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Agricultural intensification, rainfall patterns, and large waterbird breeding success in the extensively cultivated landscape of Uttar Pradesh, India

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ABSTRACT

In countries with high human populations, using agricultural areas as multifunctional systems to produce food for humans and retain wildlife may be an efficient conservation strategy for many species. Inclusion of natural habitat and species requirements on agricultural landscapes explicitly into planning processes are precluded by lack of information on drivers of species persistence. Climate change is an additional emerging complexity, and adaptation plans for agricultural landscapes are biased towards intensification to secure long-range food production. I examine the conservation potential of an agricultural landscape in two districts of Uttar Pradesh, north India where agricultural intensification and altered rainfall patterns are predicted to occur. I assess stressors affecting breeding success over eight years of two large waterbirds of conservation concern – Sarus Cranes and Black-necked Storks. Both species had high breeding success that improved with total rainfall and more wetlands in breeding territories. Agricultural and township expansions deteriorated territory quality and reduced breeding success. Sarus Crane populations were predicted to decline relatively rapidly if development activities continued to displace breeding pairs. Black-necked Storks appeared resilient over the long-term notwithstanding reduced breeding success in low-rainfall years. Waterbird nesting habitats (wetlands and trees) were retained in Uttar Pradesh as community lands by villages and by state government via legal provisions suggesting the utility of multiple conservation approaches. Incorporating species requirements explicitly, alongside traditional land use practices conducive for habitat conservation, into adaptation planning and conservation policy will be necessary to retain long-term multifunctionality of such agricultural landscapes.

1. Introduction

Two of the most important global conservation themes currently are maximizing the potential of agricultural landscapes to retain biodiversity and adaptations to reduce the negative effects of changing climate on biodiversity (Novacek and Cleland, 2001; Hannah et al., 2002; Millenium Ecosystem Assessment, 2005). In tropical and sub-tropical regions with high human population densities like in South Asia, human needs for land are making conventional conservation strategies for biodiversity (e.g., increasing protected reserves; Madhusudan and Rangarajan, 2010; Sodhi and Ehrlich, 2010) and climate change-related strategies to conserve individual species (e.g., assisted colonization to improve chances of species persistence; Loss et al., 2010) increasingly untenable. Maximizing the potential of agricultural landscapes, which is the primary land use in many tropical and subtropical regions (Ramankutty et al., 2002), to enable persistence of at least some species may instead prove to be an efficient long-term strategy. Planning for biodiversity conservation given climate change is biased towards protected natural areas and biodiversity hotspots, and there is an urgent need to better understand how climate change may affect multifunctionality of agricultural landscapes: their ability to produce food for humans and retain biodiversity (Mawdsley et al., 2009; Wills and Bhagwat, 2009).

Land use change is predicted to be more important relative to climate change for terrestrial biodiversity declines, but an understanding of specific factors influencing species persistence on agricultural landscapes and how these interact with climate change is meager (Sala et al., 2000; Sodhi and Ehrlich, 2010). Agricultural landscapes are increasingly being recognized as refugia and even as primary habitat for a large number of species including those of global conservation concern (Wills and Bhagwat, 2009; Athreya et al., 2010; Sundar and Subramanya, 2010). Birds have featured prominently as valuable indicator taxa to understand effects of agriculture and climate change, and to develop policies and strategies to reduce detrimental impacts of agriculture on biodiversity (Millenium Ecosystem Assessment, 2005; Jetz et al., 2007). Stressors associated with agricultural landscapes, such as habitat loss, reduction in prey abundance, changes in cropping species and patterns, and human disturbance, can limit avian breeding success

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(Newton, 2004; Radford et al., 2005; Sundar, 2009a; Schaub et al., 2010). Similarly climate, especially rainfall, affects avian breeding success due to changes in the timing of habitat formation and food availability (Kushlan, 1986; Dickey et al., 2008; Gaston et al., 2009). Very few studies simultaneously assess the impacts of agricultural intensification and climatic conditions (Kleijn et al., 2010).

The Gangetic floodplains in North India are one of the four most intensively cultivated landscapes globally with the fifth highest human density (Ramankutty et al., 2002), yet remain multifunctional producing 22% of the rice grown in the Indian subcontinent and retaining high avian diversity (Sundar and Subramanya, 2010). Factors contributing to this multi-functionality include the preponderance of flooded rice paddies that resemble wetland habitat and facilitate flooding of persisting wetlands during the breeding season, cultural practices of retaining wetlands for community use, religious reverence towards birds, and absence of mechanized cultivation that could increase mortality of unfledged chicks and increase intensification (Scott, 1989; Sundar, 2009a,b). Scientific attention to wildlife persisting in the Gangetic floodplains is recent, but adverse effects of agricultural intensification including reduced occupancy rates of numerous bird species are already apparent (unpublished data). The world's largest known breeding population of two large waterbirds of conservation concern, the Sarus Crane *Grus antigone* (vulnerable) and Black-necked Stork *Ephippiorhynchus asiaticus* (near-threatened), also occur in this region (Sundar, 2003, 2009a). Predictions of future conditions in North India suggest increased agricultural intensification due to large-scale immigration forced by sea-level rise, and increased aridity in surrounding regions and countries (CENTRA Technology Incorporated and Scitor Corporations, 2009), and reductions in crop productivity (Welch et al., 2010). Rainfall amounts are also predicted to change with an increase in extreme events including droughts and high-rainfall years (Goswami et al., 2006; Kumar et al., 2006). There is currently limited discussion on, or planning for, these predicted events and these plans do not include species that persist here (Rosencranz et al., 2010).

The goal of this paper is to understand the value of this human-dominated landscape for two large waterbird species of conservation concern, and identify factors that require attention to aid in the conservation of these and species with similar requirements. Using an eight-year data set of breeding success of territorial pairs of Sarus Cranes and Black-necked Storks in the districts of Etawah and Mainpuri in Uttar Pradesh state, I evaluate (1) the relative importance of persisting natural habitat and rainfall patterns on breeding success and (2) use population viability analyses and sensitivity analyses to understand stressors influencing longer-term persistence of both species on this agricultural landscape.

2. Materials and methods

2.1. Study area

This study was conducted at Etawah and Mainpuri districts of Uttar Pradesh in the upper Gangetic flood-plains which are influenced by the tributaries of the Yamuna and Ganges rivers and several irrigation canals (Fig. 1a and b). The state of Uttar Pradesh with 199 million people has the highest population of any Indian state with over 800 people km^{-2} (Office of the Registrar General of India, 2011). The terrain was flat dominated by open agriculture with human habitation, alkaline wastelands and irrigation canals, and remnant patches of wetlands, scrublands, and woodlands (Fig. 1b–d). The primary crops were flooded rice during the rainy season (July–October), wheat-mustard during the winter (November–February), with fields mostly left fallow or used to grow vegetables and fruits during the summer (March–June). Rainfall was strongly seasonal occurring as the south-western monsoon in July–October in normal years. The past decade included five episodes of non-normal rainfall in terms of timing and volume, including the year with the most delayed rains in four decades (Francis and Gadgil, 2009), congruent with global climate change related predictions for the region. During the study, wetlands declined in extent due to expansion of settlements and conversions to crop fields (Fig. 1d) mirroring predicted future changes.

2.2. Focal species biology and data collection

Breeding pairs of both focal waterbird species were perennially territorial with territories comprising wetland areas and agricultural land (Sundar, 2003, 2009a). I located 253 Sarus Crane pairs and 29 Black-necked Stork pairs (Fig. 1c), and monitored breeding success for eight years between 1999 and 2010. Roads were traversed to locate and monitor breeding pairs, and detailed behavioral observations of breeding pairs over three years (1998–2000) were used to determine extent of territories. Sarus Crane territories were <50 ha, and Black-necked Stork territories were estimated at 3–5 km^{-2} (Sundar, 2009a, personal observations). Both species timed nesting with the monsoon and all surviving chicks fledged in the winter and stayed in natal territories until the subsequent breeding season (Sundar, 2003, 2009a). Individual territories were surveyed 1–5 times between January and April, and number of fledged chicks in each territory was noted. When breeding status for a pair in any year was unclear due to either inability to visit immediately after chicks fledged, the pair was not included in the analysis for that year. On average, breeding status was assessed for 83% (range: 43–100%) of Sarus Crane pairs and 94% (range: 83–100%) of Black-necked Stork pairs annually. Rainfall data were collected from district headquarters, and pooled from Karhal and Etawah weather stations. Each year, rainfall was described by two parameters well known to affect waterbird breeding success (Kushlan, 1986; Frederick and Collopy, 1989; Monadjem and Bamford, 2009): (1) total annual rainfall, and (2) post-monsoon rainfall during October to February. Sarus Cranes built nests in wetlands, and chicks remained in natal territories until the subsequent breeding season (Sundar, 2009a). Black-necked Storks nested on trees but required wetland habitat to forage in, and chicks foraged in select wetlands inside natal territories until they dispersed (Sundar, 2003). Wetlands were retained on the landscape as community lands by village councils or as very small patches in private fields, and trees were retained as common property, private holdings, or managed by the state forest department (personal observation). Territories with more wetlands improved Sarus Crane chick fledging (Sundar, 2009a), and also appeared to be important for Black-necked Stork chick survival (personal observations). To explicitly account and test for habitat effects, wetlands were described by two parameters: (1) territory quality measured as percentage of the territory that was wetlands in October 2001; territories were categorized into groups based on extent of wetland presence (1 – 0–10% wetlands, 2 – 10–20% wetlands, etc., to 10 – 90–100% wetlands), and (2) an index of wetland decline in each territory due to either agriculture or expansion of settlements (0 – no attrition of wetlands within a particular territory in any year; 1–3 – additional events of wetland attrition in a particular territory in successive years; 4 – complete removal of wetlands).

2.3. Statistical analyses

2.3.1. Regression analyses

Since both species are poorly studied, I present commonly derived descriptors of breeding success. Rainfall variables were log-transformed to achieve near-normality. I assessed all possible 1-, 2-, 3-, and 4-parameter additive models, a null model, and a

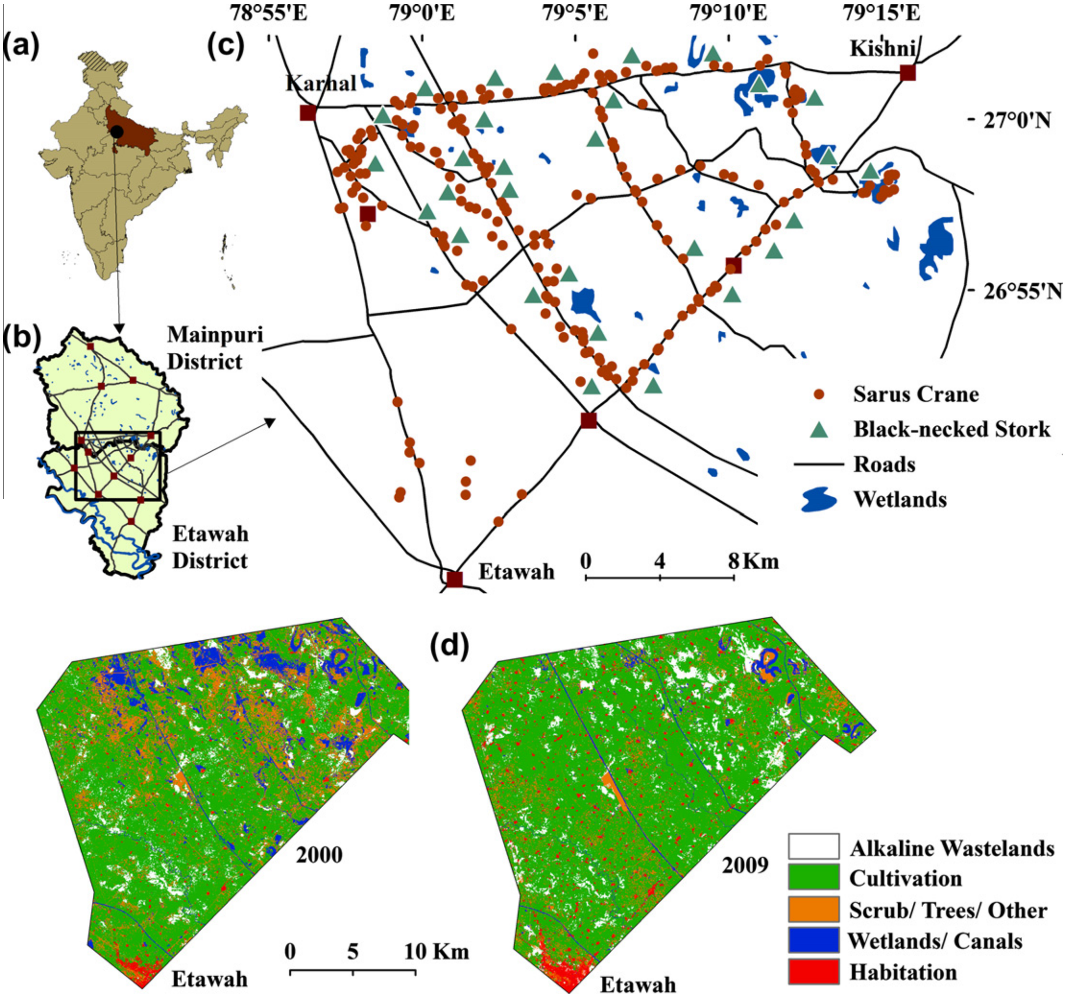

Fig. 1. Map of study area showing (a) location of Uttar Pradesh state in India (disputed international boundaries are hatched) and location of study area in the state, (b) Etawah and Mainpuri districts with location of study area showing major towns, canals, roads and wetlands (>10 ha) in the two districts, (c) locations of monitored pairs of Sarus Cranes and Black-necked Storks, and (d) satellite imageries showing winter land use change in the study area from 2000 (01 October; LANDSAT ETM+) to 2009 (06 February; IRS LISS-III).

model with year to assess potential inter-annual variations for both species. I ascertained the best models using Akaike Information Criteria for small sample sizes (AIC_c), and influence of individual parameters using summed model AIC_c weights (w_i) across models containing the variable of interest when model selection indicated uncertainty (multiple models with $\Delta AIC_c < 2$ units; Burnham and Anderson, 2002; Arnold, 2010). Sarus Crane brood size was 0–2, and I analyzed the effects of variables on total chicks produced assuming a Poisson distribution. I carried out generalized linear mixed modeling using the package glmmML in R (Broström, 2009). Pair location was included as a random effect to avoid potential spatial autocorrelation. Black-necked Stork brood sizes varied from 0 to 4, the distribution of chick numbers was bimodal, and models using pair location for a repeated measures design did not converge likely due to low sample sizes. Therefore, to reduce complexity, I analyzed productivity as a binary response – whether or not pairs raised chicks. I carried out logistic regression using the function glm with a binomial function in R (R Development Core Team, 2011) to assess how variables affected the ability of stork pairs to raise chicks.

2.3.2. Population viability and sensitivity analyses

I evaluated viability of the population of both species using deterministic population models in the software VORTEX (Lacy et al., 2007). A full list of parameters required and values used to run models, and predictions using current conditions for both species are provided in Table 1. Survival rates for first year birds for both species were from the study area (Sundar, 2003, 2009a). For Sarus Cranes, estimates of survival of 1–3 year old Blue Cranes *Anthropoides paradiseus* in agricultural landscapes that closely resembled conditions in Uttar Pradesh were used (Altwegg and Anderson, 2009). Survival rates are unavailable for Black-necked Stork chicks, and I assumed a conservative rate of 10% mortality at each age group. I modeled environmental variation ("Catastrophe" in VORTEX) for observed effects due to wetland attrition and rainfall. To assess effects of low-rainfall years, a condition that occurred three out of eight years, or 38%, during the study, I use rainfall as the second catastrophe using an over-estimate of 10% decline of breeding success for both species ignoring positive effects during high-rainfall years. This scenario is analogous to future conditions if flooded rice is not cultivated during low-rainfall years, which is likely to increase drier conditions and exacerbate chick mortality. Mortality of breeding pairs due to electrical wires, poisoning and other reasons were not considered since such territories were quickly occupied by pairs without breeding territories (personal observations). I conservatively estimated 1250 and 125 breeding pairs of Sarus Cranes and Black-necked Storks, respectively, in the study area and districts contiguous with Etawah

Table 1
List of variables and values used to model persistence of one breeding population each of Sarus Cranes and Black-necked Stork in Etawah and Mainpuri districts, Uttar Pradesh, India. All sex ratios were assumed at 50%, mortality rates were assumed to be similar across sexes, and additional parameters available in VORTEX not listed here were not used to model simulations. Values in bold represent current situation from field studies (see Sections 2 and 3 for details), values assuming realistic improvements given conservation intervention are underlined, values assuming future deterioration are italicized, and values that are either assumed (lack of data) or from other studies are unmarked.

Variable	Sarus Crane	Black-necked Stork
Scenario settings		
Iterations	500	500
Number of years	50, 100	50, 100
Extinction definition	Only one sex remains	Only one sex remains
Species description: Dispersal		
EV concordance of reproduction and survival	0.5	0.5
Number of catastrophes	**2**	**2**
Species description: Reproductive system	Long-term monogamy	Long-term monogamy
Age of first offspring (female)	3	3
Age of first offspring (male)	3	3
Maximum age of reproduction	40	40
Maximum No. broods annually	**1**	**1**
Maximum brood size	**2**	**4**
Species description: Reproductive success		
% Adult females breeding (EV)	**100% (0)**	**65% (5)**
Distribution of broods annually		
Zero	**68**	**56**
One	**32**	**44**
Brood size distribution		
One	**70**	**11.5**
Two	**30**	**47.9**
Three	**-**	**36.5**
Four	**-**	**4.1**
Species description: Mortality rates		
Age: 0–1 year	55, **68**, *75*	10, *25*
Age: 1–2 year	27	10
Age: 2–3 year	27	10
Age: 3+	10	10
Catastrophes: 1. Rainfall		
Frequency (%)	**38**, *50*	**38**, *50*
Severity – reproduction	*0.8*, **0.9**	*0.7*, **0.8**
Severity – survival	**1**	**1**
Catastrophes: 2. Habitat attrition		
Frequency (%)	7.5, **9.7**, *12*	**6.5**, *10*
Severity – reproduction	*0.8*, **0.9**	**0.8**, 0.9
Severity – survival	*0.8*, **0.99**	*0.9*, **1**
Initial population size (No. breeding pairs)	1250	125
Carrying capacity (No. breeding pairs)	1250	125
Number of total scenarios	288	64

and Mainpuri with the same cropping patterns and cultural ethos of retaining wetlands and trees (unpublished information). For the purposes of this paper, instead of altering carrying capacity values in VORTEX for both species, I represent this as <1 probability of survival of pairs and relate this to habitat attrition (see Table 1). In VORTEX, altering carrying capacity values requires knowledge of change in rates over specific time periods. I avoided assuming these rates, and instead provided a constant annual rate based on number of pairs permanently displaced over the study period. Opportunities for the number of breeding pairs to increase appeared bleak given high human densities, agricultural extent, and rate of growing settlements (Fig. 1d). Rate of survival therefore only declined for scenarios. Scenarios specifically tested for variations across five broad parameters that were of specific interest to this study: (1) rate of change in territory quality, (2) change in breeding success due to territory quality, (3) change in frequency of dry years, (4) change in breeding success due to dry years, and (5) change in survival rate of breeding pairs (for Black-necked Storks, this assumes removal of nesting trees). Scenarios for these five parameters, and mortality rates of 1–4 year old birds, were constructed assuming plausible optimistic (practical levels of conservation intervention) and pessimistic conditions (accelerated but plausible level of effects) and population metrics were modeled. Sarus Crane breeding success was affected by more variables relative to Black-necked Storks (see Section 3), and total number of scenarios that were required to be considered were far more for the cranes (288 versus 64). I ran 500 simulations for each scenario to assess probability of extinction (PE) of both species over 50 and 100 years (congruent with medium- and long-term planning), the modeled rate of population change (*r*), and estimated size of persisting population for each scenario (*N*). To assess relative importance of the factors on *N* and *r*, I carried out sensitivity analyses by varying effects of each parameter individually on breeding success or pair survival at −20%, −10%, +10% and +20% of current levels (see Miller and Lacy, 2005). These variations were much more severe than the plausible optimistic and pessimistic scenarios (see Table 1), and were intended to help detect variables with the strongest effect on predicted *N* and *r* and help focus conservation planning. I generated predictions of *N* and *r* using 500 simulations each time, and used line graphs to identify the most important variables.

3. Results

3.1. Sarus Cranes

Annually, wetland attrition due to expansion of agriculture and towns reduced territory quality of 9.7% of Sarus Crane pairs. Expansion of towns permanently displaced 0.7% of pairs annually. Sarus Crane fledging success and annual reproductive success reduced perceptibly during years of reduced rainfall (Table 2, Fig. 2). Support was unambiguous for the full model (>551 AIC_c units from the next-best, $w = 0.99$). Breeding success increased with more wetlands in territories and increased rainfall, but decreased with wetland removal (Table 3). Simulations using values for current conditions and all plausible scenarios indicated decline of the population (see Appendices A and Ba). For 50-year scenarios, PE was low (average: 0.03 ± 0.06 SD; range: 0–0.26), but predicted *N* was also low (average: 45 ± 38 SD; range: 7–139). Probability of extinction at 100-years was high (average: 0.89 ± 0.21; range: 0.32–1) with very low estimated *N* (average: 2.9 ± 2.02; range: 0–7). Simulated variations in survival of breeding pairs caused the highest variations in both *N* and *r* relative to any other variable (Fig. 3a and b).

3.2. Black-necked Storks

Annually, agricultural expansion caused reduced quality of territories of 6.7% of breeding pairs, and none were permanently displaced. Two broods of four chicks fledged within the study area following years of above-normal rainfall (Table 2). In addition, four broods of four chicks and one with five chicks were observed near the study area following the high rainfall in 2008. Black-necked Stork breeding success improved during both years of above-normal rainfall (Fig. 2). Model selection indicated high uncertainty with the top seven of the 16 models being within 2 AIC_c units, but all top models included total rainfall. Strong positive effects of total rainfall ($\Sigma w = 0.99$) and post-monsoon rainfall

Table 2
Descriptive statistics of breeding success of Sarus Cranes and Black-necked Storks in Etawah and Mainpuri districts, Uttar Pradesh, India during 1999–2010. (N = number of pairs monitored.

Nesting year	Sarus Crane				Black-necked Stork		
	N	% Successful pairs	% Successful with two chicks	Average chicks fledged per breeding female[a] (SD)	*N*	% Successful pairs	Average chicks fledged per breeding female[a] (SD)
1999	108	33.3	36.1	0.45 (0.7)	24	50	1.17 (1.3)
2000	208	29.8	41.9	0.42 (0.7)	29	13.8	0.28 (0.8)
2001	253	28.5	30.6	0.37 (0.6)	28	32.1	0.50 (0.8)
2003	221	44.8	40.5	0.66 (0.8)	27	74.1	1.78 (1.2)
2004	228	27.2	27.4	0.35 (0.6)	29	48.3	1.03 (1.2)[b]
2005	229	29.3	14.9	0.34 (0.6)	25	20	0.40 (0.9)
2008	227	37	31	0.48 (0.7)	26	88.5	2.4 (1.0)[b]
2009	215	22.8	22.5	0.28 (0.6)	29	24.1	0.55 (1.0)
Average (SD)		31. 6 (10.2)	31.4 (6.8)			43.9 (26.6)	

[a] Following Murray (2000); includes females of pairs that failed to raise any chick.
[b] Years with at least one Black-necked Stork brood of 4 fledged chicks.

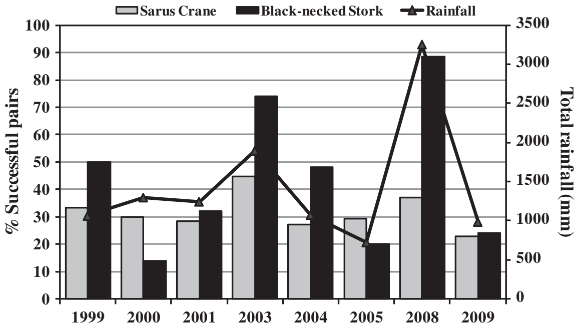

Fig. 2. Percentage of breeding pairs of Sarus Cranes and Black-necked Storks successful in raising at least one chick annually versus total annual rainfall. Note that data was not collected for 2002, 2006 and 2007.

Table 3
Influence of habitat and climatic variables on Sarus Crane breeding success. Model selection indicated very strong support for a single model ($w = 0.99$ of 16 candidate models; the next-best model was >552 AIC_c units;), and only results for the top model is shown. Rainfall data was log-transformed for analysis.

	Best model	
	Effect	SE
Model selection criteria		
$\Delta\mathrm{AIC}_c$	0	–
w	0.99	–
Deviance	1712	–
Variables		
Intercept	−4.29	0.64
Territory quality	0.23	0.02
Wetland attrition	−0.27	0.06
Total rainfall	0.86	0.19
Post-monsoon rainfall	0.02	0.04

($\Sigma w = 0.56$) on ability of stork pairs to raise chicks were evident (Table 4). Territory quality ($\Sigma w = 0.43$) and wetland attrition ($\Sigma w = 0.4$) had weak positive and negative effects respectively on breeding success (Table 4). Simulations indicated a positive growth rate even with the most pessimistic plausible scenario (see Appendices A and B). Modeled population parameters for 50- and 100-years were identical showing persistence of nearly all the population (average N: 247 ± 1.6; range: 243–250) and PE = 0. Variations in survival of pairs due to habitat attrition caused the highest variation in N relative to other variables (Fig. 3c). Population growth rate was affected to the greatest extent by declines in breeding success due to deterioration of territory quality, number of dry years, and decreased survival of pairs (Fig. 3c and d).

4. Discussion

Breeding success of Sarus Cranes and Black-necked Storks was affected by declines in wetland extent within territories and changes in rainfall patterns in Etawah and Mainpuri. Descriptive breeding success parameters for the two species over multiple years are absent from other areas disallowing a ready comparison of observed inter-annual variation. Average values for Sarus Crane demographics from various sites with 1–3 years of observations (see Sundar and Choudhury, 2003), however, suggests that the breeding success parameters of the Etawah–Mainpuri crane population are the highest known despite including dry years with low breeding success. Breeding success metrics for single-nesting storks are not readily available. For both species, breeding success improved with more wetlands in territories, and permanent removal of breeding pairs was the most important factor affecting modeled population metrics of both species. Rainfall-related effects on breeding success appear to be less important relative to habitat conversion for both species currently. Despite high farmer activity and few wetlands persisting, monitored Sarus Crane pairs fledged 702 chicks, and Black-necked Stork pairs fledged 253 chicks with several broods of four and one of five. Broods of four have rarely been recorded, and broods of five fledged chicks never recorded, for single-nesting storks anywhere (Thomas, 1981; Sundar et al., 2007). This suggests that remnant wetlands amid croplands can offer substantial merits to maintaining even large, carnivorous species like Black-necked Storks. In other locations, human persecution of nests and removal of nestlings for trade are the most important reasons for declines of the two species (Rahmani, 1989; Clements et al., 2007). Farmer attitudes towards the two species and towards wetlands and trees, in Etawah and Mainpuri have helped retain conducive conditions.

4.1. Development and waterbird populations

The wetland-nesting Sarus Cranes appear to be more vulnerable relative to the tree-nesting Black-necked Storks despite a much smaller breeding population of the latter in Etawah and Mainpuri. While both trees and wetlands were removed from the landscape during the study, the larger territory sizes of Black-necked Storks and numbers of surviving trees disallowed permanent displacement of any pair, and appear adequate for the storks' long-term persistence. Permanent displacement of Sarus Crane pairs occurred due to expansion of towns. Annual rates of permanent displacement (or "survival of breeding pairs" in VORTEX models) were relatively low at 0.7% of pairs, but a continuation of this rate is adequate to halve the breeding population within a decade

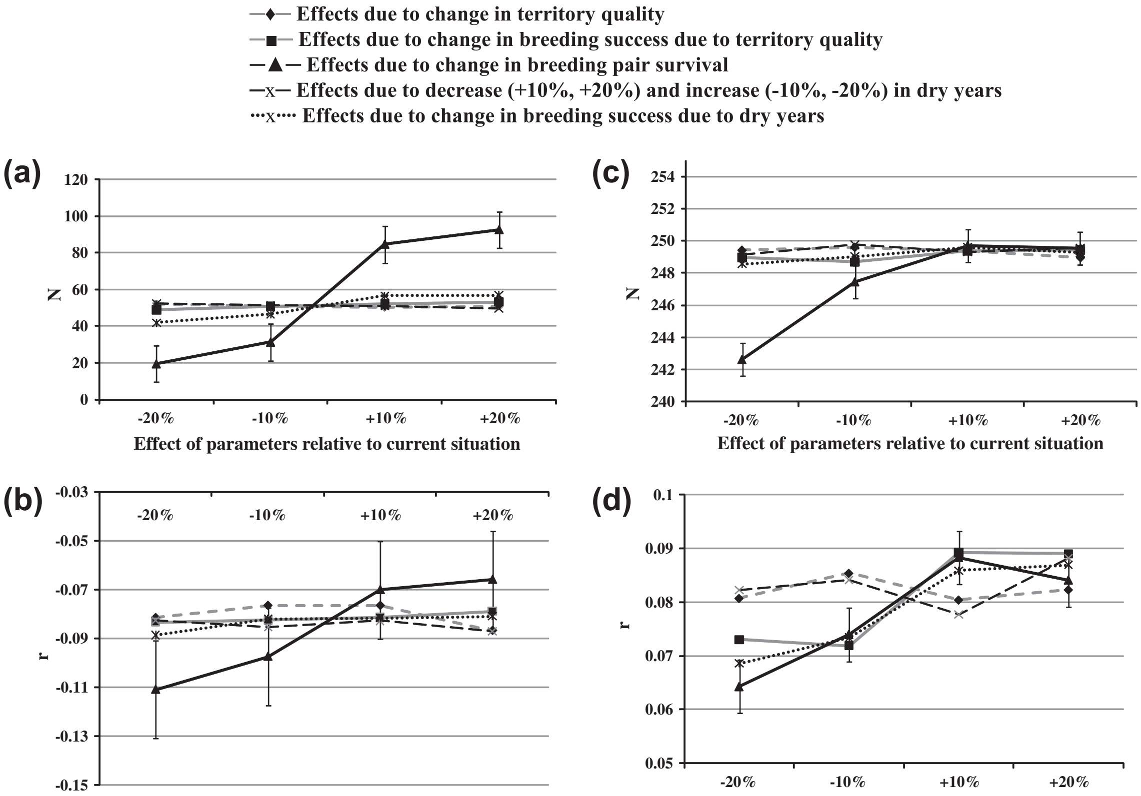

Fig. 3. Sensitivity analyses of five parameters affecting breeding success and survival of breeding pairs of two large waterbird species in Etawah and Mainpuri districts, Uttar Pradesh, India. Persisting population size in 50 years (*N*), and rates of population change (*r*) of Sarus Cranes (a and b) and Black-necked Storks (c and d) averaged from 500 iterations are provided. SD bars are shown only for the variable with the biggest observed changes.

Table 4

Influence of habitat and climatic variables on Black-necked Stork breeding success. Model selection indicated high uncertainty (top seven out of 16 total models were within 2 AIC_c units), and the effects of the top three models are indicated here. Rainfall data was log-transformed for analysis.

	Best model		2nd Best model		3rd Best model	
	Effect	SE	Effect	SE	Effect	SE
Model selection criteria						
ΔAIC_c	0.00	–	0.81	–	1.08	–
w	0.29	–	0.19	–	0.17	–
Deviance	276.50	–	277.31	–	273.58	–
Variables						
Territory quality	–	–	0.16	0.09	0.16	0.1
Wetland attrition	–	–	–	–	-0.03	0.22
Total rainfall	5.33	0.93	4.91	0.91	5.4	0.94
Post-monsoon rainfall	0.31	0.17	–	–	0.32	0.16

(Appendix A). Accelerated township development and construction of an airport fueled by political interests occurred during the study period, but were stopped after a shift of political power (see Fig. 1d; Prasad, 2006). This spurt of development displaced several breeding crane pairs permanently and deteriorated quality of several territories. Another reversal of political power seems untenable in the near future (Rangarajan, 2007). This suggests that the assumed steady rate of decline in breeding pairs and modeled declines in Sarus Crane population are overly pessimistic. However, observations over eight years and long-term modeling provide the unambiguous conclusion that development plans failing to consider retaining the farmland-wetland mosaic will result in rapid declines of populations of wetland bird species.

Agricultural projects such as a regional-scale wasteland development project also occurred during the study period resulting in the conversion of wetland areas and alkaline soil patches to agriculture (Sethi, 2001). Large-scale conversions of farmland-dominated villages to towns have occurred in recent years in India in part due to an archaic Land Acquisition Act set up in 1894 (e.g., Narain, 2009). Variations in rainfall especially increase in dry years can prompt rapid sales of farmland to development (Deininger et al., 2009). Until very recently, legislation in India allowed conversion of farmlands, or transfer of agricultural land, to development (Maurya, 1981), and impacts on wetlands due to projects directed at increasing agriculture were not considered (Sethi, 2001). Declines of community-managed habitats in India despite cultural norms have been fuelled by pressure for land and corrupt management resulting in illegal conversions to private farmlands. This has led to legal action by farmers against such conversions and recent Court rulings that disallow further conversions and emphatically require their restoration (Singh v. State of Punjab, 2011). Such deep-rooted beliefs and traditional lifestyles that explicitly retain habitat amid agriculture, combined with the newly developed policy and legal tools, provide substantial opportunities to retain large waterbirds in South Asian agricultural landscapes over the long term.

4.2. Nest sites and conservation of species in agricultural lands

Trees were managed by farmers as private property, or village councils as common property, and by the state forest department, while larger wetlands were managed only by village councils with very small patches being maintained as private property (personal observation). This suggests the requirement of multiple conservation strategies to retain nesting habitat for waterbirds here. Breeding pairs of cranes required very small patches of wetlands well spread out to enable territorial pairs to nest (see Sundar, 2009a), and these patches are also used by Black-necked Storks for foraging. Small wetland patches currently do not feature in conservation discussions or strategies. Conservation attention will be required across large landscapes but working at a very high resolution focusing on individual territories of breeding pairs to maintain and enhance conditions for a suitably large number of breeding pairs of both species. Conservation attention to larger wetlands that are community lands is increasing, but those will cater to a very small proportion of breeding pairs suggesting that an explicit landscape approach, and not the conventional site-based protectionist approach, is mandatory for large waterbirds (see Sundar, 2005). This will necessarily require collaborations across multiple governmental departments, and the use of multiple scientific and sociological disciplines to achieve conservation success. Generic strategies commonly employed, such as raising the legal protection status of species or designating one or few protected wetland sites, will be of little to no utility for ensuring long-term persistence of species like Sarus Cranes and Black-necked Storks in agricultural landscapes.

Etawah and Mainpuri have the least agricultural intensification and human density relative to other locations in the Gangetic floodplains (unpublished data). In a recent survey across the Gangetic floodplains covering various levels of intensification, Black-necked Storks occurred only in areas with the least intensification, and Sarus Crane occupancy declined with increasing intensification (unpublished information). For the two focal species, breeding population size and density in Etawah and Mainpuri are the highest known anywhere globally (Sundar, 2003, 2009a). Stressors in other locations are poorly understood, and long-term monitoring is absent. Given the predicted declines of Sarus Cranes in Etawah and Mainpuri if development resumes, and the small population size of Black-necked Storks in South Asia (<1000; unpublished information), long-term scientific and conservation effort in other parts of their distribution range are urgently required. Species outside of formal protected wildlife reserves are currently accorded minimal attention and resources by the federal and state governments in India (Sundar and Subramanya, 2010). This ethos requires alterations if species like Sarus Cranes and Black-necked Storks are to persist over the long-term in the Gangetic floodplains and other agricultural landscapes.

4.3. Waterbirds, habitat change and rainfall

Relative effects of habitat alterations and changes in climate on avian breeding success in intensively farmed landscapes are rarely studied and underscore the importance of retaining habitat (Kleijn et al., 2010). Studies on waterbirds have documented a wide range of effects of rainfall on breeding success including improved success in years of above-normal rainfall (Kushlan, 1986; Frederick and Collopy, 1989; Monadjem and Bamford, 2009), mixed results during drought or below-normal rainfall ranging from improved survival of chicks (Dinsmore, 2008), above-normal productivity the subsequent year (Frederick and Ogden, 2001), to reduced success (George et al., 1992; Gonzáles, 1998; Altwegg and Anderson, 2009). In landscapes like the Gangetic floodplains, severe effects of rainfall on avian breeding success may become dominant over land use-related effects if frequency of dry years increase and less wet crops are favored over flooded paddies.

4.4. Methodological caveats

Some features of field methods and population viability analyses warrant clarification. Monitoring was restricted to pairs along few roads (see Fig. 1). Albeit being a convenience-based method, this was superior to monitoring pairs only in large wetlands since the majority of breeding pairs of both species maintained territories outside of wetlands in the cultivated landscape (see Sundar, 2005). Roads were present in 40% of the Sarus Crane territories, and occurred in at least one side of 100% of the monitored territories (unpublished information). Roads were present in 100% of the Black-necked Stork territories. The relatively high density of roads in the region likely affects the majority of Sarus Crane breeding pairs, and all the Black-necked Stork pairs. Monitoring long-term breeding success of pairs along roads is therefore thought to be representative of the larger population of both species.

Estimates of survival for chicks >1 year were unavailable for both species. Population studies to determine these are required, and will enable improved viability analyses. Territory quality was measured only in October 2001, and served as a single-point measurement carried out during the early part of the study after a medium-rainfall year (see Fig. 2). Annual variability in territory quality is therefore not explicitly included in the study. Behavioral observations on few pairs that could be reliably identified due to number of chicks with them each year suggested that inter-annual variation in territory extent was either trivial or absent. The one-time assessment of territory quality, followed by observations of attrition annually, is therefore deemed adequate to assess the importance of habitat for the two species. Wetland attrition is presented only as being caused by humans though extent of wetlands in territory varied due to rainfall. In high-rainfall years, extent of wetlands did not necessarily increase as farmers strengthened dykes to enable continued cultivation, but number of wet days was higher relative to either normal-rainfall years or dry years. This metric is likely of importance to chick survival of both species, but was not measured in this study. Early drying of wetlands in dry years reduced availability of wet areas to territorial pairs. Wetlands in this region, however, were not perennial, and unless dry wetland areas were modified to agriculture or other human development, it was not necessary to represent drying as attrition.

I ignored the positive effects of high-rainfall years as a separate variable in the population viability analyses (see Section 2). Effects due to rainfall effects are reflected in part in the sensitivity analyses where a much higher degree of change of rainfall relative to observed patterns (both increase and decrease) resulted in trivial changes in predicted N and r (Fig. 3). The exception was the predicted values of r for Black-necked Storks that varied significantly when frequency of dry years changed (Fig. 3d). This suggests that increasing frequency of high-rainfall years is likely to be greatly beneficial for the species' population given the apparent positive response observed during two years of high rainfall (see Fig. 2).

4.5. Agricultural landscapes, climate change and biodiversity conservation

This study focuses on only two species, but results reveal the value of restraining rapid development and retaining habitat patches to aid persistence of species in cultivated landscapes even when human population densities are high. Other wetland species with similar requirements, and those requiring non-wetland habitats, are therefore also likely to benefit from habitats retained amid cultivation. Congruent with results of modeled global species requirements (Jetz et al., 2007), and few field studies (Kleijn et al., 2010), these results underscore the importance of paying immediate attention to habitat loss as a critical conservation requirement over potential changes due to climate change. Discussions of adaptation planning of agricultural landscapes are skewed towards strengthening human food security via intensification and incentivizing ecosystem services (Nelson et al., 2008; Rosencranz et al., 2010). Conservation planning on agricultural landscapes has favored retention of habitat patches usually through farming policy regulations to benefit persistence of species (Mattison and Norris, 2005; Kleijn et al., 2010), or international agreements (Harrop, 2007). However, neither method has been consistently beneficial to ensure long-term persistence of biodiversity on agricultural landscapes (Secchi and Babcock, 2007; Nelson et al., 2008). Cultural practices that retain habitat on cultivated landscapes are wide spread, but are largely ignored in conservation and planning discussions (Scott, 1989; Acharya, 2000; Mattison and Norris, 2005; Maathai, 2010; Sodhi and Ehrlich, 2010; Singh v. State of Punjab, 2011). The best opportunities to revive, encourage, and strengthen existing cultural traditions towards maintaining relatively vast multifunctional landscapes are in areas like South and South-east Asia, Latin America, and Africa that have traditional agricultural methods (Food and Agriculture Organisation of the United Nations, 2002; Maathai, 2010; Sundar and Subramanya, 2010). Extending research across multiple agricultural landscapes and improving interdisciplinary discussions to develop suitable mechanisms for biodiversity conservation alongside climate change related adaptations on cultivated landscapes are urgently required (Hannah et al., 2002; Mattison and Norris, 2005; Harrop, 2007; Wills and Bhagwat, 2009). The three pillars for efficient biodiversity conservation in the Gangetic floodplains and similar agricultural landscapes are: (1) conserving and restoring wetlands via encouragement and strengthening of traditional norms alongside legal means, (2) strengthening regional policy to include habitat management and conservation in long-term agricultural expansion plans, and (3) encouraging explicit protection of farmlands and farmland biodiversity in federal and regional policies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2011.09.012.

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