Supplementary Material:

Waning grasslands: a quantitative temporal evaluation of the grassland habitats across human-dominated upper Gangetic Plains, north India

Authors

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Appendix S1:

Method

Radiometric correction of Landsat images:

Using the Radiometric tool implemented in ERDAS software, we performed atmospheric corrections (for pixels with cloud cover), noise reduction (for pixels with zero reflectance values), haze reduction (for pixels with unclear reflectance values) and histogram equalization (to improve contrast in images) on the Landsat images (Nalluri & Ramesh 2019).

Accuracy of LULC classification:

We randomly generated another 100 points throughout the study area representing different LULC classes in ArcGIS 10.2.2 and further validated them through additional field surveys. For accuracy assessment, a confusion matrix was generated (with 100 points across six LULC types) characterized by ground-truthed and image classification values along X and Y axes respectively, correct classes along the diagonal of the matrix and incorrect classes situated in the off-diagonal areas of the matrix. The values of the confusion matrix were used to calculate overall accuracy and Kappa coefficient.

Details of radio-collaring operation:

The individuals were captured using *c*. 150 m long nylon-mesh drive nets. The animals were acclimatized to the nets for about three months before final capturing operations were conducted with a group of *c*. 60 field staff. Once captured, the animals were blindfolded and administered with a mild dose of sedative Azaperone (40mg/ml dose) and fitted with GPS Vertex Plus satellite collars (Vectronic Aerospace). The collars were equipped with the GPS module, the VHF beacon integrated within the collar (for manual tracking), the internal sensors (activity/mortality/temperature), the communication modem (Iridium) and UHF radio-communication module (for remote downloading of data). The collars were set to provide information on latitude, longitude, time and temperature at 2-hour intervals. A qualitative assessment of ribs, spine/backbone, hip bone, belly, flank, brisket, pin bone and tail head revealed that both the female swamp deer had good body condition.

Details of trajectory path continuity analysis:

We extracted the data locations of collared individuals covering each LULC class and used trajectory path tool in ArcMet package (ArcGIS 10.2.2) to create temporal continuities in GPS fixes. We also evaluated the proportion of points that could not be joined temporally (isolated points) in each habitat class (Wall et al. 2014).

Details of camera trapping sessions:

The camera trap efforts included 84 trap nights (seven cameras) during July in Session 1, 148 trap nights (11 cameras) during November in Session 2 and 144 trap nights (12 cameras) during April in Session 3 with an average density of five cameras/km^2.

Details of spatial filtering of presence points, selection of uncorrelated covariates and MaxEnt parameter settings:

We used earlier published data on swamp deer presence points (direct sighting, antlers and genetically identified pellets) (Paul et al. 2018, 2020). A total of 9159 points were spatially filtered by selecting one presence point in every one km^2 area (as the species is mostly restricted to habitat patches of around one km^2 currently within this landscape) using the Spatially Rarefy Tool of SDM tool Box in ArcGIS (Brown 2014). Based on swamp deer species ecology, we initially selected some Bioclimatic (Annual mean temperature and precipitation), habitat (LULC class), topographic (DEM) and demographic variables (Nightlight, Distance from Water and Human Population Density) to model habitat suitability. All the variables were rescaled to one km^2 resolution. Correlated variables were removed as it might lead to model overfitting (Dormann et al. 2013). We used ''Pearson correlation coefficient'' to identify highly correlated variables, where a threshold value of 0.75 was selected to choose the final covariates (Pearson et al. 2002; Kalboussi & Achour 2018) (Table S2). Finally the habitat suitability was modelled in Maxent software version 3.3.3k (Phillips et al. 2006) using five covariates viz. six LULC classes, Annual Precipitation (mm), Human Population Density (per km^2), Nightlight and Distance from Water (km) (details in Table S3). We developed models with 10000 background sampling points as environmental space (Wilting et al. 2010). We randomly assigned the presence localities as training and testing dataset (70% as training, 30% as test). Rest of the settings for each parameter were kept default in each run. We ran the final model (default parameter settings) with 10 replicates of 5000 iterations in MaxEnt to derive the average model (Phillips et al. 2006). An auto feature limiting function was used to fit the species environmental curves and to train the MaxEnt models. We used the logistic model output, which displays a suitable value from 0 (unsuitable) to 1 (suitable).

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Figure S1: Map of the study area covering the states of Uttarakhand and Uttar Pradesh. The study area consists of two protected areas (JJCR and HWLS) and other non-protected regions.

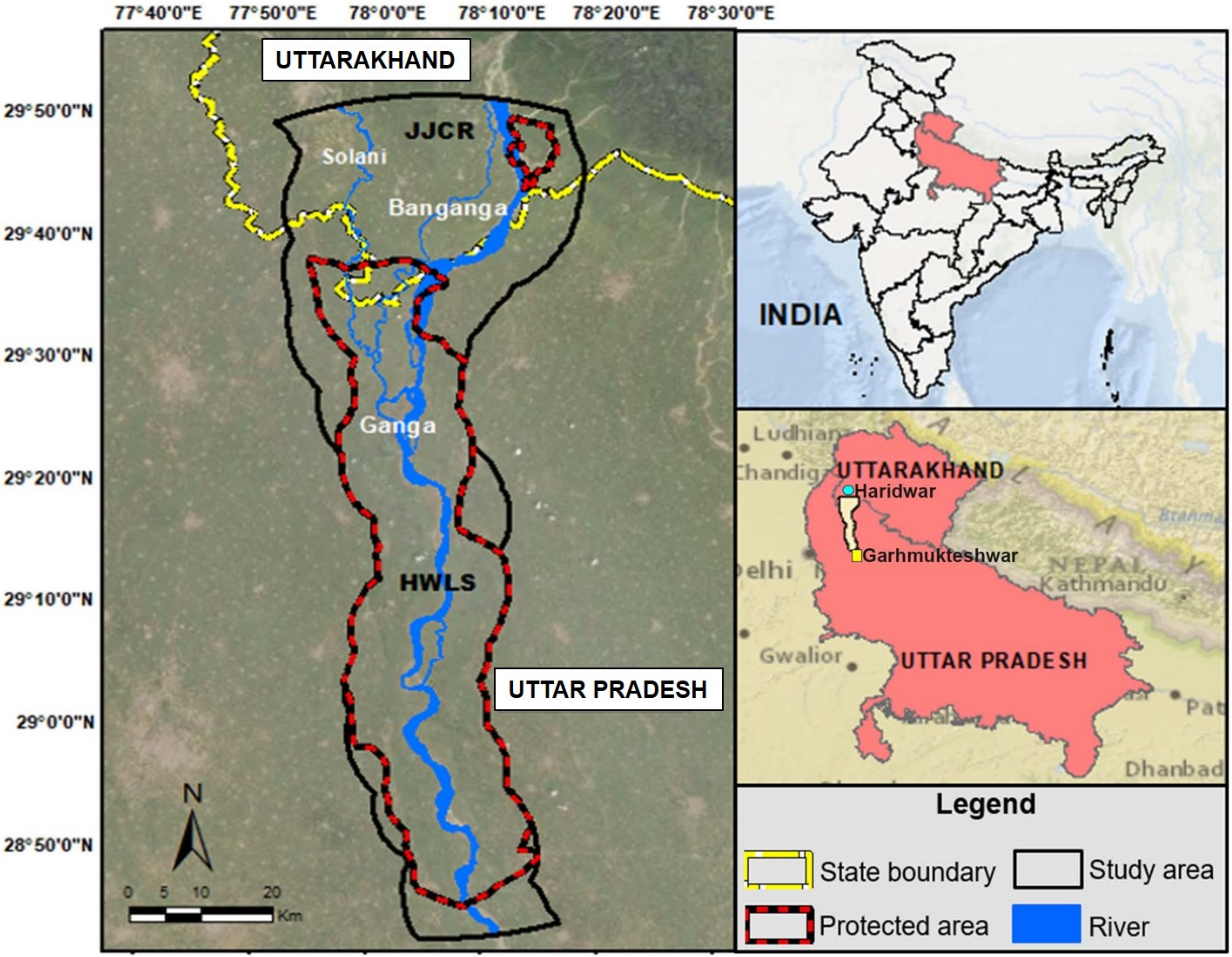

77°40'0"E
77°50'0"E
78°0'0"E
78°10'0"E
78°20'0"E
78°30'0"E
29°50'0"N
29°40'0"N
29°30'0"N
29°20'0"N
29°10'0"N
29°0'0"N
28°50'0"N
UTTARAKHAND
JJCR
Solani
Banganga
Ganga
HWLS
UTTAR PRADESH
N
0 5 10 20
Km
INDIA
Ludhiana
Chandig
UTTARAKHAND
Haridwar
Garhmukteshwar
Delhi
NEPAL
Kathmandu
Gwalior
UTTAR PRADESH
Pat
Dhanbad
Legend
State boundary
Study area
Protected area
River

Figure S2: A schematic diagram representing the various independent components used for grassland assessment in this study

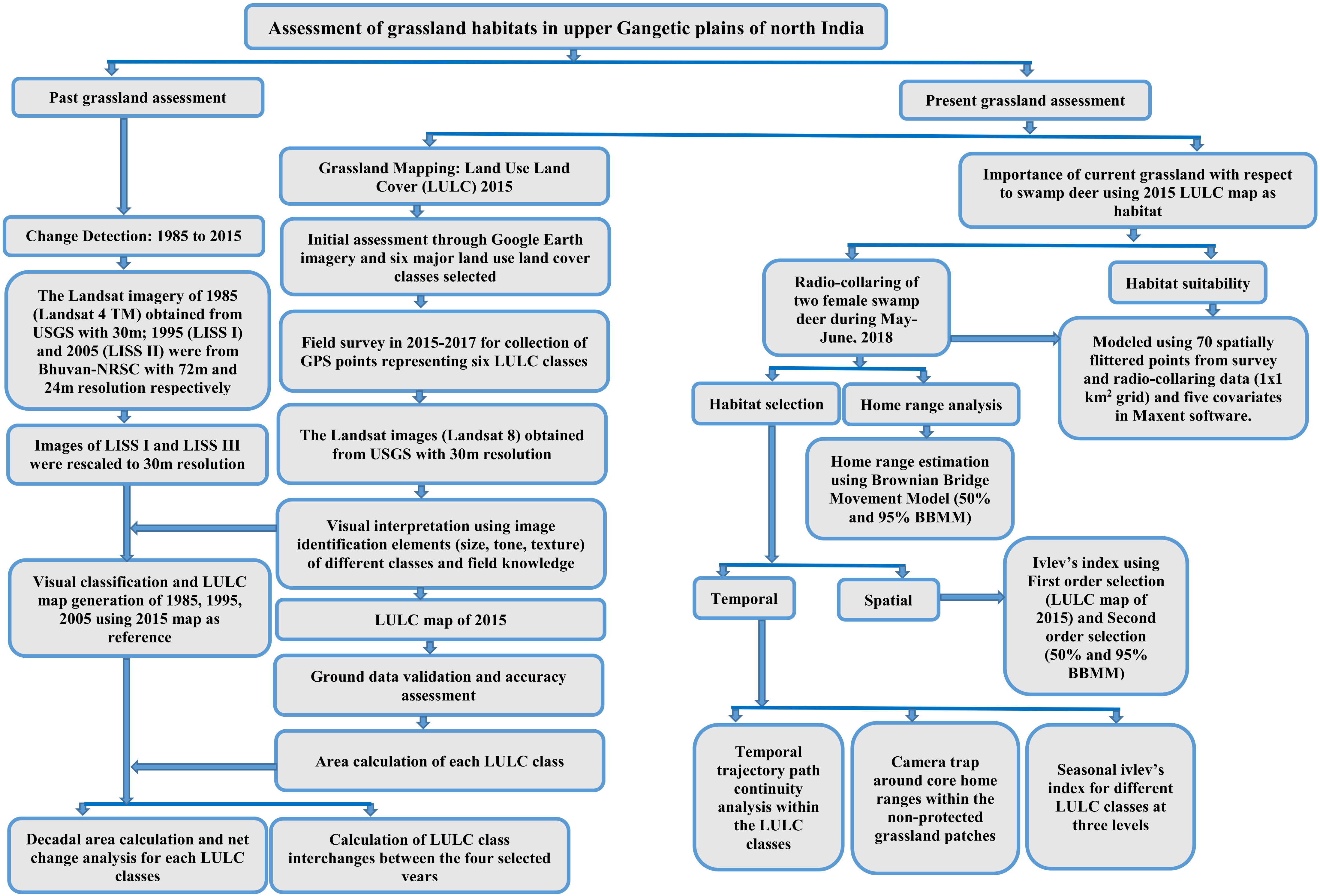
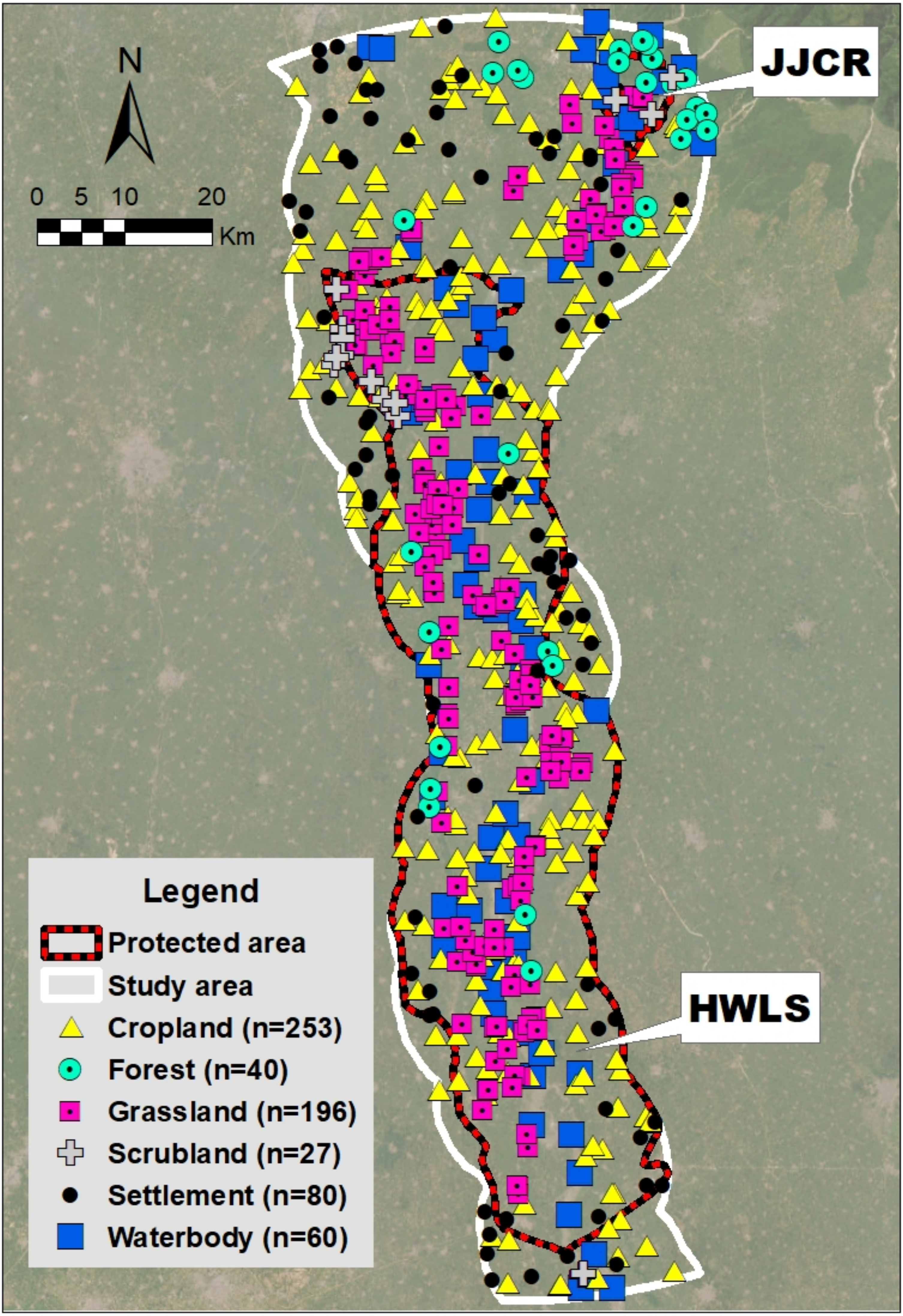
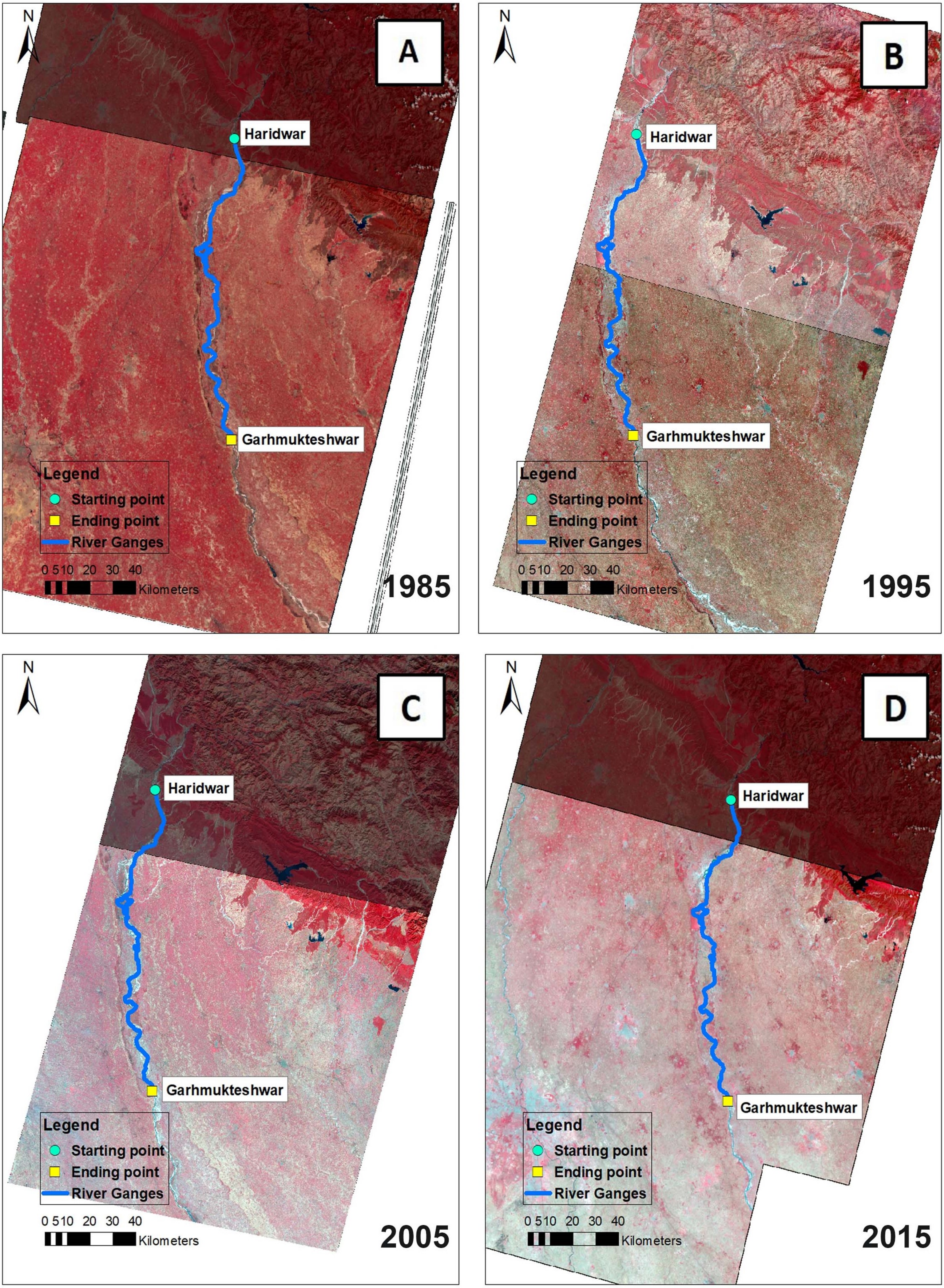

Assessment of grassland habitats in upper Gangetic plains of north India
Past grassland assessment
Present grassland assessment
Change Detection: 1985 to 2015
The Landsat imagery of 1985 (Landsat 4 TM) obtained from USGS with 30m; 1995 (LISS I) and 2005 (LISS II) were from Bhuvan-NRSC with 72m and 24m resolution respectively
Images of LISS I and LISS III were rescaled to 30m resolution
Visual classification and LULC map generation of 1985, 1995, 2005 using 2015 map as reference
Decadal area calculation and net change analysis for each LULC classes
Calculation of LULC class interchanges between the four selected years
Grassland Mapping: Land Use Land Cover (LULC) 2015
Initial assessment through Google Earth imagery and six major land use land cover classes selected
Field survey in 2015-2017 for collection of GPS points representing six LULC classes
The Landsat images (Landsat 8) obtained from USGS with 30m resolution
Visual interpretation using image identification elements (size, tone, texture) of different classes and field knowledge
LULC map of 2015
Ground data validation and accuracy assessment
Area calculation of each LULC class
Importance of current grassland with respect to swamp deer using 2015 LULC map as habitat
Radio-collaring of two female swamp deer during May-June, 2018
Habitat suitability
Modeled using 70 spatially flittered points from survey and radio-collaring data (1x1 km^2 grid) and five covariates in Maxent software.
Habitat selection
Home range analysis
Home range estimation using Brownian Bridge Movement Model (50% and 95% BBMM)
Temporal
Spatial
Ivlev's index using First order selection (LULC map of 2015) and Second order selection (50% and 95% BBMM)
Temporal trajectory path continuity analysis within the LULC classes
Camera trap around core home ranges within the non-protected grassland patches
Seasonal ivlev's index for different LULC classes at three levels

Figure S3: Details of spatial locations of all 656 points (representing six LULC classes) used in training of visual classification.



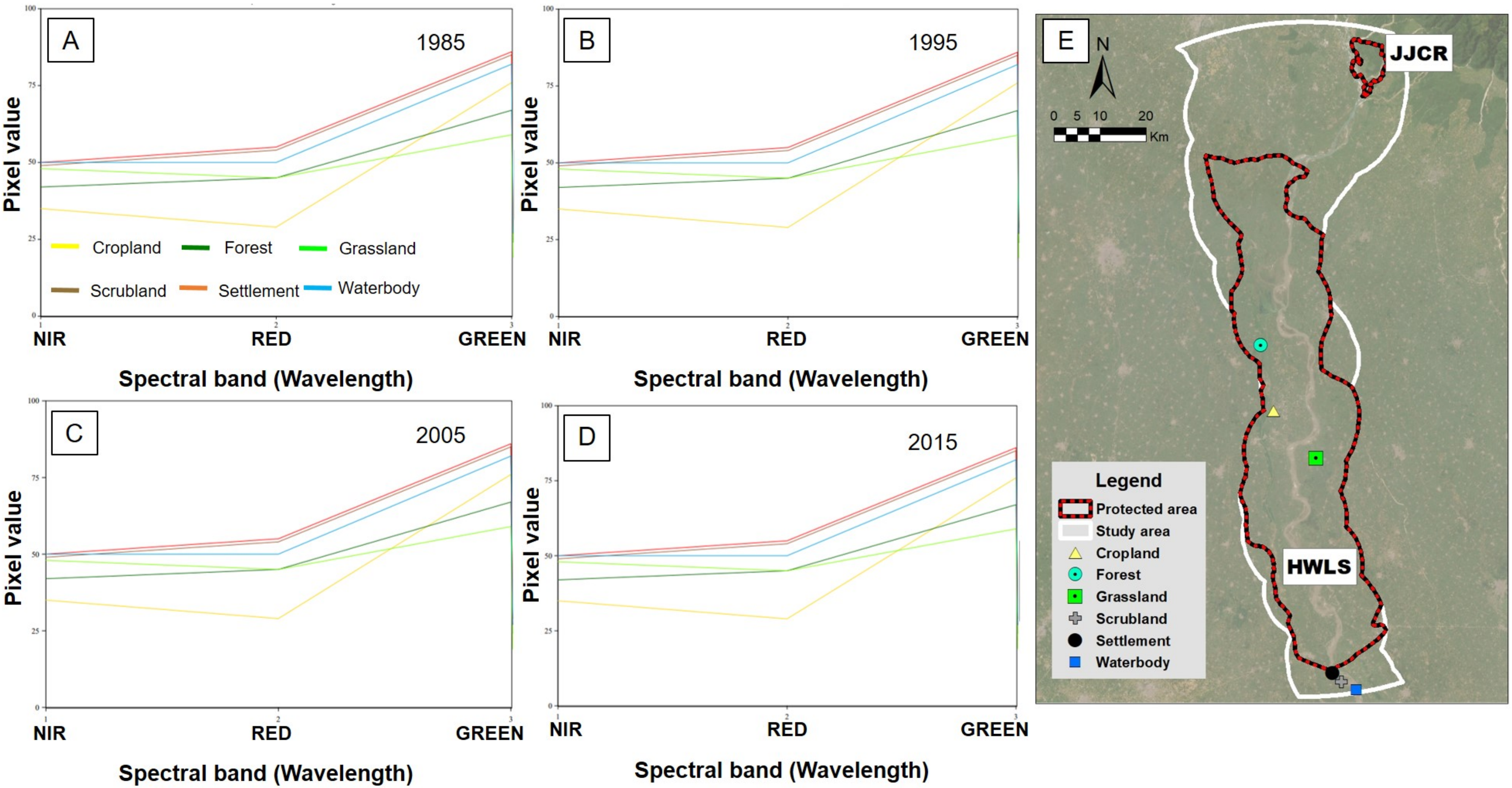
JJCR
N
0 5 10 20
Km
Legend
Protected area
Study area
Cropland (n=253)
Forest (n=40)
Grassland (n=196)
Scrubland (n=27)
Settlement (n=80)
Waterbody (n=60)
HWLS

Figure S4: Landsat images of study area used in visual classification- (A) 1985; (B) 1995; (C) 2005 and (D) 2015.



A
N
Haridwar
Garhmukteshwar
Legend
Starting point
Ending point
River Ganges
0 5 10 20 30 40
Kilometers
1985
B
N
Haridwar
Garhmukteshwar
Legend
Starting point
Ending point
River Ganges
0 5 10 20 30 40
Kilometers
1995
C
N
Haridwar
Garhmukteshwar
Legend
Starting point
Ending point
River Ganges
0 5 10 20 30 40
Kilometers
2005
D
N
Haridwar
Garhmukteshwar
Legend
Starting point
Ending point
River Ganges
0 5 10 20 30 40
Kilometers
2015

Figure S5: Spectral profiles of six LULC classes- (A) 1985; (B) 1995; (C) 2005; (D) 2015 and (E) spatial representation of location points used for generating spectral profile.



A
1985
B
1995
C
2005
D
2015
Pixel value
Cropland
Forest
Grassland
Scrubland
Settlement
Waterbody
NIR
RED
GREEN
Spectral band (Wavelength)
E
N
0 5 10 20
Km
JJCR
HWLS
Legend
Protected area
Study area
Cropland
Forest
Grassland
Scrubland
Settlement
Waterbody

Figure S6: Grassland habitats, biodiversity and disturbances encountered in some of non-protected areas between JJCR and HWLS (A) Digitized locations of major grassland patches between the two protected areas. Based on the habitat use patterns from the collared females, camera trapping was conducted in locations 2, 3, 4, 6, and 9; (B) Camera trap image showing rutting behavior of a male during late monsoon; (C) Capture of swamp deer fawn with a female indicating the importance of the grassland habitats as fawning and breeding grounds; (D) Evidence of fishing cat using the habitats; (E) Evidence of hog deer in these habitats; (F) Human disturbances in the form of exploitation/extraction of grasses; (G) Overgrazing of the habitats by livestock.

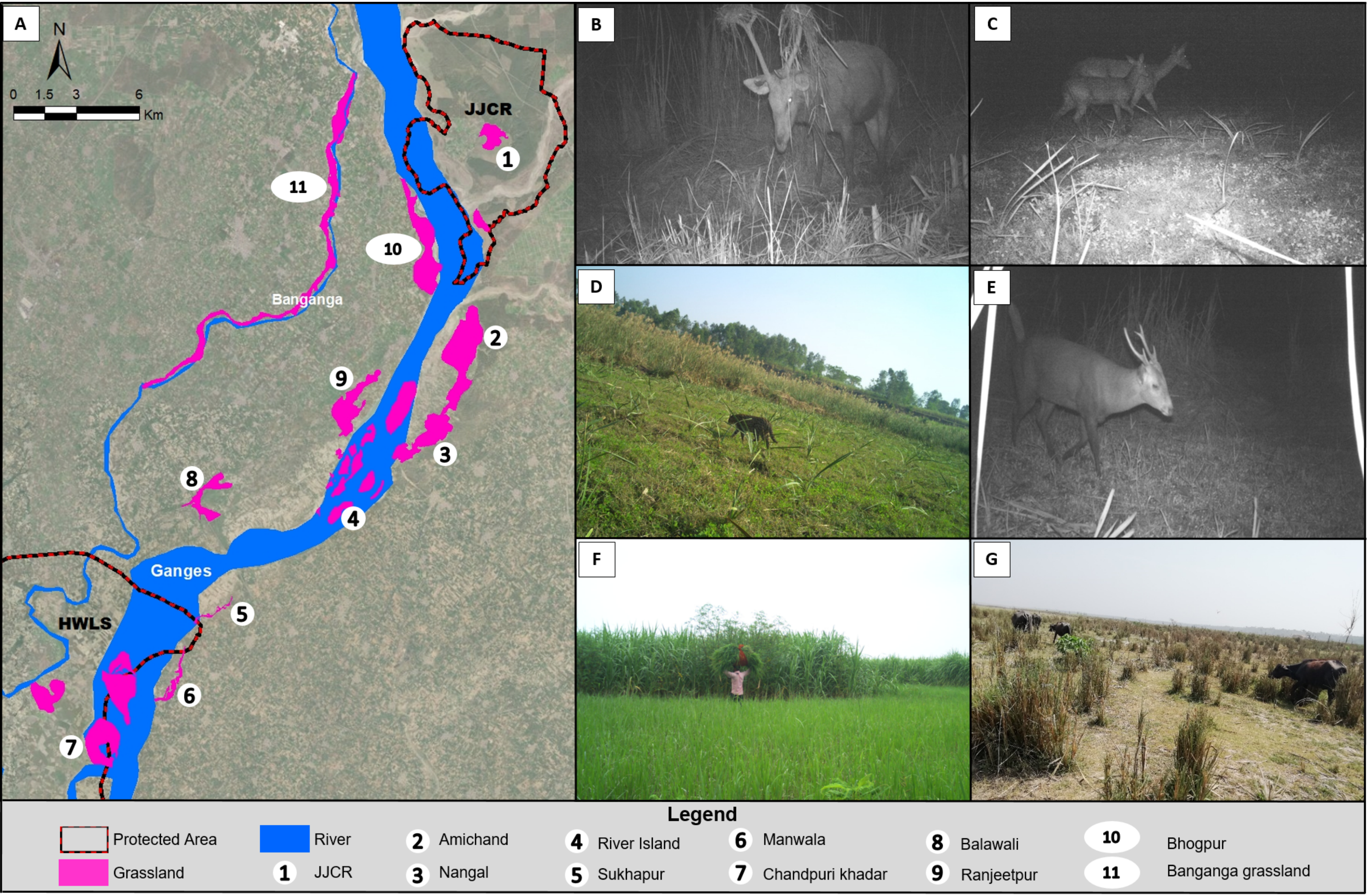

A
B
C
D
E
F
G
N
0 1.5 3 6
Km
JJCR
HWLS
Banganga
Ganges
1
2
3
4
5
6
7
8
9
10
11
Legend
Protected Area
Grassland
River
1 JJCR
2 Amichand
3 Nangal
4 River Island
5 Sukhapur
6 Manwala
7 Chandpuri khadar
8 Balawali
9 Ranjeetpur
10 Bhogpur
11 Banganga grassland

Figure S7: Jackknife tests of variable importance and Receiver operating characteristic (ROC) curve for predicted habitat suitability of swamp deer, (A) Jackknife test using training gain, (B) Jackknife test using test gain, (C) Jackknife test using AUC on test data, (D) ROC curve for the training omission rate and predicted area averaged over the replicate runs.

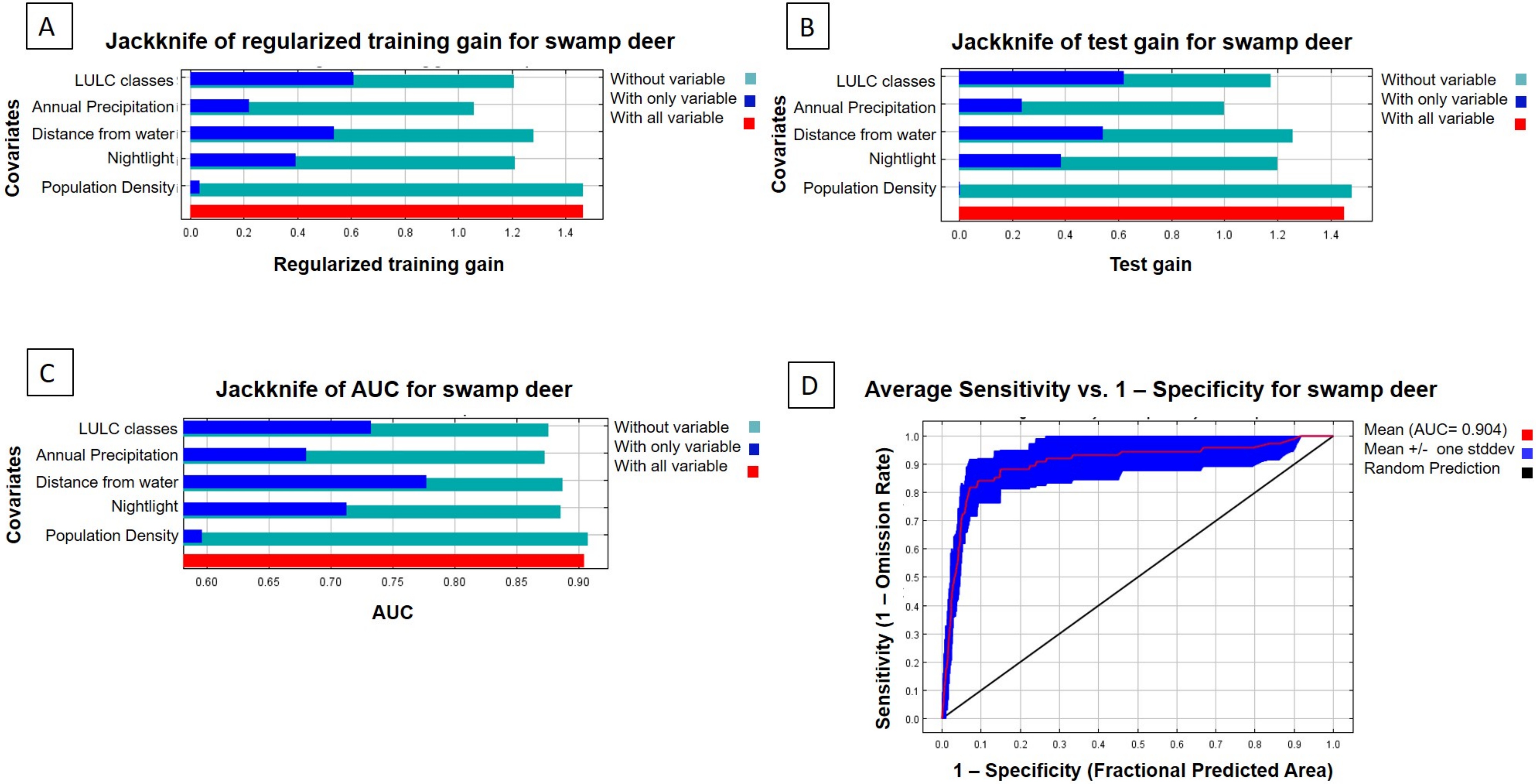
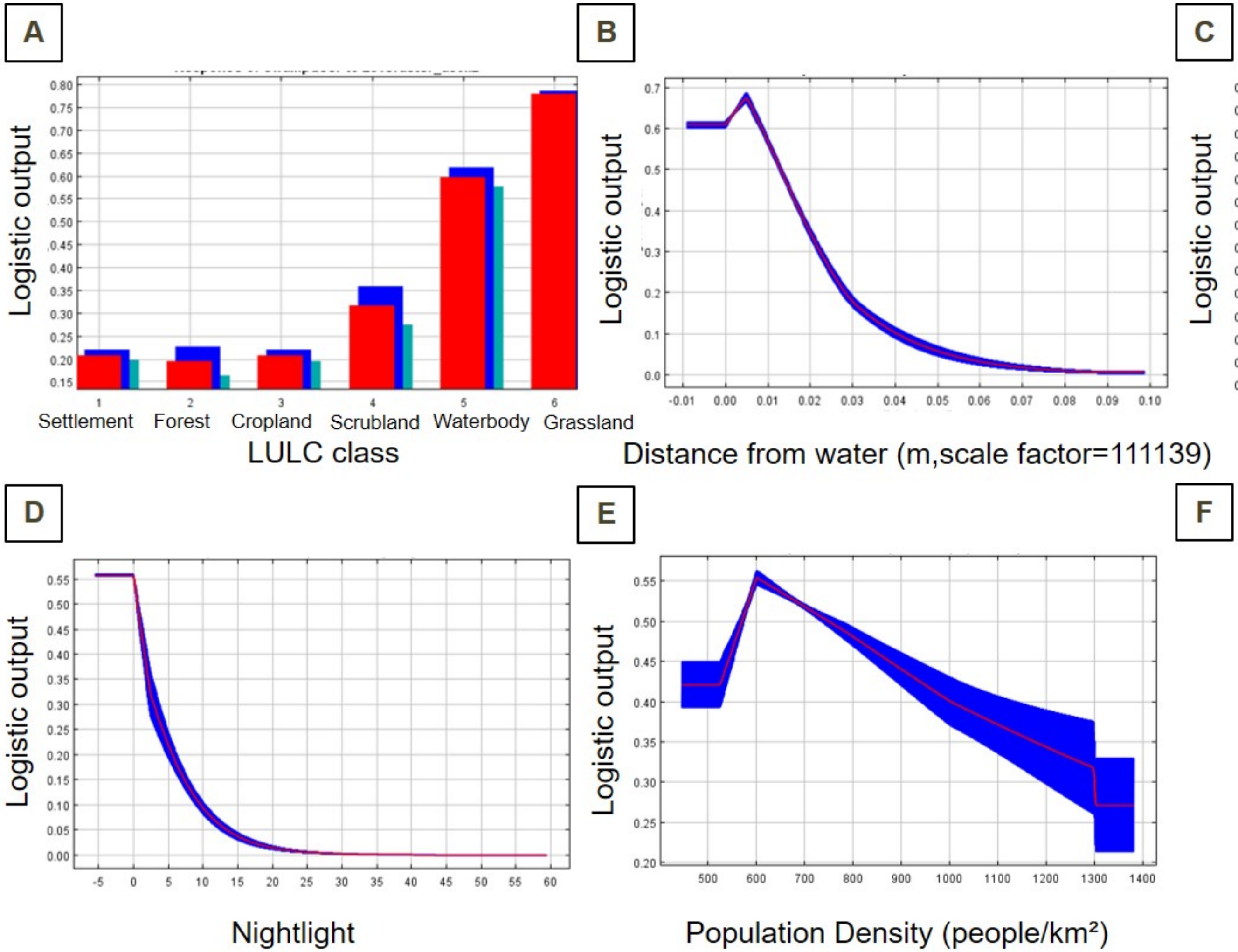

A
Jackknife of regularized training gain for swamp deer
LULC classes
Annual Precipitation
Distance from water
Nightlight
Population Density
Covariates
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
Regularized training gain
Without variable
With only variable
With all variable
B
Jackknife of test gain for swamp deer
LULC classes
Annual Precipitation
Distance from water
Nightlight
Population Density
Covariates
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
Test gain
Without variable
With only variable
With all variable
C
Jackknife of AUC for swamp deer
LULC classes
Annual Precipitation
Distance from water
Nightlight
Population Density
Covariates
0.60 0.65 0.70 0.75 0.80 0.85 0.90
AUC
Without variable
With only variable
With all variable
D
Average Sensitivity vs. 1 – Specificity for swamp deer
Sensitivity (1 – Omission Rate)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
1 – Specificity (Fractional Predicted Area)
Mean (AUC= 0.904)
Mean +/- one stddev
Random Prediction

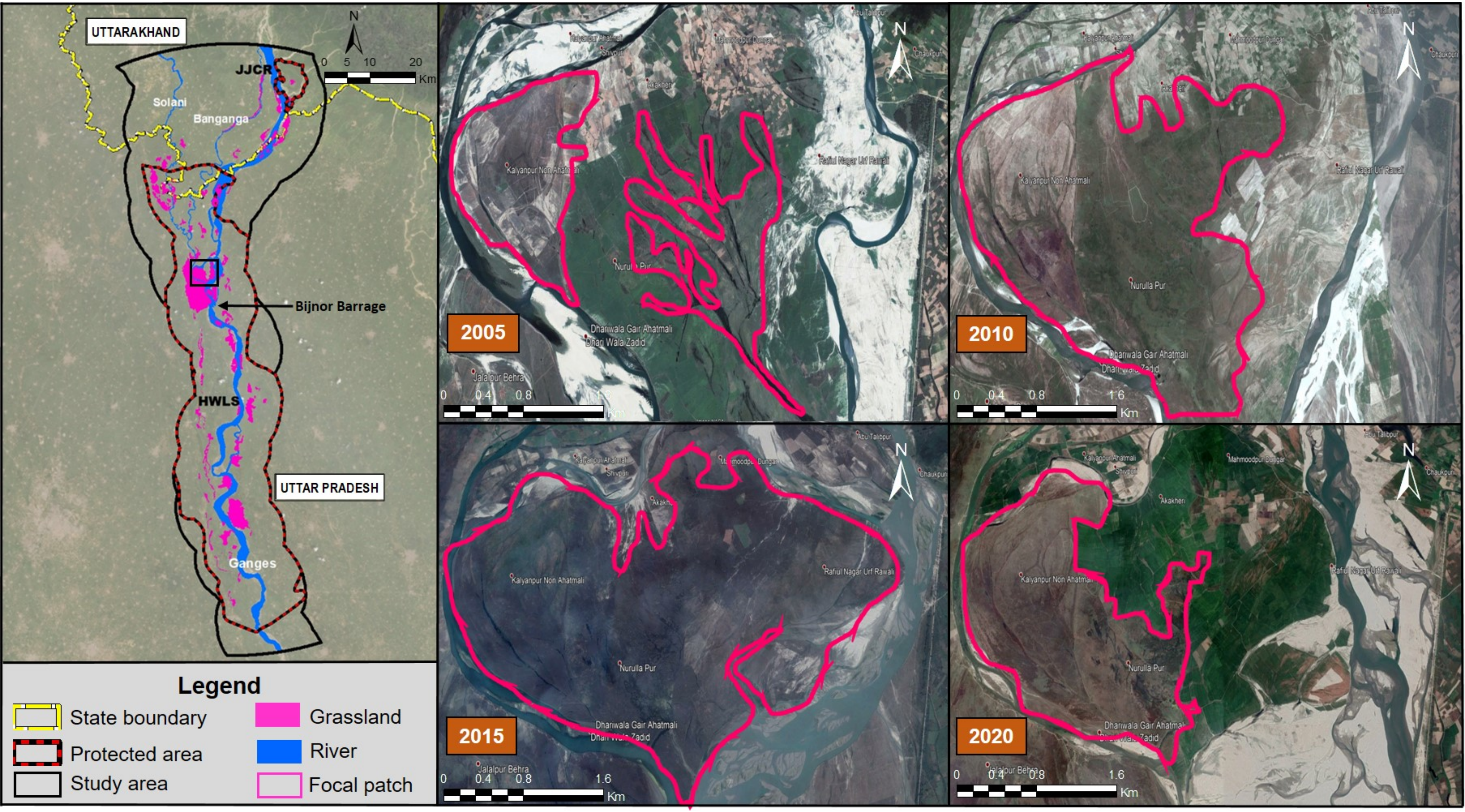
Figure S8: Figure showing the response curves of five covariates used in the MaxEnt model for swamp deer habitat suitability. Figures A-E shows the response curves, whereas F lists the estimates of relative contributions of the respective covariates in the MaxEnt predictions.



F

Covariates	Percent Contribution
LULC class	26.8
Distance from Water	25.4
Bio 12	25.2
Nightlight	22.3
Population Density	0.3

Figure S9: Times-series presentation of grassland dynamics within a selected river island area (Rauli Ghat, presented in the left pane of the figure) of the upper Gangetic Plains. The changes in the grassland habitat area are presented every 5-year time frame during last two decades (2005, 2010, 2015 and 2020).



UTTARAKHAND
JJCR
Solani
Banganga
0 5 10 20
Km
N
Bijnor Barrage
HWLS
UTTAR PRADESH
Ganges
Legend
State boundary
Protected area
Study area
Grassland
River
Focal patch
2005
2010
2015
2020
Kalyanpur Non Ahatmali
Nurulla Pur
Dhariwala Gair Ahatmali
Rafiul Nagar Urf Rawali
Jalalpur Behra
0 0.4 0.8 1.6
Km

Table S1: Detailed features of Landsat images used in this study.

Satellite	No. of Tiles used	Path/Row	No. of Bands	Time Period	Grid cell size (m)
Landsat 8	2	146/39, 146/40	11	2015	30
LISS III	2	97/50, 97/51	4	2005	24
LISS I	2	28/46, 28/47	4	1995	72
Landsat 4	2	146/39, 146/40	7	1985	30

Table S2: Results of multi-collinearity test (Pearson correlation coefficient, r) among the covariates to identify highly correlated variables

	Annual precipitation	Annual mean temperature *	DEM*	Distance from water	Nightlight	Population density	Habitat
Annual precipitation	**1.000**	**-0.777**	**0.812**	-0.155	0.169	-0.018	0.063
Annual mean temperature *	**-0.777**	**1.000**	**-0.860**	0.196	-0.289	-0.231	0.022
DEM*	**0.812**	**-0.860**	**1.000**	0.009	0.289	0.222	-0.079
Distance from water	-0.155	0.195	0.009	**1.000**	0.169	0.111	-0.327
Nightlight	0.169	-0.289	0.289	0.169	**1.000**	0.121	-0.079
Population density	-0.018	-0.231	0.222	0.111	0.121	**1.000**	-0.108
Habitat	0.063	0.022	-0.079	-0.327	-0.079	-0.108	**1.000**

Table S3: Details of all environmental and ecological covariates used in swamp deer habitat suitability modelling.

Category	Variables	Data source	Units/Range	Variable type	Predicted effect of selected covariates
Bioclimatic	Annual Precipitation	WorldClim (https://worldclim.org/data/bioclim.html)	Mm	Continuous	May influence the grassland vegetation occurrence
Demographic	Nightlight	Defence Metrological Satellite Programme-Operational Line Scan System	0 to 63	Continuous	May negatively influence swamp deer occurrence
	Distance from Water	Waterbodies digitized in Earth Explorer and Euclidean distance calculated	M	Continuous	May negatively influence swamp deer occurrence
	Human Population Density	SEDAC (https://sedac.ciesin.columbia.edu/)	people/km^2	Continuous	May negatively influence swamp deer occurrence
Habitat	Land use Land cover	USGC Earth Explorer		Categorical	May positively influence swamp deer occurrence

Table S4: Confusion matrix for accuracy assessment of LULC map 2015.

	Cropland	Forest	Grassland	Scrubland	Settlement	Waterbody	**Total (User)**
Cropland	25	0	0	0	0	2	27
Forest	1	13	0	1	0	0	15
Grassland	1	0	18	0	0	1	20
Scrubland	1	0	0	8	0	0	9
Settlement	0	0	0	0	13	0	13
Waterbody	3	0	0	0	0	13	16
Total (Producer)	31	13	18	9	13	16	100
Overall Accuracy = 90%							
Kappa coefficient = 0.88 (88%)							

Table S5: Seasonal Ivlev's index (Summer, Monsoon, Winter; n= two individuals) calculated for each LULC class type in three different levels (50%BBMM, 95%BBMM, Landscape)

Habitat Selection (seasonal Ivlev's index)							
Female 1		**Cropland**	**Forest**	**Grassland**	**Scrubland**	**Settlement**	**Waterbody**
Summer	**50% BBMM**	-0.92	-1	0.10	-	-	-
	95% BBMM	-0.86	-1	0.33	-0.94	-	-0.75
	Landscape	-0.97	-0.96	0.88	-0.94	-1	-0.31
Monsoon	**50% BBMM**	0.30	-	0.17	-	-	-0.72
	95% BBMM	-0.41	-1	0.40	-	-	-0.53
	Landscape	-0.78	-1	0.85	-1	-1	0.31
Winter	**50% BBMM**	-0.48	-	0.003	-	-	-
	95% BBMM	-0.49	-1	0.095	-	-	-
	Landscape	-0.87	-1	0.88	-1	-1	-1
Female 2		**Cropland**	**Forest**	**Grassland**	**Scrubland**	**Settlement**	**Waterbody**
Summer	**50% BBMM**	-0.79	-	0.21	-	-	-0.91
	95% BBMM	-0.79	-1	0.46	-0.82	-	-1
	Landscape	-0.94	-1	0.88	-0.21	-1	-0.96
Monsoon	**50% BBMM**	0.02	-	-0.02	-	-	-0.21
	95% BBMM	0.007	-	0.05	-	-	-0.49
	Landscape	-0.17	-1	0.76	-1	-1	-0.5
Winter	**50% BBMM**	-0.46	-	0.24	-	-	
	95% BBMM	-0.55	-	0.42	-	-	-0.35
	Landscape	-0.60	-1	0.86	-1	-1	-0.58