Satellite image based quantification of invasion and patch dynamics of mesquite (*Prosopis juliflora*) in Great Rann of Kachchh, Kachchh Biosphere Reserve, Gujarat, India

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The invasion of alien species is a significant threat to global biodiversity and the top driver of climate change. The present study was conducted in the Great Rann of Kachchh, part of Kachchh Biosphere Reserve, Gujarat, India, which has been severely affected by invasion of *Prosopis juliflora*. The invasive weed infestation has been identified using multi-temporal remote sensing datasets of 1977, 1990, 1999, 2005 and 2011. Spatial analyses of the transition matrix, extent of invasive colonies, patchiness, coalescence and rate of spread were carried out. During the study period of three and half decades, almost 295 km^2 of the natural land cover was converted into *Prosopis* cover. This study has shown an increment of 42.9% of area under *Prosopis* cover in the Great Rann of Kachchh, part of the Kachchh Biosphere Reserve during 1977 to 2011. Spatial analysis indicates high occupancy of *Prosopis* cover with most of the invasion (95.9%) occurring in the grasslands and only 4.1% in other land cover types. The process of *Prosopis* invasion shows high patch initiation, followed by coalescence, indicating aggressive colonization of species. The number of patches within an area of < 1 km^2 increased from 1977 to 2011, indicating the formation of new *Prosopis* habitats by replacing the grasslands. The largest patch of *Prosopis* cover increased from 144 km^2 in 1977 to 430 km^2 in 2011. The estimated mean patch size was 7.8 km^2 in 1977. The mean patch size was largest during 2011, i.e., 9 km^2. The annual spread rate for *Prosopis* has been estimated as 2.1% during 2005–2011. The present work has investigated the long term changes in *Prosopis* cover in the Great Rann of Kachchh, part of Kachchh Biosphere Reserve. The spatial database generated will be useful in preparing strategies for the management of *Prosopis juliflora*.

1. Introduction

Historical changes in land surface have impacted several aspects of ecosystems, resulting in climate change, biodiversity loss and fluctuation of biogeochemical and hydrological cycles (Mitsuda and Ito 2011). The biological invasion of alien species is recognized as the most serious threat to biodiversity and the top driver of global climate change (Mooney and Drake 1987; Reddy 2008). The spatial information is considered necessary to develop policies aimed at invasive species management (Wittenberg and Cock 2001). There is an increasing attention on analysis of invasive species occurrence and distribution at the landscape level, at which spatial and temporal patterns of invasion can be linked to proximate causes, the rate of spread and the effectiveness of management practices (Robinson *et al.* 2008).

Keywords. *Prosopis juliflora*; mesquite; invasion; patch; coalescence; Kachchh; India.

Remote sensing offers a cost effective means to study vegetation cover changes (Langley *et al.* 2001; Reddy *et al.* 2007). Because of the systematic observations at various scales, remote sensing extends possible data archives from present time to over few decades back (Xie *et al.* 2008). The efficacy of remote sensing data for detecting invasive plants depends on the sensor's spatial and spectral resolution. Accurate vegetation classification from a multispectral image is dependent on the degree of spectral reflectance by a range of factors including leaf chemistry, canopy structure and density (Lymburner *et al.* 2000). Satellite imagery offers the ability to efficiently map canopy dominating invasive woody species, which have reflectance characteristics that are distinct from other vegetation (Lamb and Brown 2001). Of late, there is an increase in the number of studies dealing with the application of remote sensing and GIS in the mapping of invasive species and their distribution and modelling (Joshi *et al.* 2004). However, in India, little effort has been given to map the invasive alien species and areas vulnerable to invasion.

As many as 173 invasive alien plant species have been reported in India (Reddy 2008). *Prosopis juliflora* (Sw.) DC. (syn. *Prosopis chilensis* (Molina) Stuntz) popularly known as 'mesquite' native to Central and South America is now found throughout the semi-arid and arid tropics. *Prosopis juliflora* is a major canopy dominating invasive shrub species in India and has also invaded other regions throughout the world including Saharan and southern Africa, Australia, Middle East, Pakistan and Hawaii where it strongly suppresses species native to those regions, resulting in serious environmental and social costs (Pasiecznik *et al.* 2001; Goslee *et al.* 2003). IUCN has rated *Prosopis juliflora* as one of the world's top 100 invasive alien species (IUCN 2009). It grows in varied types of soils from sandy to saline-alkaline soils. It has proved to be a versatile species for afforesting shifting sand dunes, coastal dunes, river beds, saline-alkaline lands, eroded hill slopes, mine-spoiled areas and other wastelands. *Prosopis juliflora* has now become the main source of fuel in rural areas, fulfilling more than 70% of the firewood requirements of rural people in the tropical arid and semi-arid zones of India. The seed pod is used as a livestock feed and the wood is also used in charcoal making (Muthana and Arora 1983).

The first recorded introduction of *Prosopis juliflora* in India was in 1877 from Latin America, in Cuddapah district of Andhra Pradesh (Reddy 1978). It was introduced into parts of Gujarat in 1882 (FAO 1998). Gujarat State Forest Department initially planted about 315.5 km^2 exclusively of *Prosopis juliflora* as a measure to check the advancement of the Rann during1960–1961. The most abundant distribution of *Prosopis juliflora* is recorded in arid and semi-arid zones of India covering Kachchh region of Gujarat, arid western part of Rajasthan, parts of Uttar Pradesh, Haryana, Maharashtra, Karnataka, Tamil Nadu and Andhra Pradesh (FAO 1998). Champion and Seth (1968) have mentioned that *Prosopis juliflora* is spreading rapidly in Rann of Kachchh, imparting characteristic physiognomy and considered desirable to erect a separate subtype in Rann saline thorn scrub.

Venugopal (1998) has used SPOT multi-temporal data to monitor the infestation of water hyacinth (*Eichhornia crassipes*) using Normalised Difference Vegetation Index. Joshi *et al.* (2004) have reviewed remote sensing techniques to map canopy dominant invasive species and possibilities to map noncanopy invasive species. Anderson *et al.* (1993) mapped *Ericameria austrotexana* infestation in a large homogenous area using Landsat TM imagery. The ability of the Landsat data to map the extent of *Prosopis* in parts of South Africa has demonstrated a high degree (72%) of accuracy (Berg *et al.* 2013). The present study has been carried out in Great Rann of Kachchh region to address spatial dynamics of *Prosopis juliflora* using remote sensing and GIS techniques. The study also aims to address delineation of spatial extent of *Prosopis juliflora* to assess the severity of invasion, patch dynamics and rate of spread using multi-temporal satellite data over three and half decades (1977–2011).

2. Study area

Great Rann of Kachchh region is located in the northwestern, north and northeastern parts of Kachchh mainland – Kachchh district in Gujarat state, India (figure 1). It includes Kachchh Desert Wildlife Sanctuary (total geographical area: 7505.22 km^2) and forms part of Kachchh Biosphere Reserve (total geographical area: 12,454 km^2). The area represents a unique combination of saline deserts (white desert), seasonal wetlands and the eastern part of little Banni. It represents the only area in India where flamingo congregate in enormous numbers to breed and is referred as 'Flamingo city'. The climate is arid and the rainfall extremely erratic and variable in distribution, both in time and space. The total annual rainfall, occurring through southwest monsoon between June and September, is very low with an average of 300 mm per year with a coefficient of variation of 65%. The average maximum temperature is 42°C, the average minimum temperature is about 12°C and average relative humidity is about 25%. However, maximum temperature as high as 50°C and

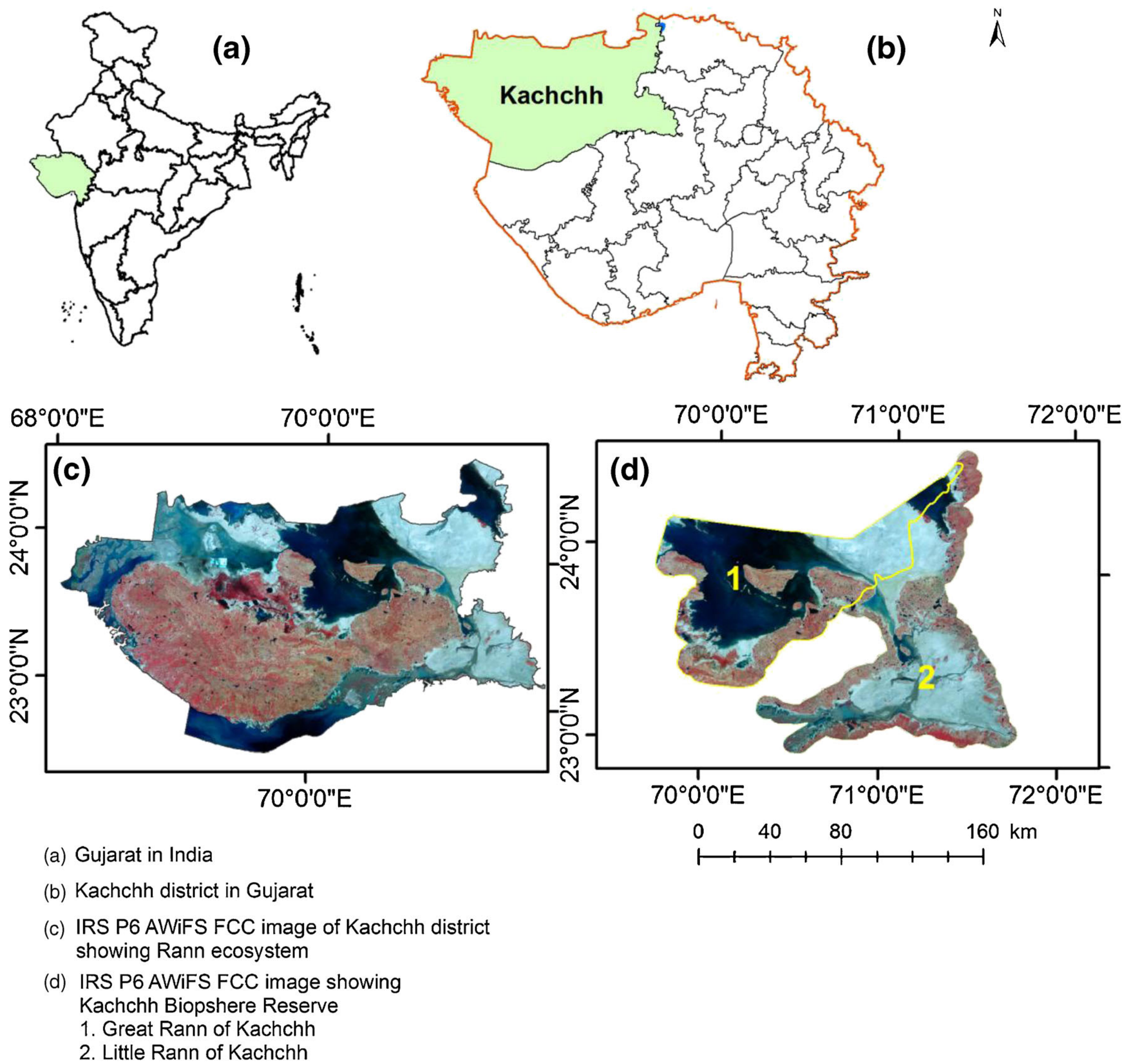

Figure 1. Location map of Great Rann of Kachchh (GRK) in Kachchh Biosphere Reserve, Gujarat, India.

minimum temperature as low as 0°C has also been recorded. The area has the highest rate of evaporation in the country. The Rann may experience unseasonal rains or violent southwest winds at anytime. Topography of Great Rann of Kachchh rises from altitude of 0–458 m. The highest peak in Kachchh is Kalodungar hill at an altitude of 458 m (Anonymous 2005).

3. Data used

The multi-spectral Landsat MSS data of 17 January 1977, Landsat TM of 2 November 1990, Landsat ETM+ of 18 October 1999, IRS P6 LISS-III of 9 October 2005, 26 March 2006 and 18 December 2011 were analysed. Survey of India topographical maps and multi-season IRS P6 AWiFS images of 2005 and 2012 were used as ancillary data.

4. Methodology

Image to image registration was performed using GCPs selected from ortho-rectified Landsat TM data (http://glcf.umd.edu/research/portal/geocover/) using a first order polynomial transformation. Datasets were corrected with a root-mean-square error of <1 pixels for all data. The images were georeferenced to the Universal Transverse Mercator coordinate system and WGS84 datum. To reduce the error due to various atmospheric conditions, Top-of-Atmosphere reflectance was performed on multi-temporal remote sensing datasets (Chavez 1996).

Different land use/land cover categories and areas with infestation of *Prosopis juliflora* cover were surveyed using Global Positioning System during 2012 and 2013. The information collected from the field was entered into a Geographic Information System. The on-screen visual interpretation technique was used to map land use/land cover types on multi-temporal satellite data. In the study area, *Prosopis juliflora* remained evergreen throughout the year, while grasslands and thorn scrub vegetation types showed senescence/deciduousness. *Prosopis* cover shows dark red, brownish red and dark pink tone in the standard false colour composite images depending on its date of acquisition.

Spatial analysis was carried out in three different phases. Phase 1 assesses the total net area under each land cover category. Phase 2 analyses the land cover conversions between categories by change area transition matrix with reference to *Prosopis juliflora*. Phase 3 has identified the spatial tracking of extent of invasive colonies and rate of spread of *Prosopis juliflora* to analyse the impact of invasion. ERDAS Imagine and ArcGIS were used for digital image processing and GIS respectively. Using GIS spatial analyses, *Prosopis* patch dynamics were computed based on mean patch size, largest patch index and patch density. The annual rate of *Prosopis* cover change is derived from the compound interest formula (Puyravaud 2003).

$$r = \frac{1}{(t_2 - t_1)} \times \ln \frac{a_2}{a_1}$$

where r is the annual rate of change (percentage per year), a_1 and a_2 are the area estimates at time t_1 and t_2, respectively.

Quantitative assessment of the accuracy of mapping for *Prosopis* classification and other land covers in the study area was undertaken (Landis and Koch 1977; Congalton and Green 1999). To assess the accuracy of *Prosopis* classification, a total of 300 points were generated randomly on the classified map and verified in the field. It was performed by determining the percentage relationship between *Prosopis* presence observed in the field and that classified based on visual image interpretation technique in an error matrix (confusion matrix). Outline of methodology was presented in figure 2.

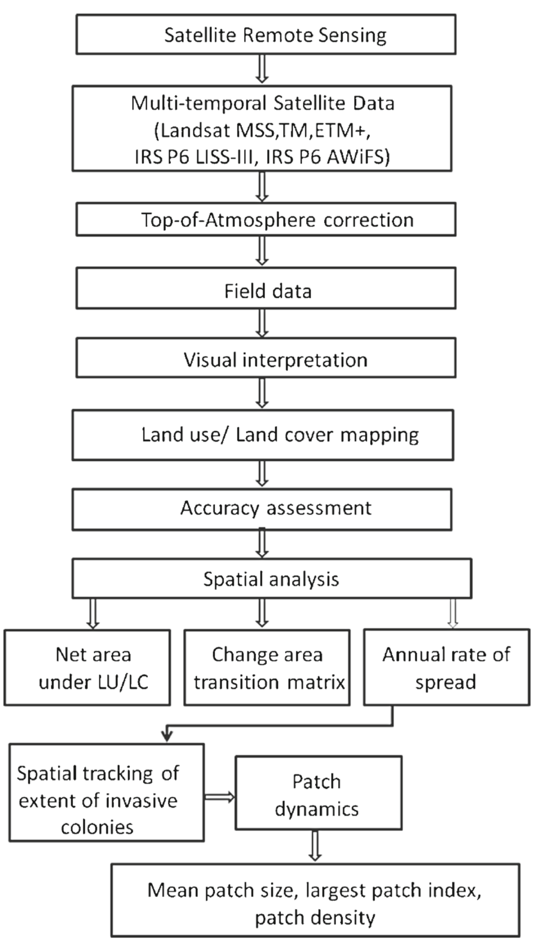

Figure 2. Flow chart showing methodology used in the study.

5. Results and discussion

5.1 *Quantification of Prosopis spread*

Seven land cover types identified in the study were analysed and the area statistics was derived from classified maps (figure 3). The area under study is predominantly a wetland which occupies 2/3rd of total geographical area of Great Rann of Kachchh in Kachchh Biosphere Reserve. Thorn scrub is mixed type represented by *Euphorbia caducifolia, Capparis decidua, Grewia tenax, Commiphora wightii, Salvadora oleoides* and *Mimosa hamata*. *Prosopis* scrub is a gregarious type and mainly constitutes *Prosopis juliflora* as the canopy dominating species. The results confirm that land cover in the Great Rann of Kachchh, Kachchh Biosphere Reserve has changed significantly since 1977 with grassland being transformed to *Prosopis* scrub. *Prosopis* invasion follows a process of high patch initiation, followed by coalescence, rate of spread with the maximum quantity of recruitment and coalescence. It has formed mono-specific thickets in the grasslands. Coalescence of *Prosopis* cover has increased in the study area since 1977 (figure 4; table 1). Analysis indicates increase of 42.9% of area under *Prosopis* cover during 1977–2011.

During the period of analysis (1977–2011), almost 295 km^2 of the natural land cover has been converted to *Prosopis* cover (figures 4 and 5). Spatial analysis indicates that *Prosopis* cover was highly dispersed with most of the invasion (95.9%)

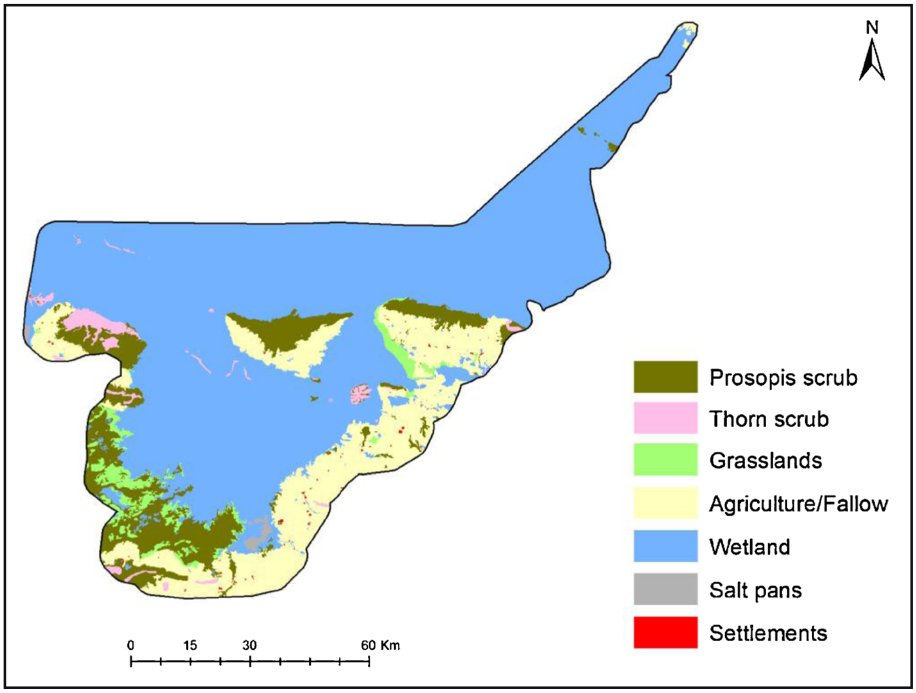

Figure 3. Classified map showing distribution of land use/land cover (LU/LC) in Great Rann of Kachchh, Kachchh Biosphere Reserve: 2011.

occurring in the grasslands and only 4.1% outside of grasslands. About 56.3% area of grassland was reduced during 1977 to 2011 (figure 6). Table 2 clearly indicates rapid spread of *Prosopis* cover in the Kachcch landscape preferring grasslands rather than thorn scrub and wetlands. There was a decline in grassland area which was recorded as 283 km^2. About 9 km^2 of wetland was converted to *Prosopis* scrub in the period of 1977 to 2011, indicating wider adaptability and invasive nature of the species.

5.2 *Patch dynamics*

Spatial and temporal dynamic analysis through patch level understanding elucidates the recruitment of new plant patches and coalescence of expanding patches. *Prosopis* invasion shows high patch initiation followed by coalescence as observed by Robinson *et al.* (2008). There has been a significant change in the number of patches of *Prosopis*. There were 87 patches of *Prosopis* in the study area during 1977 showing expanding trend in the following years (figure 6; table 3). The coalescence in *Prosopis* scrub decreased from 125 patches to 108 patches which may be attributed to joining of fragments. The number of small patches (< 1 km^2) has been increasing from 1977 to 2011, indicating colonization of new invasive colonies. The patches in Khadir Bet almost showed stabilization and reached a climax while other patches of *Prosopis* in southern part of study area, i.e., parts of little Banni showed very high spatial dynamics conversely leading to patch succession and coalescence.

Prosopis as an aggressive coloniser has been increasing its largest patch from 144 km^2 in 1977 to 430 km^2 over the past 35 years. The largest *Prosopis* patch delineated during 1990, 1999 and 2005 period was 186, 190 and 209 km^2 respectively. Accordingly, largest patch index was very high (44.3) during 2011, followed by 24.4 in 2005. The minimum largest patch index was 21.2 during 1977. The mean patch size was 7.8 km^2 in 1977 and the explicit mean patch size was very high during 2011 and reached 9 km^2 by 2011 (figure 7).

5.3 *Spatio-temporal pattern of invasion*

Presently, *Prosopis juliflora* dominates the landscape of Rann ecosystem forming homogeneous patches. The total area of *Prosopis* infestation mapped for the year 2011 was 971 km^2, which is significantly high as compared to 1977. The annual spread rate for *Prosopis* as per compound interest formula has been estimated as 1.2% during 1977–1990, 0.4% during 1990–1999, 0.6% during 1999–2005 and 2.1% during 2005–2011 (figure 8). Overall annual rate of spread for *Prosopis* was 1% for the last three and half decades.

The study by Sastry *et al.* (2003) has recorded 9.85% of the area under *Prosopis* cover in Banni grasslands during 1980 and predicted its spread

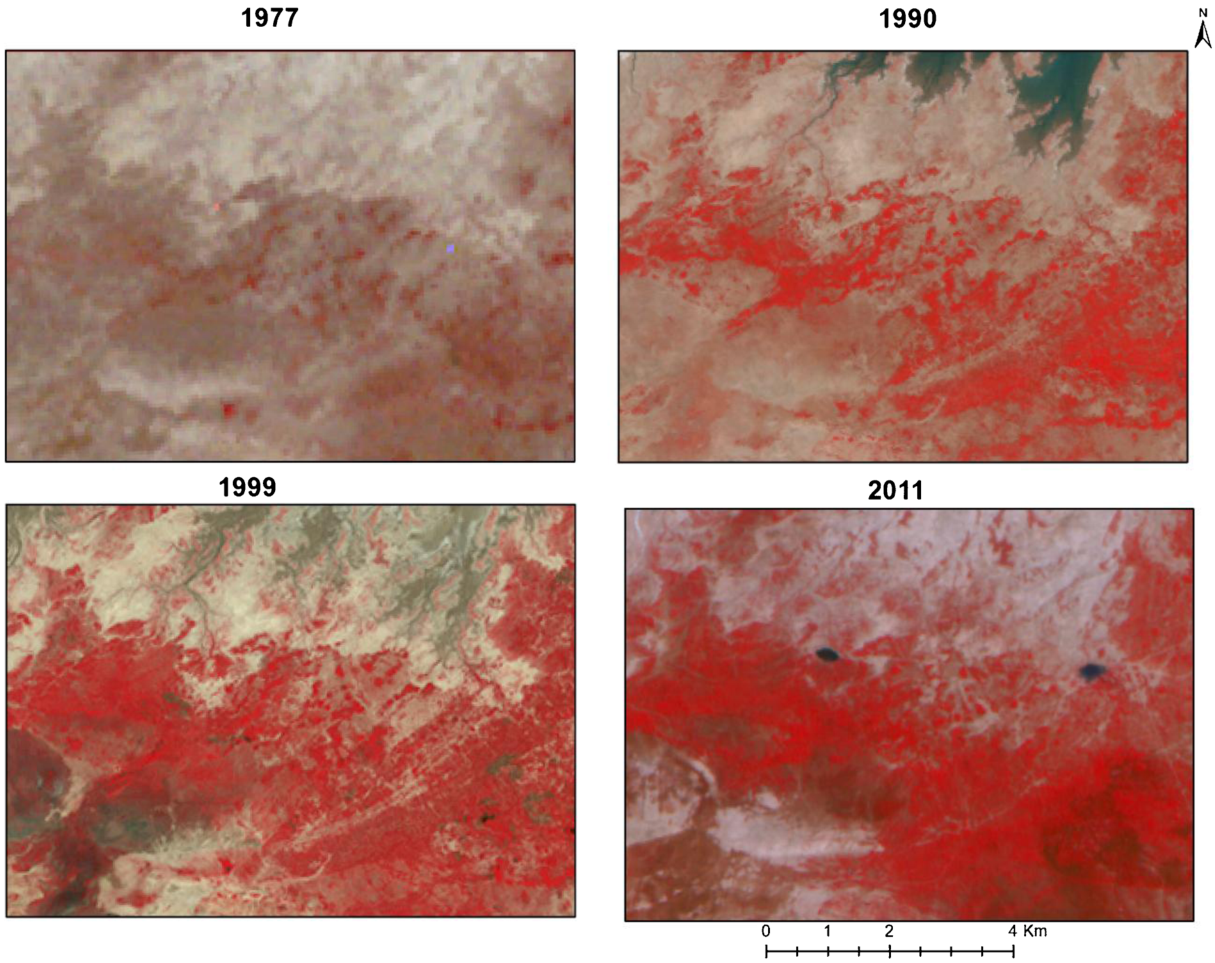

Figure 4. False colour composite images of southern part of Great Rann of Kachchh, Kachchh Biosphere Reserve showing expansion of *Prosopis* in different time periods.

Table 1. *Areal extent of land use/land cover of Great Rann of Kachchh, Kachchh Biosphere Reserve (area in km*^{2}*).*

	1977		1990		1999		2005		2011	
Class	Area	% of area	Area	% of area	Area	% of area	Area	% of area	Area	% of area
Thorn scrub	160	1.7	157	1.6	158	1.7	158	1.7	159	1.7
Prosopis scrub	679	7.1	797	8.4	827	8.7	855	9.0	971	10.2
Grasslands	612	6.4	467	4.9	446	4.7	392	4.1	268	2.8
Agriculture/fallow	1679	17.6	1665	17.4	1655	17.3	1649	17.3	1649	17.3
Wetland	6402	67.1	6447	67.6	6432	67.4	6456	67.7	6455	67.6
Settlements	10	0.1	10	0.1	11	0.1	11	0.1	11	0.1
Salt pans	0	0	0	0.0	15	0.2	20	0.2	31	0.3
Grand total	9543	100	9543	100	9543	100	9543	100	9543	100

further to 31.23% of area by 1998. It has been recorded that area under *Prosopis* has increased from 378 to 684 km^2 (an 81% increase) during 1980–1992 in Banni grassland (FAO 1998) is expanding at a rate of about 25 km^2 per year. Based on present study covering Great Rann of Kachchh, part of Kachchh Biosphere Reserve, its expansion during 2005 to 2011 was 19.2 km^2 per year. In previous periods its expansion was 9 km^2 per year during 1977–1990, 3.3 km^2 during 1990–1999 and 4.8 km^2 during 2000–2005. Hence it is clear that spread and dominance of *Prosopis* in the study area is related to the factors of successive droughts, increasing salinity and intense livestock pressure.

The annual rate of expansion of *Prosopis* in Banni grassland is about 44.8 km^2/year (Jadhav *et al.* 1992). The studies by GUIDE (1999) and

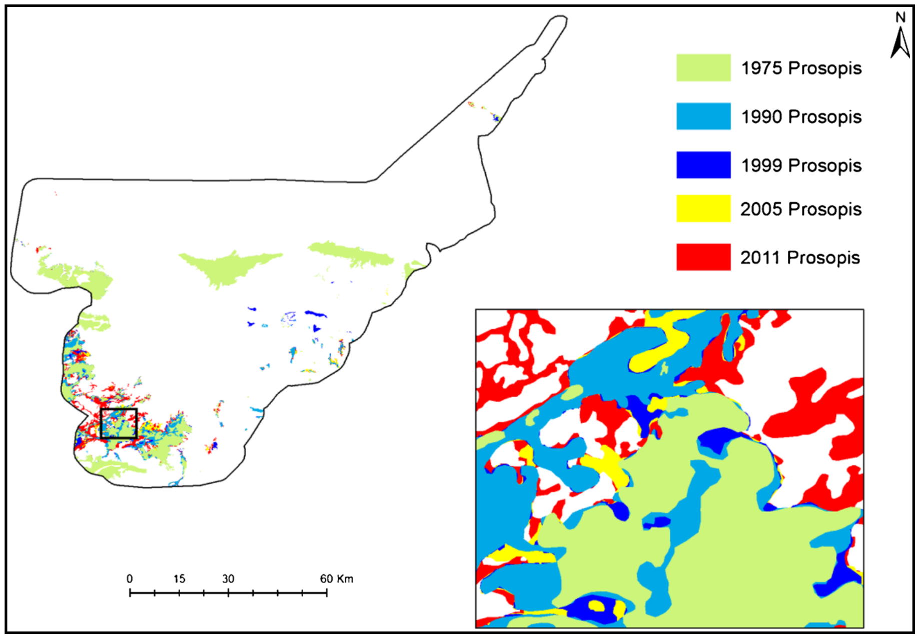

Figure 5. Classified map showing spatial expansion of *Prosopis* in different time periods.

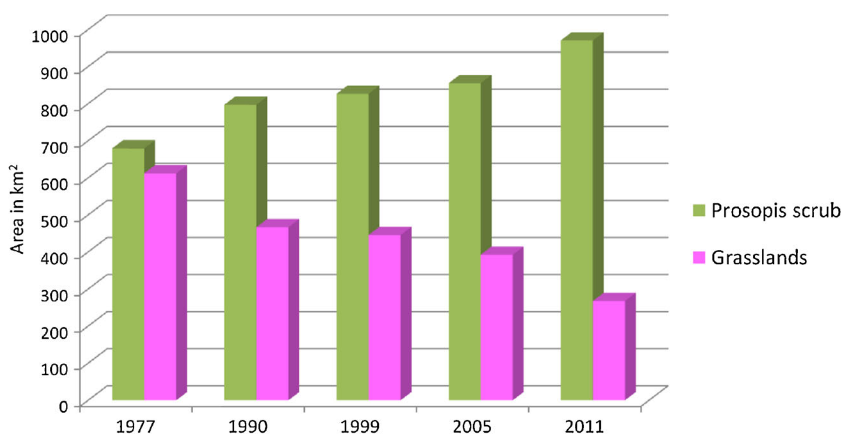

Figure 6. Changing spatial pattern of *Prosopis* scrub and grasslands.

Table 2. *Transition matrix for invasion of Prosopis in land cover types of Great Rann of Kachchh, Kachchh Biosphere Reserve (area in km^2).*

Change class	1977–1990	1990–1999	1999–2005	2005–2011	1977–2011
Thorn scrub	2	0	1	0	3
Grasslands	114	26	25	118	283
Wetland	1	4	3	1	9
Grand total	118	30	29	119	295

Shah and Somusundaram (2010) have reported that the area under *Prosopis* dominance during 1997 of about 6% and in 2008 it increased to 27.5% of the total area of Banni. The result clearly indicates that the grass cover has reduced and the *Prosopis* dominant area has increased between 1999 and 2008. One of the recent studies showed that 45% of area in Banni is falling under *Prosopis* cover (Shah and Somusundaram 2010) and it shows a very alarming situation for Banni grasslands. The phase-wise removal of *Prosopis* will give a better conservation measure for the grassland restoration (GUIDE 1999). The study has found that invasive species populations can be detected only after they

Table 3. *Patchiness of invasive colonies of Prosopis juliflora (area in km²).*

Sl. no.	Patch size (km^2)	1977 No. of patches	1977 Area	1990 No. of patches	1990 Area	1999 No. of patches	1999 Area	2005 No. of patches	2005 Area	2011 No. of patches	2011 Area
1	< 1	60	12	72	17	86	24	89	25	97	71
2	1–10	18	41	25	67	24	69	26	75	4	27
3	10–50	4	90	5	117	5	135	5	138	2	34
4	50–100	2	151	2	151	2	150	2	150	2	150
5	> 100	3	385	3	444	3	449	3	467	3	688
Grand total		87	679	107	797	120	826	125	855	108	971

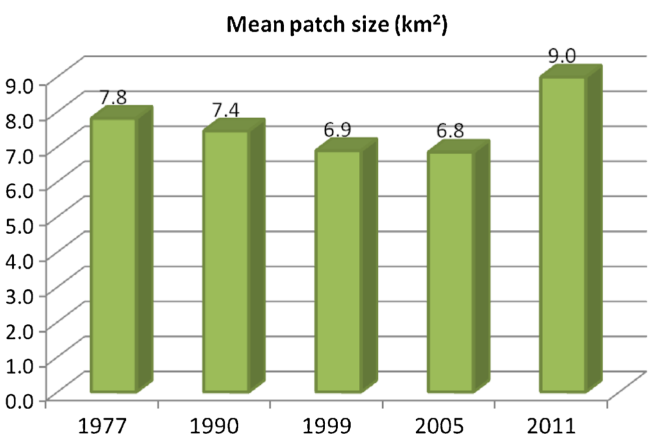

Figure 7. Mean patch size of *Prosopis juliflora*: 1977–2011.

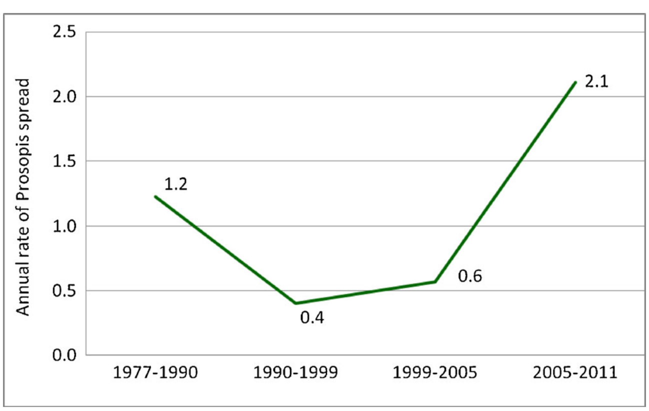

Figure 8. Annual rate of spread of *Prosopis juliflora*: 1977–2011.

become dense and widespread. According to the study in southern Gujarat, *Prosopis* cover represents an area of 257 km^2 which occupies 4% of total vegetation area in 2006 (Bhatt *et al.* 2013).

Overall accuracy summarizes the total agreement/disagreement between the classified maps. It incorporates major diagonals and excludes error of commission and error of omission. In the present study, overall classification accuracy for *Prosopis* cover mapping has been assessed as 92.7% (table 4) and kappa coefficient of 0.86 for the period of 2011. The omission error (8.7%) describes the number of points that should have been classified as *Prosopis* but were omitted from the class. The commission error (6%) describes the number of points that were classified as *Prosopis* but in reality belong to other classes.

Table 4. *Error matrix of the relationship between reference data and the result of the IRS P6 LISS III image interpretation (2011).*

Classification	*Prosopis* present	*Prosopis* absent	Row total	Producer accuracy
Prosopis present	141	9	150	94.0
Prosopis absent	13	137	150	91.3
Column total	154	146	300	
User accuracy	91.6	93.8		

This invasive species is both beneficial and harmful (Tessema 2012). Leaves of mesquite contain a greater amount of inhibitors and suppress and replace the indigenous biodiversity (Getachew *et al.* 2012). Mesquite has replaced large areas of grasslands by aggressive colonization and allelopathic effects. It starts branching closer to the ground which makes under canopy seedling establishment of other species very difficult. Several areas of grasslands and agricultural fields are now being invaded reducing the livestock population in the study area. Being a drought tolerant, *Prosopis* is providing socioeconomic benefits as it is able to grow well on arid saline lands. It has soil binding capacity. In Gujarat, farmers raise *Prosopis* along field boundaries to meet fuel wood requirements (Saxena and Venkateshwarlu 1991). The poor women in northwestern India benefit from the sale of *Prosopis* fuel wood and charcoal (Tewari *et al.* 2000). Now, *Prosopis* has become an additional source of income. The utilization of the species is the best option to manage the invasion for invasion-prone lands.

6. Conclusions

The present study has quantified massive invasion of *Prosopis juliflora* in Kachchh Desert Wildlife

Sanctuary, specifically on the fringes of Khavda and Bela islands and in the parts of little Banni in the Great Rann of Kachchh during 1977 and 2011. The study has found that the increasing spatial extent of *Prosopis* cover is a major threat to indigenous biodiversity and ecosystem services. The spatial database generated will be helpful in management planning in preparing strategies to control rapid invasion of *Prosopis* in Kachchh Biosphere Reserve. There is an urgent need to initiate national level systematic efforts to locate and map invasive plant species using remote sensing techniques towards conservation of biodiversity.

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