and bushland areas showed slight increases of 0.69 and 0.34 km^2/annum, respectively. The overall change detection assessment for the entire study period (1973–2004) shows that area

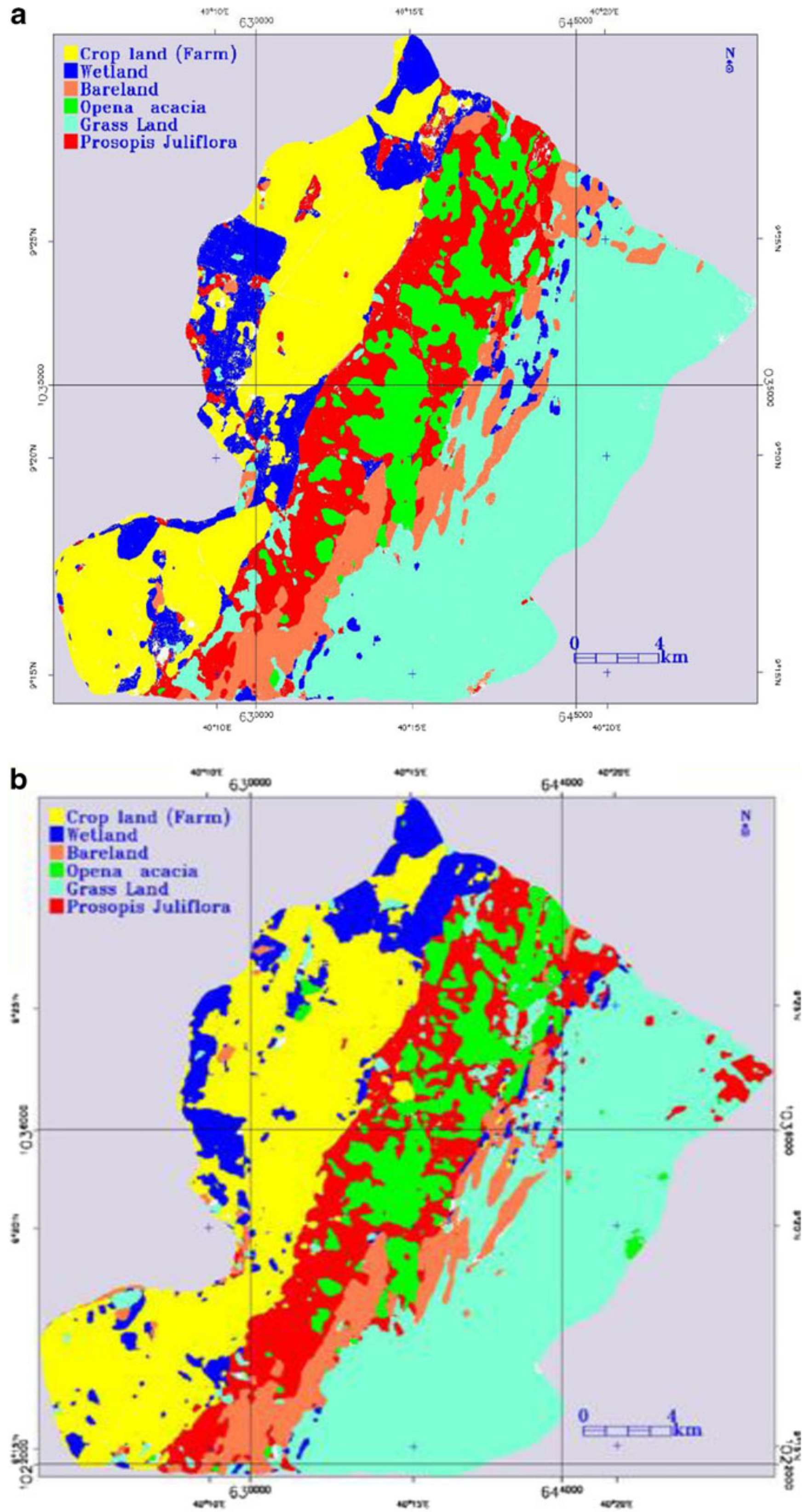

Fig. 3 Land use/land cover map of the study area for the four study years: **a** 1973, **b** 1987, **c** 1999, and **d** 2004

Fig. 3 (continued)

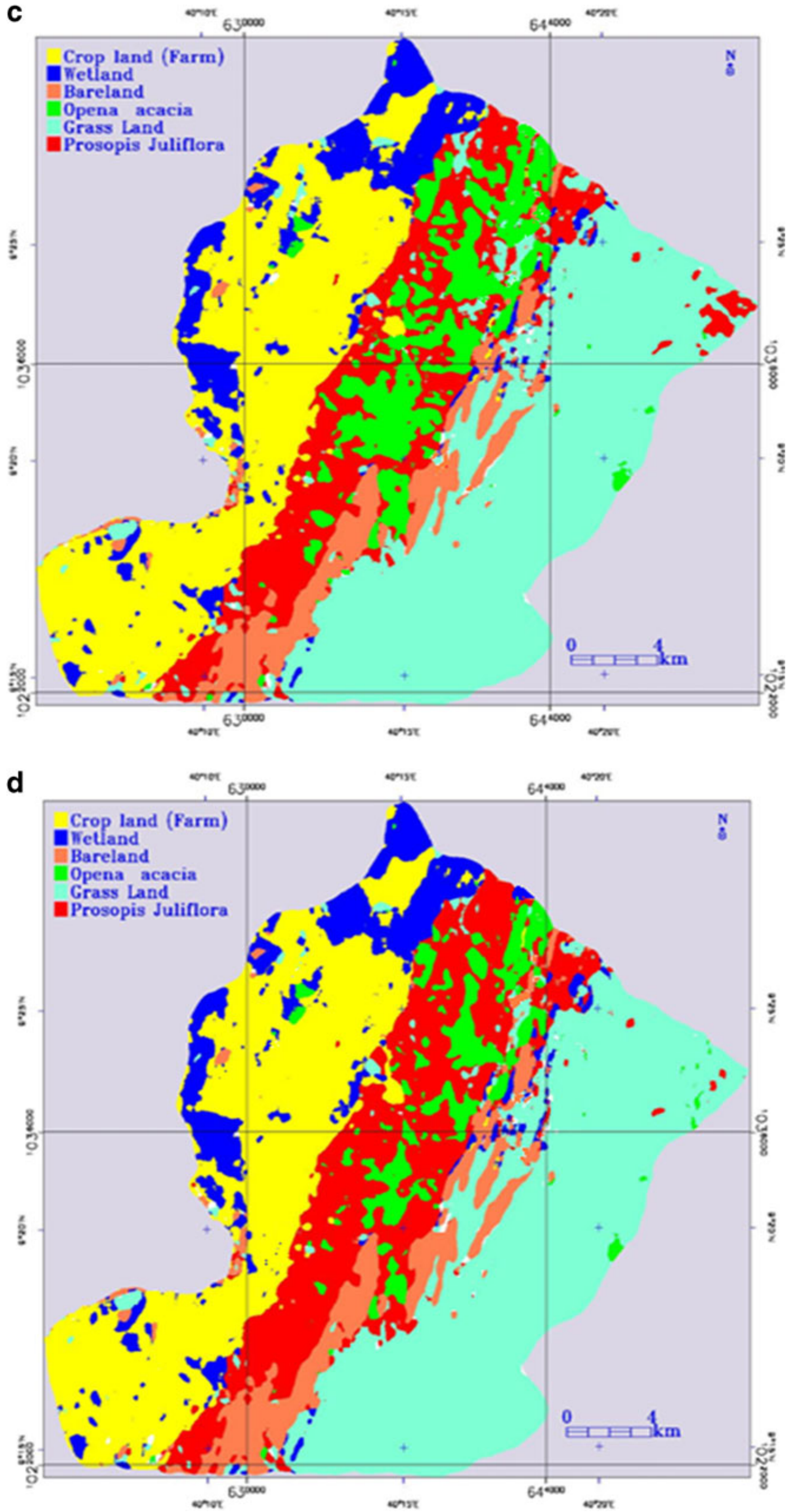

Table 2 LULC classes, their corresponding areas and the area changes from 1973 to 2004 in Amibara District, Afar Regional State, Eastern Ethiopia

LULC classes	1973 (km^2)	1987 (km^2)	1999 (km^2)	2004 (km^2)	1973–1987 (km^2/annum)	1987–1999 (km^2/annum)	1999–2004 (km^2/annum)	1973–2004 (km^2/annum)
Cropland	44.22	109.58	133.93	133.52	4.67	2.03	−0.08	2.88
Wetland	24.08	57.07	43.29	46.76	2.36	−1.15	0.69	0.73
Bare land	71.06	44.74	37.39	39.07	−1.88	−0.61	0.34	−1.03
Open acacia bushland	134.03	57.58	48.47	29.33	−5.46	−0.76	−3.83	−3.38
Grassland	254.5	180.36	176.72	171.36	−5.30	−0.30	−1.07	−2.68
Area covered by *P. juliflora*	0.00	78.56	88.10	107.86	5.61	0.79	3.95	3.48
Total	527.90	527.90	527.90	527.90	0.00	0.00	0.00	0.00

covered by *P. juliflora* and croplands expanded at the expense of open acacia and grassland areas. During this period, the *P. juliflora* coverage area increased from nil to 107.86 km^2 (i.e., 107.80 km^2 in the district had been invaded by *P. juliflora* at an average annual invasion rate of 3.45 km^2/annum). Our field survey indicated that the slight decrease in *P. juliflora* invasion during the period between 1987 and 1999 may be attributed to the mass clearance of *P. juliflora* by campaign through the involvement of the community and the expansion of state and investor farms in the district (see "Management of *P. juliflora* invasion"). Moreover, the imagery analysis indicated that grasslands, open acacia bushland, and bare land were the classes most affected by the encroachment of *P. juliflora*. This result has implications regarding the identification of the priority areas and the design of management strategies for the uncontrolled invasion of the species.

The results of this study are in agreement with the work by Mesele et al. (2006), who reported that LULC change in the Borana Plateau, Southern Ethiopia, is caused by invasive bush encroachment and cropland expansion. Similar studies in the Northern Cape Province of South Africa by Versfeld et al. (1998) revealed an 18 % per annum invasion by *P. juliflora*.

Finally, it was possible to predict the invasion rate of *P. juliflora* based on the average annual rates of change observed during the periods 1973–1987, 1987–1999, and 1999–2004. The results reveal that the area covered by *P. juliflora* could increase to 145.81 km^2 (27.62 %) and further to 163.06 km^2 (30.89 %) by the years 2015 and 2020, respectively. This suggests the need for immediate implementation of effective control management interventions.

Causes of *P. juliflora* expansion

One hundred percent of the pastoralists and agro-pastoralists and 66.7 % of the charcoal makers believed livestock droppings to be the main dispersal agent for *P. juliflora* seeds. Moreover, the types of animals that substantially contribute to the invasion, based on the focus group discussions and the key informant interviews, include cattle, goats, camels, donkeys, and sheep. According to Shiferaw et al. (2004), the number of seeds recovered from 1 kg of droppings of each animal under study (goats, camels, and cattle) ranged from 760 (goats) to 2,833 (cattle). Moreover, livestock traveling approximately 15 km/day, as is the case in many nomadic areas, would transport *P. juliflora* seeds in their digestive tracts more than 100 km/week. These data suggest that cattle are the major dispersers of *P. juliflora* seeds.

Heady and Child (1994) identified the role of livestock, deer, rabbits, and rodents in the dispersal of the *P. juliflora* seeds in semiarid and arid ecosystems. The high germination capacity of *P. juliflora* seeds under considerable moisture stress (as low as 50 mm annual rainfall) and across broad temperature ranges (20–40 °C) help the tree to continue expanding its propagation range (Hilu et al. 1982). For instance, a study by Shiferaw et al. (2004) showed that seeds that are treated with hot water or acid germinate better than untreated seeds. Seeds retained within intact pods can remain viable for up to 40 years, but exposed seeds dry out or decay more rapidly (Cronk and Fuller 2001).

P. juliflora also coppices readily and produces copious amounts of seeds in its introduced range. This high pod production and the readily consumption of the pods by livestock mean that *P. juliflora* has the ability to spread extremely rapidly, especially in its introduced range. Seed production is estimated at 630,000–980,000 seeds per mature tree per year (Harding 1987). The seeds typically germinate in soils at depths of 1–2 cm. At the seedling stage, the root/shoot growth ratio can be as high as 10. The mature trees bear fruits after 3–4 years.

Witt (2010) also highlighted the role of climate change in exacerbating the expansion of invasive species. Invading plants, such as *P. juliflora* species, respond positively to elevated levels of CO_2. Extreme weather events and disturbance regimes are likely to increase in frequency and intensity as a result of climate change, which will render many ecosystems more susceptible to invasion (Kriticos and Filmer 2007).

Impacts of *P. juliflora*

The majority (86 %) of the survey respondents identified negative impacts of *P. juliflora* on their livelihoods, yet only the charcoal makers appreciated its potential for sustainable livelihood development. Across all occupation groups, the respondents noted some positive impacts of *P. juliflora*, primarily in relation to land rehabilitation. In order of importance, the respondents of all occupation groups stated that the expansion of *P. juliflora* could decrease wind speed (60 %), improve micro-climates in the form of shading (20 %), aid in the reclamation of saline land (15 %), and reduce soil erosion and improve soil fertility (5 %), whereas the most noticeable negative impacts identified include biodiversity loss, human health risks, and livestock productivity loss. Among the identified existing and potential contributions of *P. juliflora* to their livelihoods are its use as fuel wood, animal fodder, and construction materials.

Impacts on biodiversity

According to the survey and focus group discussion, 100 % of the pastoralists, 96.7 % of the agro-pastoralists, and 40 % of the charcoal makers agreed on the negative impacts of *P. juliflora* invasion on the biodiversity of the district. Several plant species have been endangered in areas invaded by *P. juliflora* and many useful grass species that were once found in Amibara District, including Durfu (*Chrysopogon plumulosus* Hochst) and Isisu [*Cymbopogon schoenanthus* (*L.*) Spreng], are now on the verge of extinction. Studies show that its allelophatic characteristics inhabit germination, growth, and survival of other species (e.g., Warrage and Al-Humaid 1998).

Impacts on human health

The expansion of *P. juliflora* has brought associated health problems to the local community. Based on the 2008 records obtained from the Amibara Health Center, the incidence of *P. juliflora*-associated health risks in the district was rated on the basis of frequency of occurrence. Accordingly, leg and hand infections and soft tissue infections were the most frequently (>5 cases/month) recorded diseases. Other diseases, such as cellulitis, upper and lower respiratory tract infections, and blindness, have been reported to occur occasionally (<5 cases/month). Upon penetration of the eye or skin of humans and animals, the thorn of *P. juliflora* causes more inflammation than would be expected based on the physical injury. An injury from the thorn of this species does not heal easily despite the use of intensive medical treatments (personal communication with the pastoralists). This irritation may be due to waxes in the thrones (Sharma 1981). Burning the wood in a fireplace can also cause dermatitis (Duke 1983, cited in Shiferaw et al. 2004).

Impacts on livestock production

All of the respondents in the three occupation groups believed that the invasion of *P. juliflora* has a variety of negative impacts on livestock production, such as causing the loss of wild animals and grazing land and creating health risks.

According to the focus group discussions and the key informant interviews, several wild animals, including Bieyda (*Oryx gazelle*), Goroia (*Struthio camelus*), Da'ema (*Equus grevyi*), Segerie (*Madoqua saltiana*), and Goroja (*Kobus ellipsiprymnus*), have already migrated to other areas because they were unable to acquire access to feed or move around freely because of the dense thicket of *P. juliflora*.

P. juliflora invasion is also directly responsible for the alterations of resource use and patterns of mobility of the pastoralists. As a result of the significant loss of prime fertile grazing land following the invasion of *P. juliflora*, the rotational grazing (traditional patterns of mobility) system, which played a significant role in supporting the maintenance of the environment and biodiversity, has been significantly altered. For instance, the pastoralists previously practiced seasonal mobility during the wet and dry seasons to the Alleideghi Plains and the flood plains of Awash River to gain better water access and sustainable utilization of grazing lands. However, at present, due to *P. juliflora* invasion, this traditional management system is no longer being practiced. Currently, the pastoralists use the pasture beyond its carrying capacity and then move to other areas.

As a result, the livestock are now confined to marginal grazing areas, which cannot support them throughout the year. This overstocking, according to the respondents, leads to overgrazing, which in turn causes land degradation, the loss of palatable perennial grasses in favor of annual and less palatable species, seed bank disturbance, the retardation or elimination of the natural regeneration of native vegetation, compaction of soil, and loss of productivity of the land, all of which lead to the eventual decline in the capacity of the range land to support livestock.

The shrinkage of pasture land has also been cited as a major cause of ever increasing intra- and intertribal conflicts. Approximately 91.7 % of pastoralists believe that the increasing incidence of conflict between the Afar clans and neighboring tribes is primarily associated with the shrinkage of pastureland following the ever increasing invasion *P. juliflora*.

The expansion of *P. juliflora* has yielded negative impacts on livestock health as well. All of the respondents in the three occupation groups believed that *P. juliflora* has negative impacts on livestock health. According to the district's veterinary expert, livestock often sustain injury from *P. juliflora* thorns while attempting to move freely, which can lead to secondary infections and eventual death. The focus group discussions indicated that animals also develop dental problems when they feed on the pods for extensive periods. Such animals become emaciated and eventually die.

The available reports on *P. juliflora* toxicity to cattle vary. According to reports by local Afar pastoralists, the long-term ingestion of the pod will result in the death of cattle. Stomach poisoning by the pod may induce permanent impairment in the ability to digest cellulose. This impairment may be due to the high sugar content of the pod, which depresses the rumen bacterial cellulose activity and eventually kills the animal.

This conclusion is supported by other findings that the high sugar content in the seed causes goat teeth to decay and inhibits the rumen bacterial cellulase activity, which in turn causes the formation of a compacted pod ball in the stomach (Nakano et al. 2001; Shiferaw et al. 2004). *P. juliflora* leaves fed to goats were reported to suppress rumen microbes and increase the levels of ammonia in the rumen and urea in the blood (Pasiecznik et al. 2001). Furthermore, upon the slaughtering of livestock, pastoralists have found germinated *P. juliflora* seeds in the stomachs of livestock. Local elders indicated that the number of cattle killed by *P. juliflora* is larger than the number of cattle killed by drought. If timely intervention is not taken, *P. juliflora* has the potential to eliminate pastoralism from the district in the near future. Dense thickets of *P. juliflora* also provide comfortable shelter for populations of predators, such as hyenas, foxes, lions, snakes, and leopards, which kill both livestock and warthogs, damage crops, and attack the local community.

The impact of all of these effects is that the overall herd productivity is presently lower than it was in the past. As a result of all of these changes, some pastoralists have chosen alternative means of securing their livelihoods by transforming their farming system to small-scale farming through the clearing of areas invaded by *P. juliflora*, which open up opportunities to small-scale management of *P. juliflora* invasion.

Management of *P. juliflora* invasion

One hundred percent of the pastoralists and agro-pastoralists called for the complete eradication of *P. juliflora* because they believed that, under the current management system, the disadvantages of the tree outweigh the advantages. This view is clear in the following reflection of an 80-year-old pastoralist community member from Serkamo Village:

> "We know the benefits and hazardous problems of P. juliflora. Our people are exclusively dependent on animals, and the plant suppresses the growth of other plants, which our animals live on. As a result, we lost a significant number of our cattle. For instance, I myself had approximately 200 animals previously; today, I have only 35 animals. We are facing great difficulty in grazing our animals. P. juliflora causes hunger and poverty in the Afar community; we have been invaded and have lost all of our livestock, grazing and homestead land, as well as our routes and feeder roads, by this enemy. The community has lost hope and has become desperate to eradicate this plant. Unfortunately, it has become beyond our control. Therefore, from the Afarians perspective, we urge all the concerned bodies to help us in the complete eradication of P. juliflora from our land."

In contrast, 100 % of charcoal makers did not want *P. juliflora* to be eradicated because their livelihood is completely dependent on its products in the form of charcoal production.

Therefore, it is widely perceived that proper management of the species may improve its characteristics and reduce its negative impacts. In the study area, different physical/mechanical management techniques have been implemented by individual community members, cooperatives, and a commercial farm/authority. The measures that have been implemented primarily by individual community members with limited or no external support include clear cutting, burning, and the uprooting of young seedlings. The cooperatives were engaged in managing *P. juliflora* by maximizing the utilization of this species, such as for making charcoal from its wood and animal feed from its pods, whereas the commercial farms primarily conducted regular clearing using bulldozers and/or manual labor.

The information obtained from the respondents clearly shows that clear cutting without digging out the root system further aggravates the invasion of *P. juliflora* by stimulating the germination of seeds in the soil and the formation of coppices from stumps. The local elders described the cutting technique in this way: "Cutting of *P. juliflora* means hoeing it or making it aggressive and inviting it to produce more shoots instead of eradicating it." Similarly, burning would have other associated negative impacts on local biodiversity, as it leads to the indiscriminate burning of other important tree and grass species and soil microorganisms. Seedling uprooting is often practiced during wet periods when the soil is loosened, and the respondents believed that this measure could significantly reduce the invasion of this species, particularly when applied to the young seedlings. Moreover, they realized that controlling the *P. juliflora* invasion though seedling uprooting is not a one-time task because so many seeds are found in the soil seed bank. These seeds germinate whenever they are moistened. Thus, control strategies have to be designed and implemented on both a regular and long-term basis, which requires labor, time, and coordination.

In some localities, the communities established local bylaws to compel members of the community to uproot the seedlings wherever they occur; however, these efforts were found to be unsuccessful primarily because the bylaws have no legal or political recognition and, thus, have no power to levy sanctions on the community members. Moreover, there is a lack of clear working guidelines and strategies from the local or central governments that precludes the effective implementation and evaluation of these measures.

Managing *P. juliflora* at the community level is generally found to be laborious and requires strong community commitment and participation and the formulation and enforcement of bylaws. Thus, it first requires increasing of community awareness and commitment to the management of *P. juliflora* using appropriate channels. For instance, experience gained from the Ethiopian Pastoralists Forum advises the use of traditional leadership structures to facilitate the introduction of appropriate interventions, such as *P. juliflora* management, in the pastoral system. Therefore, indigenous knowledge and practices regarding the protection and mitigation of the impact of *P. juliflora* in the study area can very well be integrated with the traditional natural resource management practices and institutions, such as "Kello," "Edo," and "Fayima." Moreover, "Dagu," the Afar indigenous system of information sharing and dissemination, can be used for awareness raising/sensitization and for the dissemination of technologies. Studies from other parts of the world show that eradication is a management goal for weeds that is often prescribed but seldom achieved (Hester et al. 2004) for two main reasons: Seeds are not detectable until they germinate, and seeds can survive in the soil for a long time (Cacho et al. 2008).

Maximizing the utilization of *P. juliflora* products has been implemented as one management option to control the invasion and to develop the reclaimed area through the organization of the community into cooperatives. To achieve this goal, two types of local cooperatives have been established with the help of FARM-Africa. The first cooperative targeted the clearing and digging out of the roots of mature trees to a depth of 10–30 cm below the ground surface and the utilization of the product for charcoal and fuel wood production, followed by the implementation of reclamation measures, such as cultivation with agricultural crops and fodder grasses. The objective of the second cooperative was to minimize the dispersion of P. *juliflora* seeds through pod collection and crushing for animal feed purposes with a crushing machine and training supplied by FARM-Africa.

For the first type of cooperative, where *P. juliflora* trees were cleared in a few sites, the stumps were properly removed up to 10–30 cm below ground, and the sites were restored to farmland. As a result, the invasion was significantly reduced, and at the same time, the cooperative benefited from the charcoal revenue. However, seeking to gain similar benefits as the cooperatives, unauthorized individuals engaged in the production and marketing of charcoal by crossing local boundaries to harvest *P. juliflora*, which became a source of conflict in some areas, leaving uncleared stumps in some places that formed thickets due to the high coppicing ability of *P. juliflora* and further worsening the effects of the invasion (Fig. 4). According to the Afar Pastoralists Association (PCDP 2005), the introduction of charcoal making as a means of controlling *P. juliflora* is quickly robbing the region of its remaining forest cover.

The minimization of *P. juliflora* dispersion through the collection and crushing of pods by organized cooperatives was unsuccessful. According to the field staff of FARM-Africa, the idea of pod crushing was not well adopted by the cooperatives, mainly because of the lack of a good market for the pod feed. In the study area in particular, there is no culture of fodder purchasing. In addition, the community complained of the problem of thorns while collecting pods in areas where *P. juliflora* formed impenetrable thickets. As a result, those cooperative members who were engaged in pod collection and crushing abandoned the project and switched to charcoal marketing. Similar studies conducted in South Africa reported that the costs of harvesting and processing pods for animal feed made it an unattractive proposition on the scale that is required.

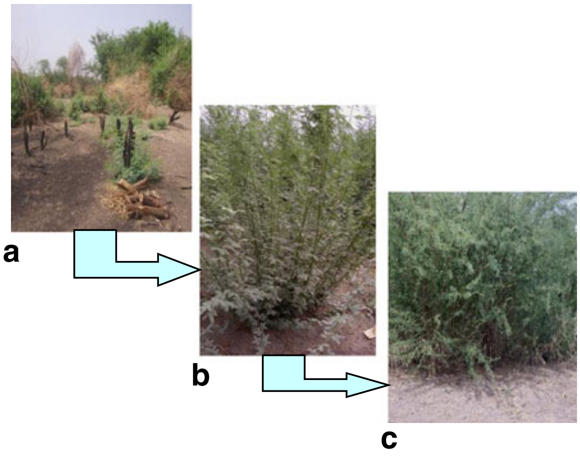

Fig. 4 Photographs showing the conditions before stumps of *P. juliflora* were removed (**a**) and coppices emerging and forming thickets after stumps were removed (**b**, **c**) in Amibara district. Areas where stumps were abandoned after the harvesting of the trees for charcoal production were severely invaded by coppices emerging from the stumps to form impenetrable thickets, which worsened the effects of the invasion

The market opportunity for ground pods may improve in the future for such cooperatives, as the pods are important feed sources as reported elsewhere. Studies show that crushed pods have high feed value (Varshney 1996, cited in Mwangi and Swallow 2005). Moreover, Geesing et al. (2004) indicated that crushing causes the protein in the seeds to be more available, and at the same time, destroying the seeds prevents the germination of new plants and thus contributes to the containment of the *P. juliflora* invasion. Therefore, a strong promotion and creation of awareness of the significance of pods as an alternative feed source and the exploration of market opportunities both within and outside of the study region could help improve the adoptability of the management intervention.

The clearing of *P. juliflora* using bulldozers and/or human labor and the burning of *P. juliflora* in farmlands, roadsides, and irrigation and drainage canals have been completed by the ABA. The authority has been clearing *P. juliflora* regularly over 36-km lengths of irrigation and drainage canals using bulldozers (1995–2002) at a cost of Ethiopian Birr (ETB) 188,100 per year in 2002. The use of bulldozers became expensive to the authority; as a result, the authority switched to using human labor (2002 to present), which helped reduce the cost to ETB 54,000 per year in 2008. At a larger scale, such as in the entire district, our assessment revealed that the cost of clearing, even using local labor, is unaffordable to the local government or other nongovernmental development organizations operating in the region.

In addition to the above-mentioned techniques, ABA and large commercial farms applied limited silvicultural measures for the mapping of *P. juliflora* invasion, primarily limited to roadside areas and areas near the office (Fig. 5). The key informant interviews with the staff from ABA, confirmed by field observations, indicated that thinning followed by pruning enhanced bole formation and provided the trees with good structures. Under this management, *P. juliflora* does not form thickets but encourages undergrowth, which allows people to move freely and opens up space between plants, creating easy access to harvest pods and other parts of the plant. This is in agreement with the work by Pasiecznik et al. (2001), who

Fig. 5 Silvicultural measures for *P. juliflora* management; *P. juliflora* trees along the roadside near the Awash Basin Authority office in Amibara that have been pruned, providing the trees with a good structure (*left*), and pruned stands of *P. juliflora* at Amibara distrcit, favoring better understory growth (*right*)

reported that pruning appears to be the single most important technique for improving tree and understory yields; weedy shrubs are turned into valuable, productive trees by the removal of side branches. Pasiecznik (2002) and Jorn (2007) also added that pruning causes the standing tree to further concentrate its annual growth more to the vertical woody bole than to the small, heavily thorny horizontal branches near the ground. This allows the tree to form the desired crown shape and structure. Through this approach, the species became more suitable for and even compatible with urban environments and urban forestry, as well as enhanced the aesthetic properties of these environments.

Conclusions

A significant land use change and conversion occurred in the study area during the period 1973–2004. The cultivated land and area covered by *P. juliflora* have expanded at the expense of grazing and open acacia bushland. *P. juliflora* in particular has become more threatening in recent years as the mechanism of expansion has begun to take different forms, and by 2020, approximately 30.89 % of the study area will be covered by *P. juliflora*. This high invasion rate will have far-reaching consequences on local biodiversity and the livelihoods of the pastoralist community through the loss of grazing land for their livestock and the presence of health-related risks to both humans and animals.

Thus, there is a general understanding by the majority of the pastoralists that this tree species needs to be eradicated if it is not contained. For this purpose, small-scale control and management interventions have been implemented both on an individual basis and through the organization of cooperatives with little external support. However, these efforts have been unable to achieve the intended result, as they have been limited to small spatial scales and improperly implemented with little follow-up and little participation of the local indigenous institutions. Moreover, the dispersal by cattle causes the control of the expansion to be more difficult in such pastoralist areas.

Therefore, a number of possible considerations can be taken to, at a minimum, contain the expansion of *P. juliflora* to new areas: (1) the formulation of clear policies and strategies regarding the management approach; (2) the engagement of the community through the use of traditional natural resource management practices and institutions, such as "Kello," "Edo," and "Fayima"; (3) the introduction of more effective and feasible measures that can be applicable at larger scales; and (4) the limiting of the number of vector animals under the framework of the villagization program that the Ethiopian government is currently implementing. The government of Ethiopia wants to group its 1.5 million scattered seminomadic people into permanent settlements on a voluntary basis within a region of their origin, largely ending a mobile lifestyle that has sustained the people for centuries. This program, if fully implemented, will eventually transform the pastoralists into a more diversified mixed farming system confined to a much smaller area. This transformation in turn will lead to a reduction in both the number of livestock owned and the distance covered by each animal in search of food. In this way, seed dispersion by livestock could be significantly reduced.

Furthermore, for similar interventions in the future, if a nonnative species has been recommended for introduction, it is considered wise to first conduct a weed risk assessment, such as the one suggested by Pheloung et al. (1999), to determine whether the species has the potential to become problematic in the future.

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