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Use of remote sensing to identify suitable breeding habitat for the Kentish Plover and estimate population size along the western coast of Saudi Arabia

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The identification of the environmental parameters affecting species' habitat preferences is a key to understanding the relationships between habitat features and species' distributions. This understanding provides the evidence base upon which to formulate guidelines for managing populations. We used distribution modelling to quantify habitat relationships and to estimate the population size during the breeding season of the Kentish Plover *Charadrius alexandrinus,* a poorly known species on the western coast of Saudi Arabia. We used a Generalised Linear Model (GLM) with four habitat variables derived from satellite data: elevation, distance to settlements, vegetation cover and soil moisture to produce a habitat suitability model. Validation of this model using a receiver operating characteristic plot suggests that it is at least 80% accurate in predicting suitable sites. We then used our estimate of total area of suitable habitat above a critical suitability threshold and data on Kentish Plover density, to estimate the total population size to be 9,955±1,388 individuals. Based on our model we recommend sites for potential protected areas to be established. Finally, we believe that our modelling approach can provide inputs for conservation planning and long-term population monitoring of Kentish Plover and other shorebirds in the region. We argue that conservation of Kentish Plover habitat will not only protect this species, but will benefit other species, particularly those with similar habitat requirements.

INTRODUCTION

Shorebirds, by virtue of their life history, behaviour, migratory and foraging habits are important indicators of the integrity of coastal ecosystems (Furness & Greenwood 1993, Piersma & Lindström 2004, Székely *et al.* 2004, Thomas & Székely 2005, Thomas *et al.* 2006). Many shorebird populations are declining, and more than half of all shorebird species are declining globally (International Wader Study Group 2003, Stroud *et al.* 2006). The principal reason for these declines is habitat loss and degradation, but other impacts, including climate change, pollution and predation, have been implicated (Barter 2002, Piersma & Lindström 2004, Stroud *et al.* 2006, Wetlands International 2006).

The Kentish Plover *Charadrius alexandrinus* is a small ground-nesting shorebird that has an extremely large geographic distribution range, extending across five continents: Europe, Africa, Asia, North and South America (del Hoyo *et al.* 1996, Wetlands International 2006). However, its Western Hemisphere form, *nivosus*, known as Snowy Plover has recently been proposed as a separate species, *Charadrius nivosus* (Kupper *et al.* 2009). Although Kentish Plovers do not currently approach the threshold for the population decline criterion of the IUCN Red List (BirdLife International 2010a), their populations are known to be declining in much of their range. For instance, some European and African populations are declining (e.g. Italy, Romania, Hungary, Bulgaria, Sweden, Egypt, Mauritania and Guinea-Bissau; Delany *et al.* 2009), and the species has disappeared as a breeding bird from the British Isles, Norway and from some parts of Spain (Montalvo & Figuerola 2006). Several factors have been identified as contributing to these declines, including degradation and loss of coastal habitats, disturbance by humans and predation (BirdLife International 2010a, Dalakchieva 2003, Delany *et al.* 2009, Montalvo & Figuerola 2006).

The ecology, distribution and temporal trends of the population of Kentish Plovers on the west coast of Saudi Arabia are poorly known. No systematic surveys have been conducted to estimate population size, with only a single survey made in the winter of 1990. This reported 335–546 birds near Jizan (BirdLife International 2010b) and 351–500 in the Farasan Islands (BirdLife International 2010c). Little detailed mapping work has been conducted for the species, although Jennings (1995) provided an "interim" atlas of breeding sites for the west coast of Saudi Arabia. The most recent report of Kentish Plovers in this region indicated that it breeds in the Farasan Islands, but gave no assessment of numbers (PERSGA/GEF 2003). Our project sought to address some of these knowledge gaps and had three main aims:

1. To create a species distribution model to characterise the relationship between Kentish Plovers and the environment

and thereby to map suitable habitat. Species distribution models over large geographical ranges using spatial data derived from remote sensing are important conservation tools (Araújo & Guisan 2006, Elith *et al.* 2006, Guisan & Zimmermann 2000, López-López *et al.* 2007, Marmion *et al.* 2008, Zarri *et al.* 2008). Moreover, identification of the environmental parameters influencing species' habitat preferences provides an understanding of the relationship between habitat features and species distribution. This can be used to support population management and develop conservation strategies (Gibson *et al.* 2004, Gottschalk *et al.* 2005, Guisan & Zimmermann 2000).
2. To estimate the density of Kentish Plovers at the suitable sites and to estimate population size on the basis of the predicted area of suitable habitat.
3. To provide guidance for the development of conservation strategies in the region, and provide a much-needed baseline for future surveys and monitoring of this and other shorebird species in the region.

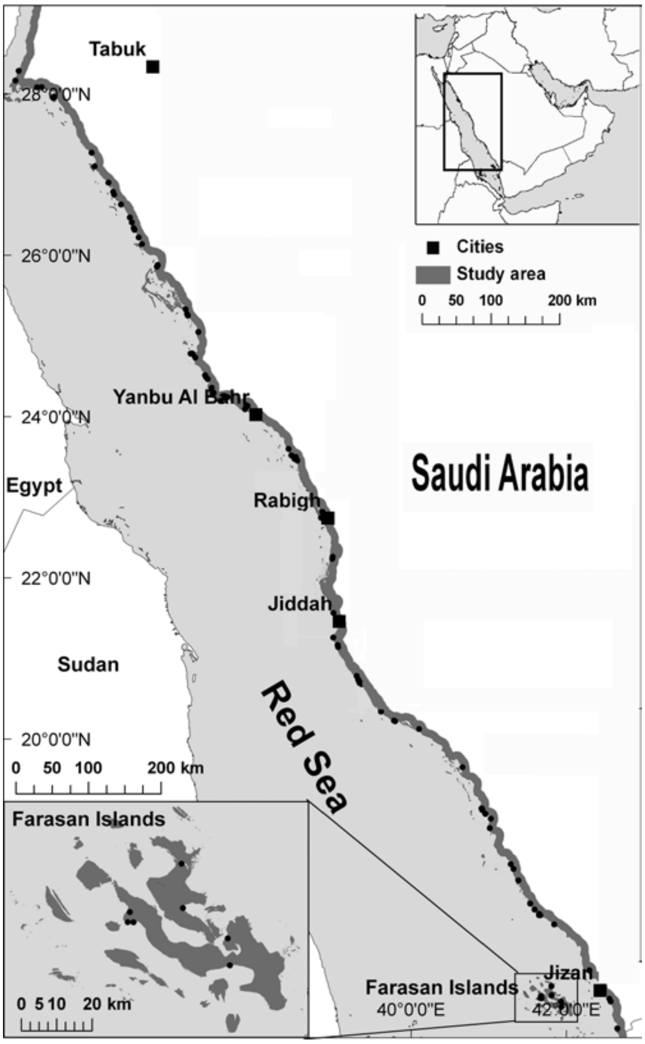

Fig. 1. Map showing the study area on the west coast of Saudi Arabia (shaded dark grey); black dots represent starting points (see text).

METHODS

Study area

This study was carried out on the west coast of Saudi Arabia including the Farasan Islands (Fig. 1). Saudi Arabia's Red Sea coastline extends about 1,840 km from the Jordanian border (29°30'N) to the border with Yemen (16°22'N) (PERSGA/GEF 2003). The Farasan Islands are located in the Red Sea about 50 km from the city of Jizan, Saudi Arabia. It is a protected area established in 1996 by the Saudi Wildlife Commission (SWC) and covers an area of 3,310 km^2; it is categorized as an Important Bird Area by BirdLife International (PERSGA/GEF 2003). The study area comprised a variety of habitat types including mangroves, wet and dry salt marshes, sand dunes, sand plains and rocky habitats. The Red Sea coast is arid with extremely high temperatures in the summer. Rainfall is sparse and the average annual precipitation is <70 mm (PERSGA/GEF 2003). The Red Sea is a semi-enclosed body of water and has almost no daily difference in tidal height in the centre, but the northern and southern ends show daily differences at spring tides from about 0.6 m in the north to 0.9 m in the south (Sheppard *et al.* 1992).

Fieldwork and data collection

A coastal line-transect survey was conducted between 2 July and 10 August, 2008. The Kentish Plover breeding season on the west coast of Saudi Arabia begins in early March and continues until September (AlRashidi unpub. data). Therefore, we selected this time because it lies toward the end of breeding season when it was easier to observe both adults and chicks.

One hundred starting points were stratified randomly within 1 km from the sea because previous observations suggested that Kentish Plovers breed sparsely up to 1 km inland (AlRashidi, unpub. data). These starting points were divided to five categories (20 each) with respect to soil moistness derived from satellite data. The five categories ranged from very dry reflecting sand dunes to very wet reflecting wet salt marshes. From each starting point a four-wheel-drive vehicle was driven parallel to the high tide line of the beach along a 2-km transect at 10–30 km/h north along the coast. We used 2-km transects because they could be surveyed quickly, permitting 98 transects to be surveyed altogether (two routes were in private areas and had to be excluded). Each transect was driven twice on the same day. The surveys took place from early morning to late evening (from 1 h after sunrise to 1 h before sunset). We did not take into consideration tidal cycles because of the small tidal range and because the Kentish Plover is not a tide-following feeder (Granadeiro *et al.* 2004).

When a Kentish Plover (adult or chick) was encountered, within 250 m from either side of the vehicle, the location was recorded with a GPS (Garmin e-Trex), the distance to the plover was estimated and the angle was measured clockwise from north to the plover. The track of each line transect was also recorded using the GPS.

All transects were plotted using a geographic information system (GIS), with the UTM 37N (WGS 1984 datum) coordinate system. Each transect shapefile was converted to a raster grid within the GIS. A 500 m buffer was created around each transect to describe its environment. In this way a set of cells used by Kentish Plovers was generated. These were then converted to a Boolean raster in which the presence cells were coded as 1 and all others as 0 (see Long *et al.* 2008).

Environmental variables

Remotely-sensed digital datasets provide a useful tool for identifying areas of suitable habitat. In particular, vegetation cover, topography and human structures can be quantified to measure the size, extent and spatial pattern of habitat features, and predict a species' realized ecological niche (Guisan & Zimmermann 2000, López-López *et al.* 2007).

We selected four habitat variables to be used in the model; elevation, distance to settlements, vegetation cover and soil moisture. We used Landsat 7 data because they have an appropriate spatial and spectral resolution, and are readily available for the study area. In order to cover the entire study area, we used 21 Landsat 7 scenes acquired in summer 1999, 2000 and 2001 (Table 1). It was not possible to find a set of images collected in the same year which were free of cloud cover because of the large study area. The source for this dataset was the Global Landcover Facility (*landcover.org*). The 21 Landsat 7 scenes for bands 1, 2, 3, 4, 5 and 7 were mosaiced separately and then clipped to within the west coast of Saudi Arabia. The total study area was 1,078 km^2 (Fig. 2). All image processing work used Idrisi Kilimanjaro (Eastman 2003).

The tasseled cap transformation (Kauth & Thomas 1976) is a useful tool for reducing the number of dimensions of satellite data and extracting biologically meaningful environmental indices (Crist & Cicone 1984). We used a tasseled cap transformation with coefficients for the Landsat ETM+ sensor (Huang *et al.* 1998) to produce two rasters: tasselled cap greenness showing the amount of green vegetation and tasselled cap moistness which describes the amount of soil moisture (Fig. 2). Finally, all transformed images were rescaled such that pixels took digital number values from 0 to 255.

Elevation data were derived from the Shuttle Radar Topography Mission (SRTM). Tiles of SRTM data corresponding to the 21 WRS-2 scenes of Landsat data used were downloaded from the Global Landcover Facility (*http://www.landcover.org*). These were then mosaiced and clipped in the same way as the satellite images. The resolution of this dataset was 90 m, but in order to overlay all layers of environmental data exactly, we resampled the SRTM to 30 m resolution to produce the final elevation map (Fig. 2) (see Long *et al.* 2008).

As a proxy measure of human impact, we made a data layer showing distance to the nearest settlement. A point shapefile containing all buildings on the west coast of Saudi Arabia was projected to UTM 37N and clipped to the study area. The source of these data was *http://www.gospatial.com*. We then converted the data to raster format in which each cell took as its value the distance (km) to the nearest settlement (Fig. 2).

Species distribution modelling

Generalised linear models (GLM) offer a simple and effective approach to modelling species' distributions (Brotons *et al.* 2004, Gibson *et al.* 2007, López-López *et al.* 2007, Mathys *et al.* 2006) and have been shown to be useful for shorebirds (Granadeiro *et al.* 2004). In order to make a GLM, the dataset must include presence and absence data. Since we were not able to collect definitive absence data for Kentish Plovers, we generated a set of pseudo-absence data (Chefaoui & Lobo 2008, Engler *et al.* 2004, Gibson *et al.* 2007). Therefore, 766 points (an equal number to the total number of presences recorded) were generated randomly within a 250 m buffer surrounding each of our transects in which no Kentish Plovers were found on either of our two surveys. The complete dataset of presences and pseudo-absences was then randomly split into two equal-sized partitions: training data and validation data (see Results).

We used a GLM with a binomial error distribution to model the probability of presence in our training dataset as a function of the environmental variables. Following Pearce & Ferrier (2000) we used linear terms in our analyses to restrict the complexity of the fitted models. We used the program R 2.7.2 for all statistical analysis (R Core Development Team 2008). We expressed our model as a habitat suitability map using map algebra on our environmental variable maps and model coefficients.

We assessed the predictive accuracy of the distribution model by using our validation dataset to compute a Kappa statistic at every possible threshold value of the predicted habitat suitability map (Pearson 2007). We then plotted a receiver operating characteristic (ROC) curve to visualise the

Table 1. Landsat scenes of the west coast of Saudi Arabia used in this study of Kentish Plover.

Path/row	Date	Sensor	Satellite	ID
p167r47	21 Jun 2000	ETM+	Landsat7	L7CPF20000401_20000630_08
p167r48	05 Apr 2001	ETM+	Landsat7	L7CPF20010401_20010630_05
p167r49	09 Sep 2000	ETM+	Landsat7	L7CPF20000719_20000930_09
p168r46	27 May 2000	ETM+	Landsat7	L7CPF20000401_20000630_08
p168r47	28 Apr 2001	ETM+	Landsat7	L7CPF20010401_20010630_05
p168r48	13 Aug 1999	ETM+	Landsat7	L7CPF19990701_19990930_14
p169r45	23 Sep 2000	ETM+	Landsat7	L7CPF20000719_20000930_09
p169r46	03 Jun 2000	ETM+	Landsat7	L7CPF20000401_20000630_08
p170r43	14 Sep 2000	ETM+	Landsat7	L7CPF20000719_20000930_09
p170r44	12 Jul 2000	ETM+	Landsat7	L7CPF20000701_20000718_08
p170r45	01 Nov 2000	ETM+	Landsat7	L7CPF20001001_20001231_07
p171r42	23 Oct 2000	ETM+	Landsat7	L7CPF20001001_20001231_07
p171r43	23 Oct 2000	ETM+	Landsat7	L7CPF20001001_20001231_07
p171r44	23 Oct 2000	ETM+	Landsat7	L7CPF20001001_20001231_07
p172r41	12 Sep 2000	ETM+	Landsat7	L7CPF20000719_20000930_09
p172r42	10 Jul 2000	ETM+	Landsat7	L7CPF20000701_20000718_08
p172r43	10 Jul 2000	ETM+	Landsat7	L7CPF20000701_20000718_08
p173r40	01 May 2001	ETM+	Landsat7	L7CPF20010401_20010630_05
p173r41	05 Oct 2000	ETM+	Landsat7	L7CPF20001001_20001231_07
p174r40	10 Sep 2000	ETM+	Landsat7	L7CPF20000719_20000930_09
p174r41	10 Sep 2000	ETM+	Landsat7	L7CPF20000719_20000930_09

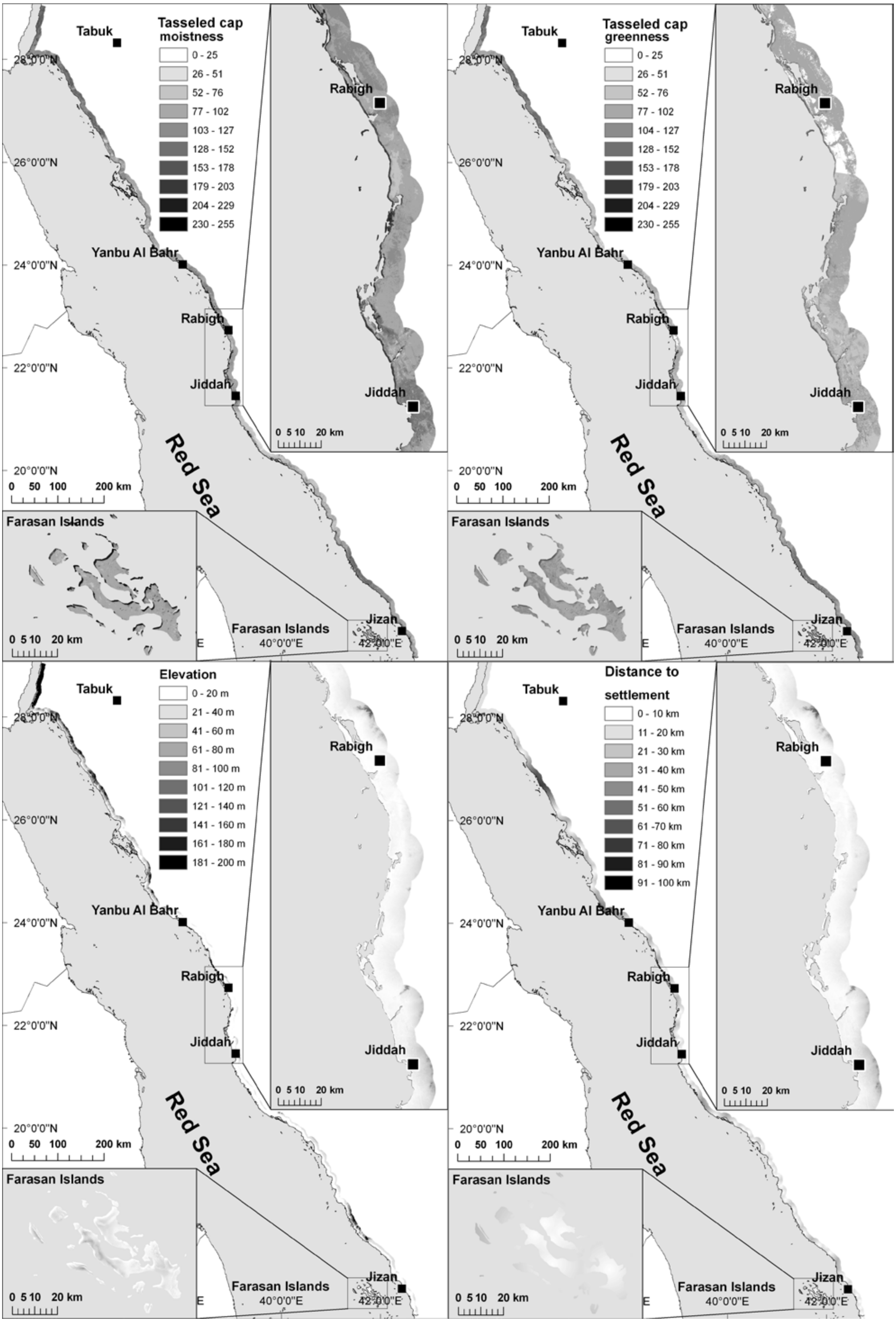

Fig. 2. Environmental variable maps for tasseled cap moistness, tasselled cap greenness, elevation and distance to the nearest human settlement used to model Kentish Plover distribution on the west coast of Saudi Arabia.

Table 2. Minimum adequate model of probability of Kentish Plover occurrence, logistic regression (GLM).

Response variable	Explanatory variable	Beta	*Z*	*P*
Kentish Plover	Intercept	9.597	9.837	<0.001
	Elevation	–0.230	–8.257	<0.001
	Tasseled cap greenness	–0.016	–3.833	<0.001
	Tasseled cap moistness	0.010	3.331	<0.001
	Distance to settlement	–0.935	–9.565	<0.001

Deviance = 1060.56, AIC = 824.4, n = 765 presences and pseudoabsence.

trade-off between the rate of omission errors (1-specificity) and commission errors (sensitivity) in our model across all threshold values. We then calculated the area under the curve (AUC) as a metric of model performance. The value of AUC can range from 0.5 for a model which performs no better than random to 1 for a model that fits the data perfectly (Elith *et al.* 2006, Pearce & Ferrier 2000). Finally, we estimated the threshold value that maximises the Kappa statistic in order to subsequently reclassify our habitat suitability map to two levels: unsuitable and suitable habitat (Liu *et al.* 2005).

Estimating population size from the habitat suitability map

First, we measured the area of habitat for Kentish Plovers at each level of suitability by plotting a histogram of the final habitat suitability map. Our Kappa-maximising threshold, the probability of occurrence above which a habitat unit likely supports Kentish Plovers, then allowed us to consider only the area of habitat predicted to be more suitable than this threshold.

Second, we estimated the density of Kentish Plovers across our study area using the program DISTANCE 6.0 (Thomas *et al.* 2009). We modelled the probability of detecting a group of plovers as a function of perpendicular distance from the transect lines. We considered the robust models suggested by Buckland *et al.* (2001). These included the uniform key function with cosine and simple polynomial expansion series, the half normal key function with cosine and hermit polynomial expansion series, and the hazard rate key function with cosine and simple polynomial expansion series. We chose the best-fitting model, which was the half normal with cosine detection function, by using Akaike's Information Criterion (AIC), where the model with the smallest AIC indicates the best model.

RESULTS

We observed 1,970 Kentish Plovers in 766 groups during our surveys of 98 transects. The mean group size was 2.57±3.22 individuals. Kentish Plovers were observed on at least one of the two surveys on 68 of the 98 transects (69%).

Distribution model

Kentish Plovers were significantly more likely to be present in landscape units at lower elevations, with less green vegetation, greater soil moisture and in areas more distant from human settlements (Table 2). The final habitat suitability map shows varying levels of habitat suitability for Kentish Plovers along the west coast of Saudi Arabia. Most of the suitable areas are concentrated from about 100 km south of Jiddah to Yanbu Al Bahr and near the city of Jizan. The suitable areas in the north are relatively small. In the Farasan Islands, the most suitable habitat is located on the northern and eastern shores (Fig. 3).

Model validation

The model performed well in predicting Kentish Plover presence when evaluated with an ROC plot (AUC mean = 0.796, SE = 0.016, Fig. 4). This suggests that in the final model, a cell predicted as suitable habitat, at any threshold of suitability, will be more suitable than a randomly selected cell in the study area at least 80% of the time.

Kentish Plover population estimate

The Kappa maximising threshold value of pr(occurrence) above which Kentish Plovers will use the habitat was a probability of 0.55. Only cells that predicted a habitat suitability value greater than, or equal to, this threshold were considered to be suitable. The total area of habitat more suitable than the threshold was 270 km^2 (Fig. 5). The mean density of Kentish Plovers across our study area was 36.87±5.14 individuals/km^2. We therefore estimated the total population of Kentish Plovers in our study area to be 9,955±1,388 individuals.

DISCUSSION

The Kentish Plover is a common but declining breeding bird in the Arabian Peninsula, and our work opens the way for further studies to estimate its total population size in the region. Using census data and remote-sensed data, we were able to estimate the number of adult plovers during the breeding period. The study area is huge and therefore a combination of fieldwork and remote-sensing is essential. Similar studies may follow-up our current work by covering inland sites.

Kentish Plovers preferred sites with low elevation, less vegetation, higher moistness and areas further away from human settlements. Distance to settlements probably has a negative influence because human activities and the density of predators, such as dogs, cats and crows, increase near settlements and impact breeding and survival rates. Specifically these influences reduce incubation and brooding efforts and decrease foraging opportunities for adults and chicks (Lafferty 2000, 2001, Montalvo & Figuerola 2006, Norte & Ramos 2004, Ruhlen *et al.* 2003). Several studies have shown that the occurrence and distribution of Kentish Plovers is influenced by human activities. Montalvo & Figuerola (2006) found that Kentish Plovers in Catalonia, Spain, were disturbed by intensive use of beaches by tourists, as well as by the presence of feral dogs and cats. Lamonte *et al.* (2006) also found that, in both the breeding and non-breeding seasons, numbers of its close relative, Snowy Plover *C. a. nivosus*, were sensitive to human disturbance in Florida. On the shores of Eel River, California, human activity and predators significantly influenced the reproductive success of Snowy Plovers (Colwell *et al.* 2005). The negative impact of human activities has been reported for many other plovers such as: Piping Plover *C. melodus* (Burger 1994), Ringed Plover *C. hiaticula* (Liley & Sutherland 2007) and Malaysian Plover *C. peronii* (Yasué & Dearden 2006).

The preference for open areas with less vegetation prob-

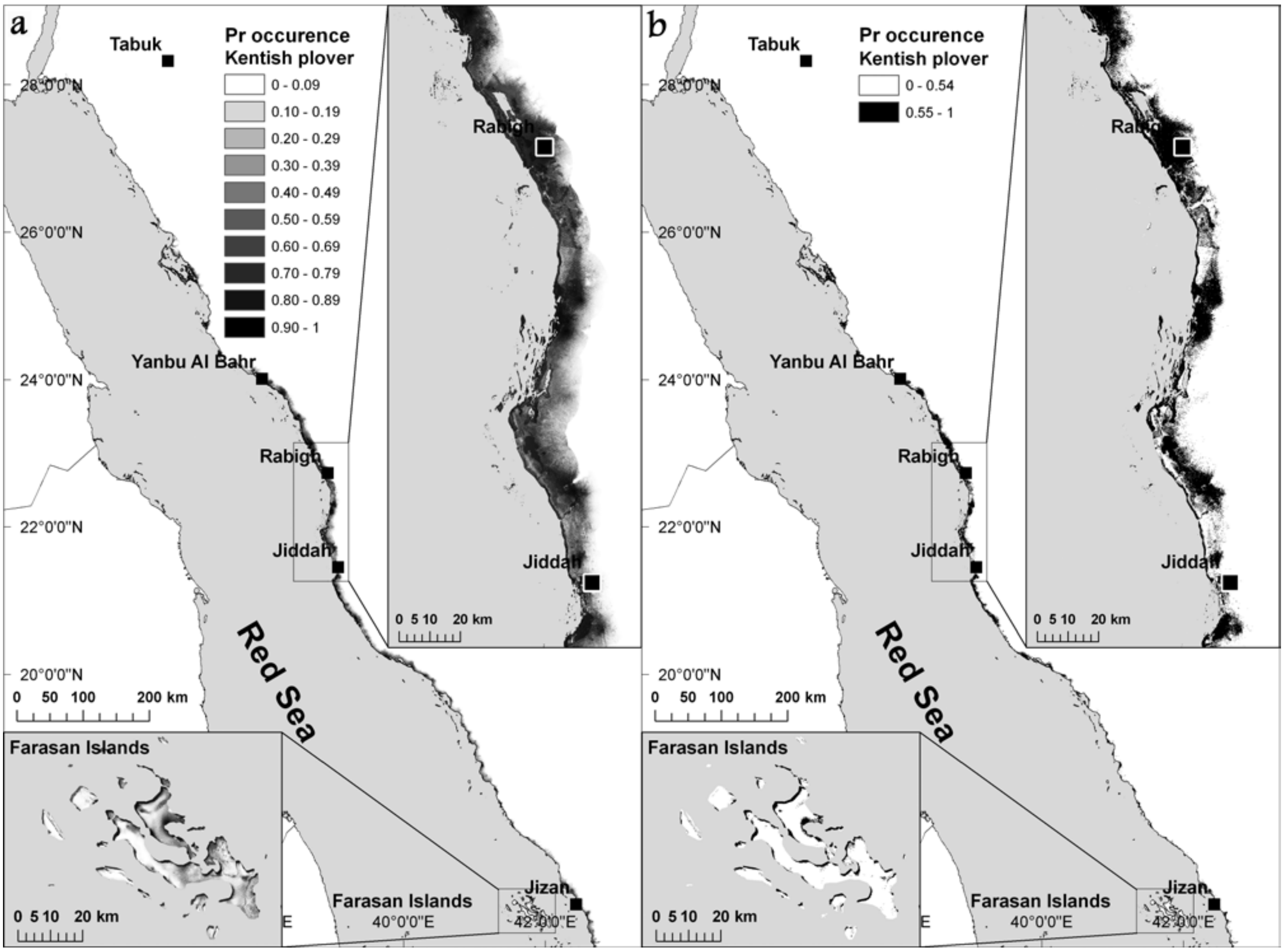

Fig. 3. Final Kentish Plover habitat suitability maps: (a) Absolute probability of occurrence of Kentish Plovers; (b) Kentish Plovers present/absent (the absolute probability of occurrence map was thresholded by the Kappa-maximising threshold).

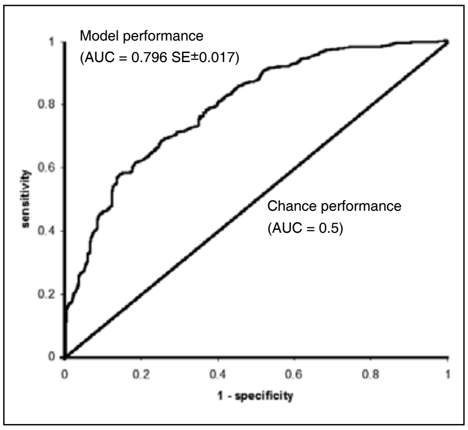

Fig. 4. Receiver operating characteristic (ROC) plot of the Kentish Plover distribution model performance relative to validation data. Sensitivity is the true positive fraction, and 1-specificity is the false-positive fraction for each unique threshold in the predicted distribution map. The diagonal line represents the model performance that would be expected by chance alone. The high AUC (0.796) of the model suggests that it has excellent power to discriminate between observed presence and absence.

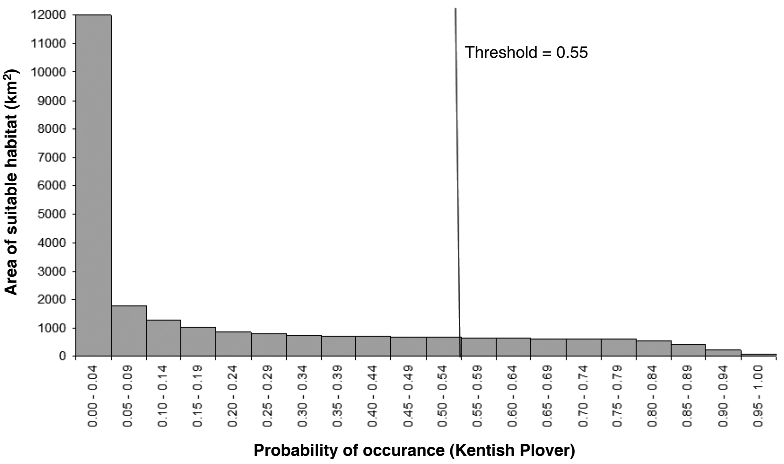

Fig. 5. Histogram of area of suitable habitat in 0.05 bins of probability of occurrence of Kentish Plovers. The vertical line represents the 0.55 sensitivity-specificity threshold derived from the ROC curve. Kentish Plovers will be absent from habitat less suitable than this threshold and present in the habitat more suitable than the threshold. The total area of the study region was 1,078 km^2, but, the area of habitat more suitable than the threshold was 270 km^2.

ably reflects the benefit of sites that afford good long-distance visibility for the detection of approaching predators (Amat & Masero 2004, Muir & Colwell 2010, Page *et al.* 1983). Snowy Plover eggs and chicks are probably more cryptic in open sites, such as saltmarshes, because of their disruptive coloration (Page *et al.* 1983). Moreover, open areas allow the mobility required for ground feeding adults and precocial young. Similarly the majority of Snowy Plover breeding locations in the Caribbean and Bahamas are associated with salt flat habitat (Gorman & Haig 2002). At Lake Atanasovsko in Bulgaria, a decline in the Kentish Plover breeding population was attributed to the overgrowing of dikes with tall vegetation (Dalakchieva 2003). In the lower Laguna Madre region of Texas, Snowy Plover nest survival decreased with increasing vegetation (Hood & Dinsmore 2007). Snowy Plover nests in open sites in north-central Oklahoma had less predation.

It is likely that the observed preference for lower elevation and high moisture reflect the availability of food resources. Shorebird distributions are known to be strongly influenced by the distribution and abundance of specific food resources, and many studies have found a positive correlation between shorebird abundance and the abundance of their prey across large spatial scales (Colwell & Landrum 1993, Placyk & Harrington 2004, Ribeiro *et al.* 2004). Food abundance, predation pressure and indirect human disturbance were not included in our model because they could not be directly measured by remote sensing. Additionally, stochastic meta-population processes may mean that some potentially suitable habitat patches may not be occupied at certain times. Our final habitat suitability map is consistent with the "interim" atlas produced by Jennings (1995). The collection of additional field data in future studies will allow a more complete assessment of the adequacy of our model.

Conservation implications and applications

On the basis of our model and observations, we recommend that the most suitable Kentish Plover habitat along the west coast of Saudi Arabia should be protected from both disturbance and predation risk through restricting access by humans and terrestrial predators (especially domestic cats and dogs). These areas should be large enough to include both good sites for foraging and nesting. We recommend that the northern and eastern shores of the Farasan Islands, one of the most important breeding areas, be given more protection by establishing new fenced areas, each of which should be at least 5 km × 1 km. We also recommend establishing new protected areas 20 km south of Jiddah, 10 km north and south of Jizan and 5 km south of Rabigh; each should be at least 15 km × 1 km.

We conclude that it is necessary to identify environmental variables defining suitable habitat for species on a large spatial scale in order to underpin conservation planning and evaluate its consequences. We believe that our modelling approach provides a foundation for conservation planning and long-term population monitoring of Kentish Plovers and other shorebirds in this region. We also believe that conservation of Kentish Plover habitat will not only protect this species but will also benefit other shorebirds, particularly those with similar habitat requirements. Finally we recommend that areas of high habitat suitability be included in future protected area planning.

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