THE CULLING AND RECOVERY OF CORVUS.*splendens* ON UNGUJA ISLAND, ZANZIBAR

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ABSTRACT

We have investigated the problem of C.*splendens* abundance on Unguja Island, Zanzibar despite repeated attempts to contain it. We found that past efforts were based on culling programmes which reduced the abundance as long as the programmes lasted, but the problem resurfaced shortly after conclusion of these programmes allegedly due to paucity of funding. We have focused in particular on the two latest culling events on the Island, first in the early to mid 1990s and the second, between 2012 and 2013. We developed two population models to analyze population dynamics in two different types of habitats which we identified on the Island. We categorized these habitats on the basis of "access" to food in relation to its "abundance". The first imposes a spatial constraint on carrying capacity due to limited access to resource irrespective of its abundance, and a simple Ricker density dependent model was applied to analyze it. We termed it, Type-1 habitat. Type-2 habitat is not constrained by space and its carrying capacity increases over time. We, therefore, developed a population model for a habitat with increasing carrying capacity, taking into account the anthropogenic and non-anthropogenic factors which affect food abundance. We also reconstructed past population estimates on the basis of our habitat classification and found that the C.*splendens* abundance was over estimated by at least 100% in the last survey conducted in 2009 due to methodological and processing errors. Model results indicated that culling was ineffective in containing abundance in the past because the population rebounded at higher rates of growth at the conclusion of programmes, due to resolution of space or food contest. We then identified three possible pathways on the two models to control the problem. We found that the "food access reduction pathway" which is focused on controlling anthropogenic organic surplus through waste management with no culling, offered the most effective, resource efficient and durable solution. The culling only pathway offered the least effective, resource inefficient and temporary resolution of the problem. The combination pathway (culling and access reduction) offered equal benefits as the access reduction pathway but was the most resource inefficient and the contribution of culling in it wore off as soon as it was terminated.

Introduction

Due to its adaptive versatility and mobility based on self-propelled and ship-assisted carriage, tremendous expansion in the range of Indian House Crow (C. *splendens)* has been reported in varying degrees in East Africa, Middle East, East Asia and many islands of the Indian Ocean (Ryall, 1994, pp. 90–99, 1995, pp. 185–187; 2002, pp. 231–239; Ryall & Meier, 2008). Ecological niche modeling predicts further invasive potential in areas such as West and Equatorial Africa, Europe, Carribean, Mexico, Central America, parts of South America (Nyari et al., 2006, pp. 306–311) , as well as parts of New Zealand (Fraser et al., 2015, pp. 725–740) and Australia(State Government Queensland, 2016, p. 10) .

Abundance among *Corvids*, in particular crows and ravens, is reported to be strongly correlated with proximity to human settlements (Marzluff & Neatherlin, 2006, p. 306). Notably, in general due to its omnivorism common to most *Corvids* (Reaume, 2013, pp. 316–376; Sakai & Carpenter, 1990, pp. 220–228), and in particular commensalism with humans resulting in enhanced reliance on anthropogenically generated organic surplus (Ryall, 1994, p. 91; Lim et al,, 2003, pp. 685–695; Marzluff & Neatherlin, 2006, pp. 309–310) *,* C.*splendens*' ecological release in non-native habitats is concomitant of flourishing human populations in settlements with poor developmental markers (Ryall, 1994, pp. 98–99).

Eradication and control programmes, where populations have significantly established, mainly based on culling (trapping, poisoning, shooting; eggs, nests and chicks destruction) have almost always culminated in failures (Brook et al., 2003, p. 809; Ryall, 2002, p. 237). The illusion of success from high intensity culling programmes, soon vanishes as it becomes increasingly difficult to maintain the tempo of the program due to mounting costs, difficulty of luring the birds to baits and traps as they become increasingly cautious, dispersal of the population from threatened habitats, and failure to control the anthropogenically generated organic surplus which serves as the major food source.

Examples of failure abound. For instance in Aden, Yemen where the administration resorted to indiscriminate intense culling in disregard to the UNEP's Report which recommended hybrid measures primarily aimed at control of food source through organic waste management (Ash, 1984). Controlled culling was recommended only as a secondary measure comprising shooting, trapping and nest destruction in the breeding season. 241,228 birds were culled during a two year period from March 1987 to June 1989 (Jennings, 1992, pp. 27–33). Ryall (2002, p. 233) reports recovery of the population in Aden and adjoining areas of Lahej and Abiyan at pest levels. In Mombasa, Kenya, a host of culling strategies applied over the past few decades (Ryall, 2002, pp. 235–236) have failed to produce significant results and the population, reported to be a few thousands in 1995, now thrives in hundreds of thousands, over the entire Kenyan Coast (Paul & Seys, 1995; The Star, Kenya, 2017). The only notable exception has been Singapore where significant reduction in house crow population densities was achieved owing to a balanced program comprising "food deprivation" and "controlled culling" (Chong et al., 2012, p. 192).

In Zanzibar as well, the story has been no different. The species was first introduced in Zanzibar, comprising Unguja and Pemba Islands, in the late Nineteenth Century (Archer, 1996, p 2) It has since, extended its range to both main islands of the archipelago, mainland Tanzania and beyond, along the East African Coast (Ryall, 1994, p. 95). Accorded pest status since 1917, the Island has wrestled with fluctuating populations of the house crow which seem to recover quickly after each episode of control and eradication. On Unguja Island, the two most recent control attempts were made between 1990-1996 and 2012-2013 in which respectively 65,000 and 253,119 birds were culled. The former project claims to have eliminated 75-80% of the population while the later effort, though more comprehensive and apparently more successful, accounted only for approximately 25% reduction in Island wide population based on original estimates (Archer, 1996, p. 2, 2001, pp. 147–152; Mwinyi, 2013, p. 7; Davenport, 2017).

Detrimental socio-economic, health and biodiversity impacts of the species C.*splendens* out of their native range have not been exhaustively studied, however, some existing literature points to negative economic implications, nuisance potential and adverse impacts on local biodiversity in the invaded habitat (Archer, 2001, pp. 147–152; Meier; & Ryall, 2007, pp. 21–22; ISSG, n.d., p. 3; Cooper, 1996, pp. 381–386; Feare & Mungroo, 1990, p. 64). This fact notwithstanding, it is equally important to focus on determining the efficacy of abundance control programmes in these habitats based on high-intensity or "burst culling" followed by long periods of inactivity. The most frequent refrain employed for eventual failure of such control models, which are mainly styled as laissez-faire or community based culling, is "insufficient funding" (Archer, 1996, p. 151; Jennings, 1992, pp. 27–33; Ryall, 2002, p. 238). However, little criticism, introspection or evaluation of the employed methodology has been undertaken.

We address the above inconsistency through evaluation of the two most recent culling programmes run on Unguja Island, Zanzibar between 1990-96 and 2012-13 respectively. Brook et al. (2003, p. 809) point out the lack of scientific rigor implicit in "burst culling" programmes and favour an informed scientific approach to serve as guideline for the management actions. Following a similar methodology, we employ population models for evaluating past programmes as well as to propose contours for an objective future programme.

We hypothesize that *culling and in particular "burst culling" does not have any significant downard impact on the population dynamics which control abundance among well established populations.* This is because, due to the perturbation event (culling), the population recovers at higher growth rates post-culling as it is exposed to higher resource abundance. Thus the conditions which would have set-in significant density dependence are eliminated through culling without setting the resource boundary any lower (Sinclair et al, 2006, pp. 121–122).

We use inputs from available and reconstructed abundance estimates at the end and beginning of the programmes in Zanzibar, as well as the culling effort applied during

these programmes, and conduct a year on year assessment of the impact of culling on real time and projected abundance using population models. We compare the real time and simulated "culling" and "non-culling" pathways on the population models, and also use the models to identify the optimum future pathway for control.

STUDY AREA

Zanzibar archipelago in the Western Indian Ocean, off the Tanzanin Coast, comprises two large islands, Unguja (also known as Zanzibar Island, shortest distance to mainland: 20.6 Km) and Pemba, besides several small islets. Our study is limited to Unguja (6.1357° S, 39.3621° E) though it makes use of some observational data from Pemba Island for statistical simulations and approximations. Unguja is the largest island in the archipelago (approx area: 1582 Km^2) and has fluctuated between being been part of the mainland and being a continental island respectively during sea-level low and high stands associated with Quarternary glacials and interglacials. The latest separation during the Holocene interglacial is estimated to have occurred between 9000-7000 years B.P. and was followed by a loss in species diversity initially due to "faunal relaxation" and later due to anthropogenic influences. The endemic species which evolved due to island conditions such as Zanzibar Leopard and Red Colobus Monkey survived for several millennia before being made extinct and endangered respectively due to habitat destruction and hunting which followed human arrival on the Island (Prendergast et al., 2016, pp. 1–23).

Administratively, the Island is divided into three regions with two districts each (Fig-1).In 2012, the population of the Island was 896,721 (2002 and 1988 population is shown on Fig-1) with an overall population density of 567 inh/ Km^2. The average population growth rate between 1967 and 2012 was 2.9%. The Western Region (Mjini-Maghribi) is the most heavily populated with a population of 593,678 and density of 2546 inh/ Km^2 followed by the North or Kaskazini Region (Population: 187455, Density: 403 inh/ Km^2), and South or Kusini Region (Population: 115,588 Density: 130 inh/ Km^2) (National Bureau of Statistics, Tanzania, 2014, p. 14). In the Western Region, Mjini with only an
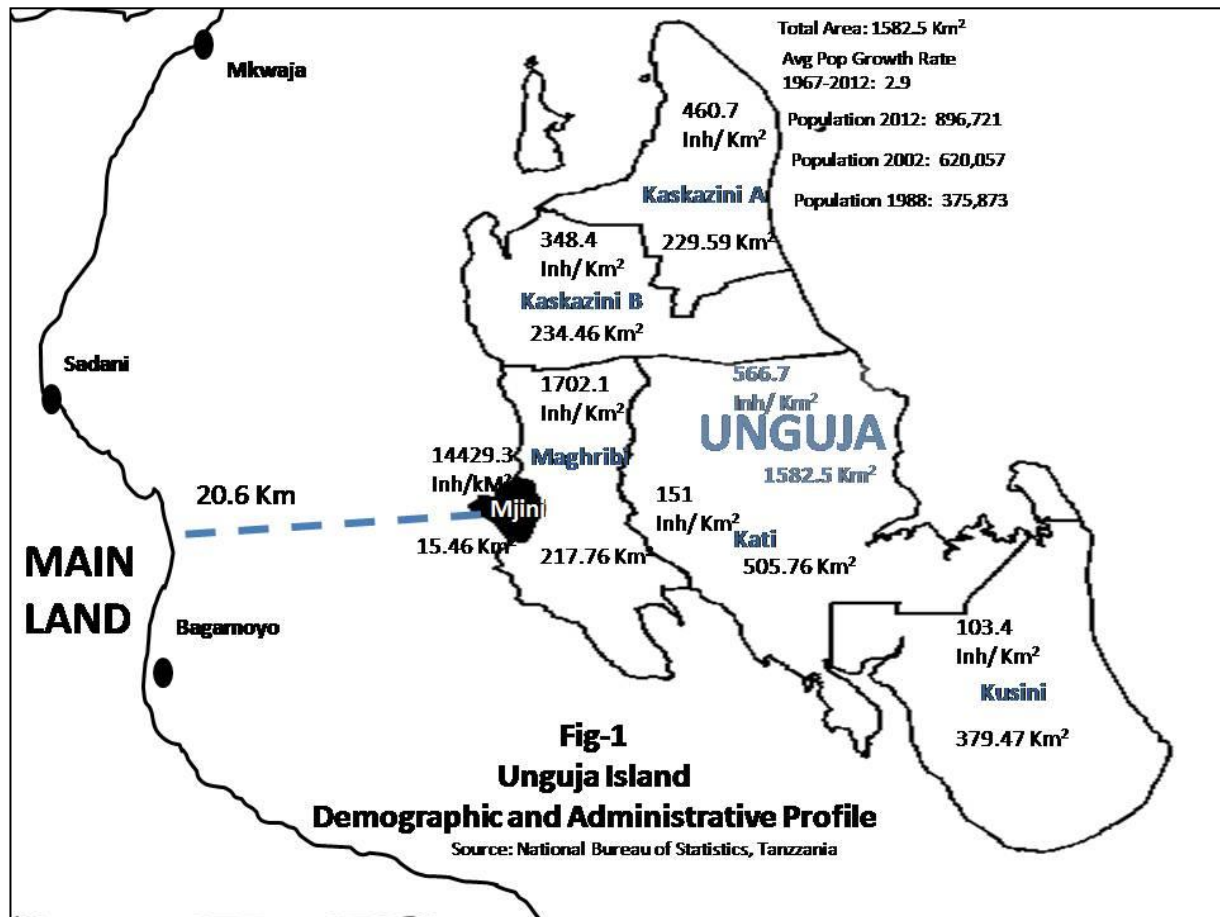

Fig-1 Demographic and Administrative Profile, Unguja Island

area of 15.46 Km^2 (less than 1% of the Island area), had a population of 223,033 (approx 25%) with some of the highest population densities in Africa at 14,426 inh/ Km^2.

The second district of the region, Maghribi-mainly a suburban district, with an area of 217.76 Km^2 (13.7% of total) had the highest population on the Island at 370,645 (41.3%) and a density of 1702 inh/ Km^2 (National Bureau of Statistics, Tanzania., 2016a, p. 16). Together the Region concentrates over 66% population in only 15% area of the Island. In the North Region, Kaskazini A with an area of 229.59 Km^2 had a population of 105,780 and of 460.7 inh/ Km^2 accounting for approx 12% population in 21% of area, while Kaskazini B (population: 81,675, density: 348.4 inh/ Km^2, area: 234.46 Km^2) had 9% population in 15% of area (National Bureau of Statistics, Tanzania , 2016b, p. 15) . In the South Region, Kati or Central District (population: 76,346, density: 348.4 inh/ $Km^{2,}$ area 505.76 Km^2) had 8.5% population in 32% area while Kusini (population; 39,242, density: 103.4 inh/ Km^2, area 379.47 Km^2) had 4.3% population in 24% of area (National Bureau of Statistics, Tanzania., 2016c, p. 15).

The climate in Zanzibar is tropical with the highest temperatures in Feb (28 C^0) and lowest in July (24 C^0). The long rainy season lasts between March and May while the short season is between November and December. The average annual precipitation is 140 mm reaching a maxima of up to 400 mm in Apr. June to October and December to February are usually dry with high levels of daily sunshine. The main economic activities are related to the tourism in urban and coastal Unguja, agriculture in inland Unguja, and fisheries on the coastal stretch (National Bureau of Statistics, Tanzania, 2014, p. xi).

METHODS   :

POPULATION SIZE/ DENSITIES

We needed two population estimates, one immediately at the end of the first culling event i.e. in 1996 to provide input to the models, and the second before the commencement of the second culling event in 2012 for comparison with projected model results. For the first estimate, we have accepted the higher of A.L. Archer's (1996, p. 2, 2001, p. 149) claims who conducted this programme, i.e. 65,000 birds

culled represented 75% of the total population on Unguja Island (lower claim is 58,000 birds culled). This leaves us with a population of 21,667 birds at the culmination of the first Culling Event in 1996.

For the second estimate, we have relied on observational data of crow population survey conducted in 2009 by the Department of Commercial Crops, Fruits and Forestry (DCFF) (Mwinyi & Said, 2009, pp. 8–18). The survey report is attached as **Appendix-**1 to this study. This survey estimates population based on samples taken in two strata i.e. urban (21 samples) and rural areas (21 samples). The estimated population on Unguja Island based on these results is 1.078 million with an average density of 704.34 crows/ Km^2 (927.66 crows/ Km^2 in urban and 481.04 crows/ Km^2). We investigated the reasons for these unusually high estimates of abundance and density and discovered serious inconsistencies in methodology and processing which led to vast errors in estimates.

The first major problem is the criteria used for stratification. It is simply described as urban and rural from which we assume that it uses human population density as the marker. It is true that commensalism of C.*splendens* makes human population density an obvious choice as a signifier, as it is positively correlated with food abundance, but some important aspects need to be considered in addition to this. Mustafa et al. (2015, p. 1149) report greater abundance of C.*splendens* in rural areas of Central Punjab (Sargodha District) in Pakistan as compared to urban areas in the same district.

Lim et al.'s (2003, pp. 690–691) study in highly but quite uniformly urbanized Singapore with 50% of the area comprising built up area accompanied by another 20% as urban green spaces such as golf courses and urban parks concludes that abundance was positively correlated with land use factors such as commercial areas, public housing and urban greenery; as well as with certain anthropogenic and environmental variable such as litter abundance, number of food centres and distance from the coast. Wilson et al.(2015, pp. 5–6) investigating the same question on the west coast of peninsular Malaysia housing the urban metropolis of Kuala Lumpur and some rural costal townships find that C.*splendens* was 45% more abundant in urban landscapes as

compared to rural landscapes. In urban landscapes abundance was positively correlated with business and residential settlements as compared to urban greenery.

Marzluff & Neatherlin (2006, pp. 301–314) conducting their study in Olympic Peninsula, Washington State characterized by coniferous forests reserves, Olympic National Park and low population densities (less than 30,000 people in an area of over 12,000 Sq Km in 2000) positively correlate the abundance (density) of American Crow (Corvus *brachyrhynchos*) with proximity to human settlements. Crow home ranges (area traversed by an individual in its normal activities of food gathering, mating and caring for young) were found to be between 1< km to >5 km but both the abundance and survivalship were found to be significantly higher at closer home ranges to anthropogenic food sources. Crows were found to have the most diverse diet among other Corvids studied, including invertebrates, road-kill, nestlings, small mammals, berries,fruits,seeds etc., but relied more extensively on anthropogenic food sources if nesting within 1 km of human settlements. Chongomwa (2011, pp. 88-97) finds nesting sites in Mombasa, Kenya located closer to food sites in areas with poor waste management.

Consideration of all the diverse factors impacting abundance and distribution of populations leads us to hypothesize that *although anthropogenic food source is an important and major part of the C.splendens diet but both availability of food as well as ease of access to food sites in relation to home range (i.e. spatial factor) impacts abundance and distribution of the species.* Such a constricted habitat with constantly increasing resource but fixed spatial access, may be compared with a room in which food is available and increasing but the access to the room is controlled by a connected narrow corridor. Only those in the corridor can enter the room, no matter how abundant the food is inside the room. We term such habitats as Type-1 habitats. Habitats without this constraint are termed as Type-2 habitats.

For this situation, we define the spatial "resource opportunity factor" O_f:

$$O_f = K_a / K_t \text{ ---------- (1)}$$

where K_t = resource availability or carrying capacity at time 't' and K_a = carrying capacity limited by absolute spatial limit on resource access and is determined by a number of ecological and behavioural variables such as vegetation, urbanization, habitat preference, breeding ecology, temperature, seasonability, home range preference (tight or relaxed), territoriality, foraging strategy etc. Broadly, it may be termed as the usable part of the habitat considering the ecological behavior and survival requirements of the species. (Sinclair et al., 2006, pp. 60–77).

Of thus represents the proportion of the available resource which can be exploited by a population, given the limit K_a. It can be thought of as the capacity of the corridor connected to the room described above, in relation to the amount of food inside the room.

We also define two abundance control variables $C_f = N_t/ K_t$------(2), and $C_s = N_t/ K_a$ -----------(3).

where N_t is abundance at time 't', C_f represents "contest for food" and determines the sufficiency (or scarcity) of a resource for a population N_t, while C_s represents "contest for space" and determines the proportion of the population N_t which has 'access' to
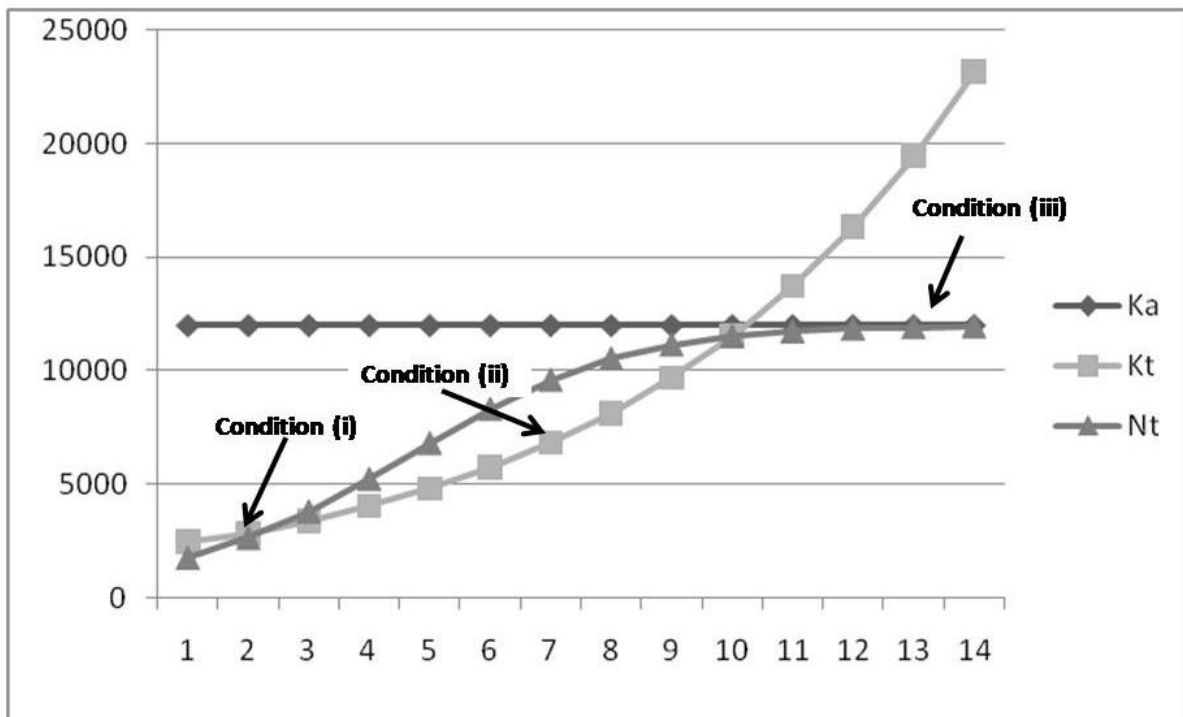

Fig-2 Conditions (i), (ii) and (iii)

resource K_t.

We set eq (1) at three conditions, (i) $K_a > K_t > N_t$ (ii) $N_{t+1} < K_a > K_{t+1}$ but $N_{t+1} > K_{t+1}$, and (iii) $N_{t+2} > K_a < K_{t+2}$. These conditions are shown graphically in Fig-2 and Fig-3 for a hypothetical population N_t (1800) with a constant growth rate higher than K_t (0.3>.0.15), and K_a=12000 for 14 discrete time steps (number of time steps arbitrarily chosen). We have assumed density-dependence only in population N_t while the resource expansion has been assumed to be exponential.
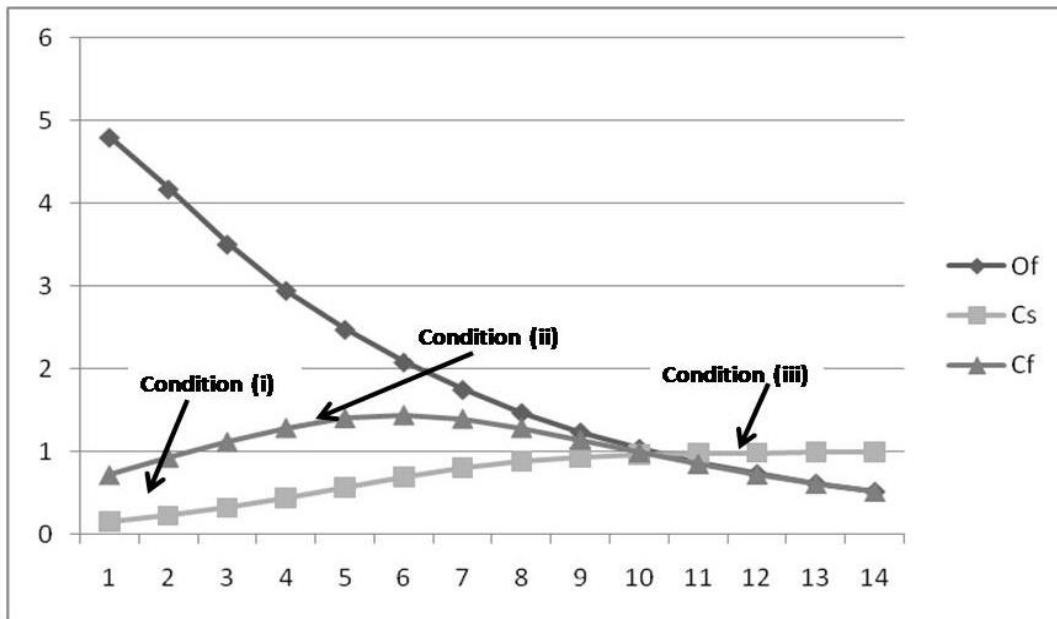

Fig-3 Conditions (i), (ii) and (iii)

Condition (i) represents an initial state. Since $K_a > K_t$, therefore, $O_f > 1$ and since also $K_a > N_t$ and $K_t > N_t$, therefore, $C_s < 1$ and $C_f < 1$. This implies that the resource and access to resource are sufficient for population N_t and there is no conflict about resource abundance and access to resource among the N_t. On the room-corridor

analogy, it may be said that the room has sufficient food for everyone in the corridor and the corridor still has space for more.

Condition (ii) represents an intermediate state where the population N_{t+1} has exceeded the resource K_{t+1} but has not exceeded the spatial limit K_a. Since $K_a > K_{t+1}$, therefore, $O_{f+1} > 1$ and since also $K_a > N_{t+1}$ and $N_{t+1} > K_{t+1}$, therefore, $C_{s+1} < 1$ and $C_{f+1} > 1$.

This implies that the resource has become scarce for the population which depends on it, although the contest for space is not in operation but the contest for resource is in operation. On the analogy, it can be said that more people have entered the room than there was food in it although the corridor still has space for more.

Condition (iii) represents the advanced state where both the population N_{t+2} as well as the resource K_{t+2} have either exceeded or tend to exceed the spatial limit. The direct relation between the population and the resource is terminated and now mediated by the spatial limit K_a. Since $K_a < K_{t+2}$, therefore, $O_{f+2} < 1$ and since also $K_a < N_{t+2}$ and relation between N_{t+2} and K_{t+2} is terminated, therefore, $C_{s+2} > 1$ and $C_{f+2} \rightarrow 0$. This implies that the resource is now controlled by the spatial limit, the contest for space is in operation and the contest for resource is irrelevant. On the room-corridor analogy, it can be said that more people have entered the corridor than it could contain although there is still food inside for more. People outside the corridor will first have to fight for space with people inside the corridor before they can get access to the room.

Unguja urban area closely approximates condition (iii) of the Eq (1). Abundance among C.*splendens* is controlled by K_a rather than K_t and *Of* is low due to limited space availability. In suburban area also condition (iii) is expected to hold though in a milder form. *Of* is higher than urban area. K_t is also higher due to higher human population but abundance is still controlled by K_a due to relatively higher but still limited space availability. Abundance in suburban areas is nonetheless, expected to be higher than

the urban area. Both Urban and Suburban Unguja thus represent habitats of Type-1 earlier defined.

In the coastal belt condition (i) is expected to hold due to higher spatial factor and increasing food resource and condition (ii) may be approaching. Here, in addition to the anthropogenic food source, natural food source is also expected to be higher than other habitats due to abundance of invertebrates and wild fruits. Of is higher than both the urban and suburban areas due to higher Ka, but Kt is less than urban or suburban areas. High Of with moderate food abundance (natural and anthropogenic) could possibly imply that the coastal belt has highest population abundance on the Island. Cs would be low and Cf may be high but constantly kept in check by increase in resource. Thus it is a habitat of Type-2.

In the inland agricultural area also condition (i) is expected to be in operation. Of is the highest, Kt is the lowest but is compensated by consistent increase in resource. Cs has not come into operation but high values of Cf are expected, which like the coastal area is compensated by consistent increase in the resource. It is also a Type-2 habitat. The above hypothesis is laid down in Table-1, relevant abundance control factor is highlighted in bold.

| Habitat Type	Ka (Spatial Limit)	Kt (Resource Abundance)	*Of (Opportunity Factor)*	Cs (Contest for Space)	Cf (Contest for Food)	Nt (Expected Abundance)
Urban (1)	Low	V.High	<1	**>1**	→0	Low
Suburban (1)	Moderate	High	<1	**>1**	→0	Moderate
Coastal (2)	High	Moderate	>1	<1	**→1**	V.High
Agriculture (2)	V.High	Low	>1	<1	**→1**	Low

. .

Table-1 Expected Abundance Of C.*splendens* In Various Habitats Of Unguja Island

The second methodological problem with the survey under consideration is that the sampling is not random. In fact, it is clearly biased in favour of known house crow concentrations. It does not cater effectively for dispersal and distribution of the population. The urban samples are restricted to within 20-25 Km^2 of Mjini's surroundings and the rural sampling is restricted to the coastal towns with high probability of large concentrations due to presence of tourist resorts and fishing centers. The sample sites for the survey are shown in Fig-2. There are virtually no samples for the suburban and the inland agricultural areas representing about 65% of the total land area of the Island.

The major methodological error of the survey, however, relates to processing of sampling data obtained from the survey. Although, the Island is clearly divided into "urban" and "rural" strata in the survey design, these strata were not treated as mutually exclusive while calculating "average densities" such that the averages obtained from "urban" samples were then further added and averaged with those obtained from "rural" samples. This implies that in effect, there was no stratification and the survey was in fact based on simple random sampling of the entire Island, while the samples were not drawn from the entire Island.

Fig-4
Crow Population Survey 2009 – Sample Points
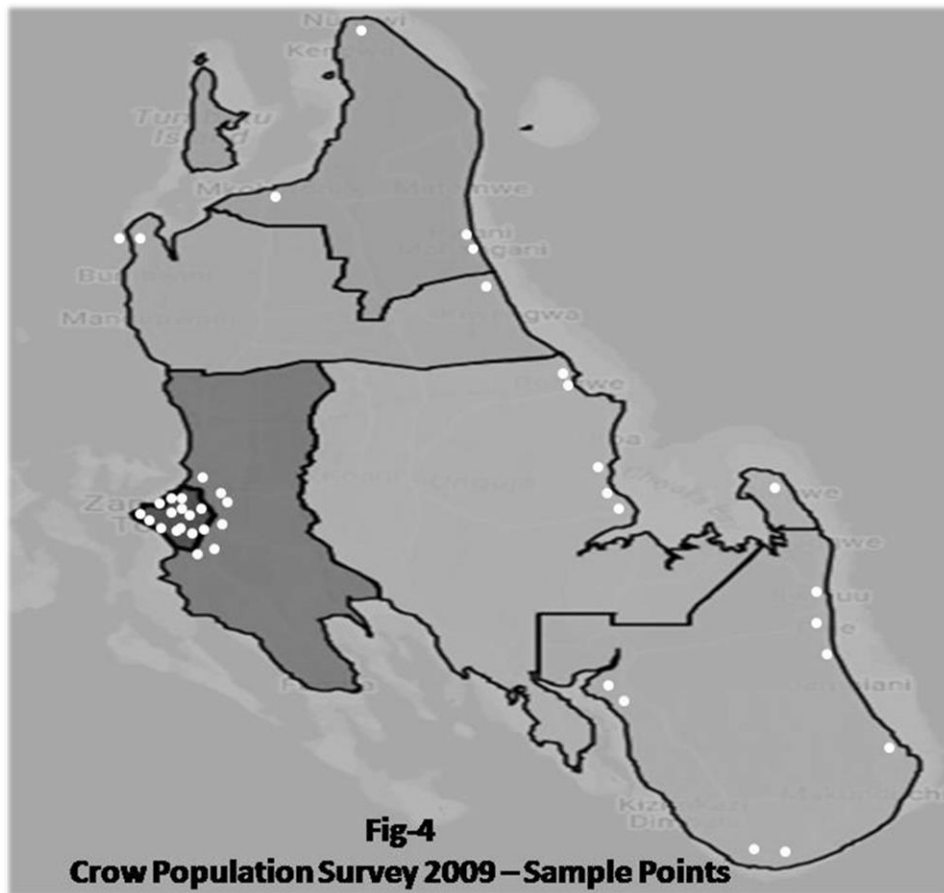
These averages of the averages were then multiplied with the total area of the Island to obtain abundance estimates. The average density from 21 "urban" samples was 927.66/km2, and 481.01/km2 from "rural" samples. These were averaged with each other to obtain an overall density of 704.34/km2 to obtain the population estimate of over 1 million. On closer examination, it can be seen that these densities are driven mainly by only two unusual concentrations in "urban" Unguja with crow numbers observed as 8992 and 1395 respectively (Mwinyi & Said, 2009, pp. 11–12). Further investigation reveals that these are two large markets on the peripheries of the urban area serving a large number of surrounding and distant populations. On the room-

Fig-5
Simulated Samples Overlay from Pemba
on Unguja Island
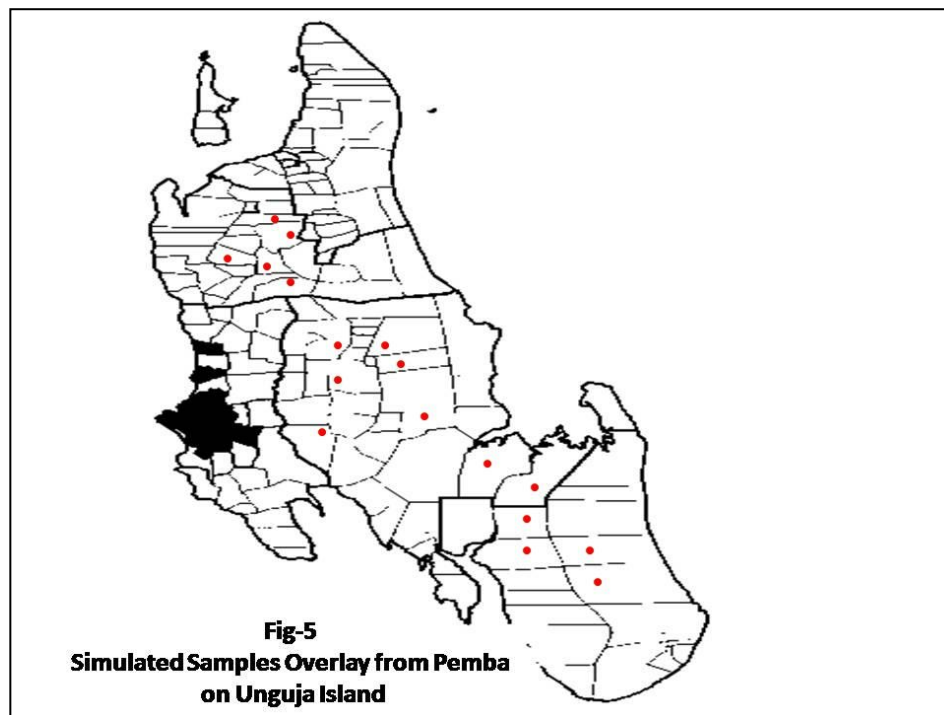
corridor analogy, these can simply be thought of as large tables with abundant and choice food inside the room where more people congregate as compared to other smaller tables with less attractive food items.

We stratified the Island in accordance with habitats defined in our hypothesis and overlaid them with original sample points in accordance with the survey data. For the

missing samples of inland agricultural habitat, we chose samples from the simultaneous survey conducted on the neighbouring Pemba Island contained in the same report (Mwinyi & Said, 2009, p. 15). This survey consists of 15 sample points in rural areas of Pemba Island. We used the official data of National Bureau of Statistics which provides demographic data down to ward level (National Bureau of Statistics, Tanzania, 2017), and investigated the demographic and area profile of these localities and overlaid them on localities having similar demographic and area profile on Unguja Island This way we overlaid fifteen sample points on the inland agricultural habitat (See Fig-5). To account for the observation that the C *splendens* population on Unguja has displaced the native Pied crow population (Corvus.albus), we considered the total crow population (C.*splendens* + C.*albus*) from Pemba observations for overlaying them on Unguja localities. We used the demographic and geographical information from the same source to estimate the areas of respective habitats. For the coastal belt, large administrative units (wards with significant area) were further divided by a factor of 0 .5, if their densities were lower than the average density of the district in which they were located. For large wards with low population densities and insignificant fishing or tourism activities, the factor applied was 0.25.

In order to avoid large errors, we isolated known food abundant localities from the observational data, such as fish/agriculture/food markets and landfills, and analyzed them as a separate habitat under the rubric "Food Centres", irrespective of the original habitat of their origin. We based this decision on the assumptions of *Optimal Diet Theory* which requires the foragers to base their foraging strategy on preferring more energetically profitable diet over less profitable diet (Sinclair et al., 2006, pp. 60–65). This can offer one plausible explanation for C.*splendens* abundance in proximity of these sites. The habitats with overlaid samples are shown in Fig-6.

The sample data was fed in Microsoft Excel and using the add-in *Bootstrap.xla*, the samples in all five habitats were bootstrapped to 1000 iterations. For the four original habitats, the bootstrap mean was divided by mean sample area to obtain mean habitat density. This was then multiplied with habitat area to obtain mean habitat abundance. 95% confidence intervals were constructed to obtain the population range in the

Fig-6
Re-stratification of the Habitat
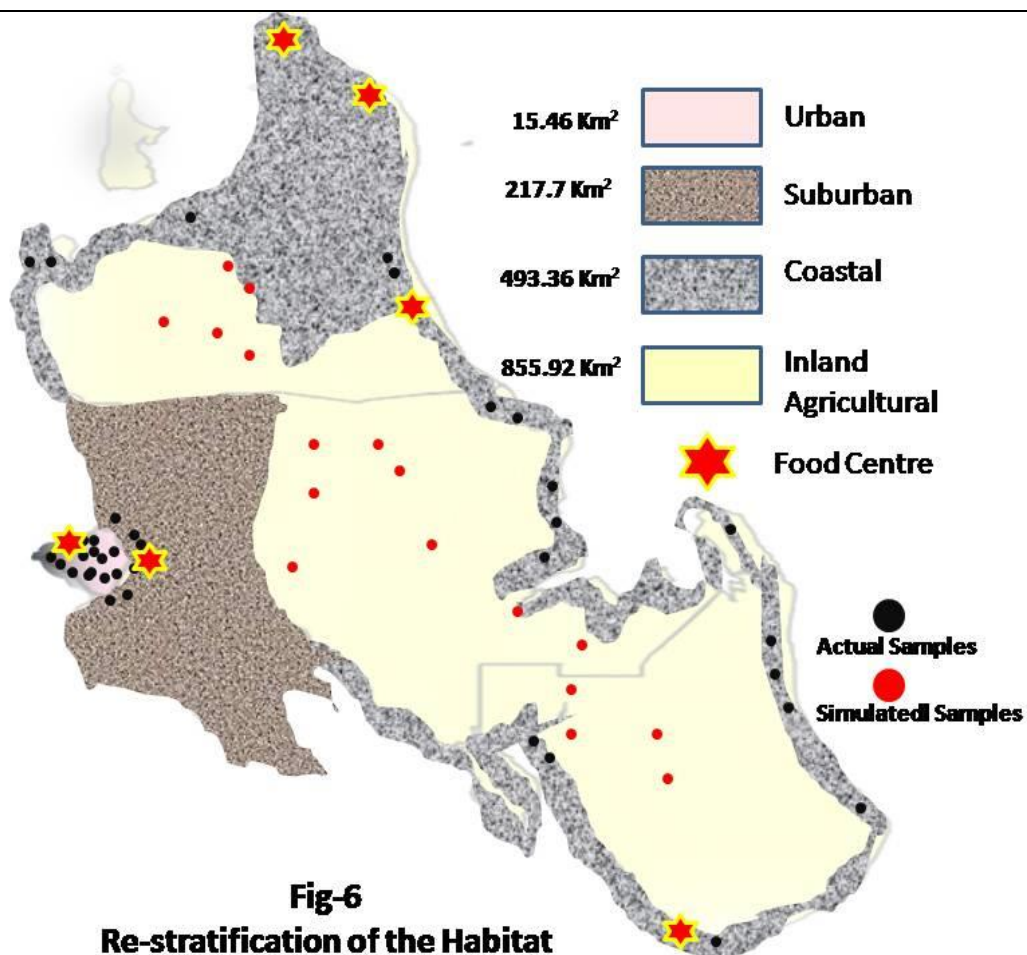
habitats. For the isolated habitat "Food Centres", the human population surrounding and benefitting from them was calculated using the geographical and demographic data. This population was divided by the total number of crows in this habitat to find the ratio $K_t/N_t = 1/C_f$ (inhs/crow) to find out the abundance of food at these locations within their original habitats. On the room-corridor analogy, simply to find out how much food
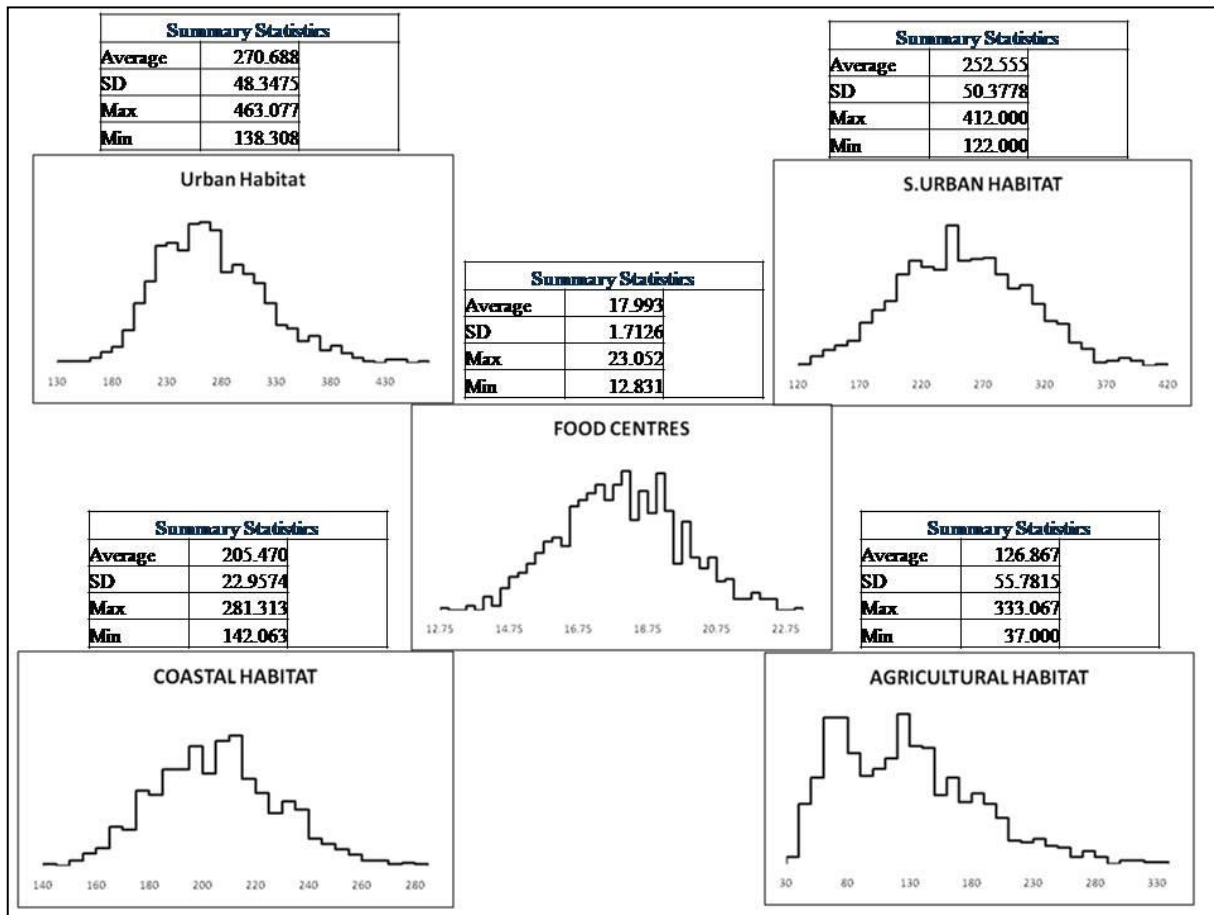

Summary Statistics	
Average	270.688
SD	48.3475
Max	463.077
Min	138.308

Urban Habitat

Summary Statistics	
Average	252.555
SD	50.3778
Max	412.000
Min	122.000

S.URBAN HABITAT

Summary Statistics	
Average	17.993
SD	1.7126
Max	23.052
Min	12.831

FOOD CENTRES

Summary Statistics	
Average	205.470
SD	22.9574
Max	281.313
Min	142.063

COASTAL HABITAT

Summary Statistics	
Average	126.867
SD	55.7815
Max	333.067
Min	37.000

AGRICULTURAL HABITAT

Fig-7 Bootstrap Iteration Results for all Habitats

was laid out on the large tables in each room. The bootstrap mean of this factor was multiplied with the total number of inhabitants in each of the orginal four habitats in order to return the samples back to their original strata after constructing the confidence intervals. The bootstrap results are shown in Fig=7.

POPULATION MODELS

Population models are needed to compare empirical findings, investigate the impact of culling and other control variables, and identify the optimum pathway for control. Ideally, a single model should be able to approximate the situation in an environment. On Unguja, however, as noted earlier, different habitats are governed by different spatial and resource dynamics. Therefore, some options have to be explored before deciding on the suitability of a model. The main task lies in establishing the correct relationship between the population under investigation and the resource it depends on. For C.*splendens*, this is not a straight forward inquiry due to persistence of generalism (the combination of omnivorism and commensalism). Further complication due to spatial limitations has already been pointed out.

We consider the discrete version of Ricker density-dependent model (Ricker, 1954, pp. 559–623; MacCallum, 2000, pp. 157–183; Sinclair et al., 2006, pp. 109–134; Brook et al., 2003, p. 811) as a point of departure. Discrete version of Ricker logistic model can be written as:

$$N_{t+1} = N_t \, e^{\, r_{max}(1 - N_t/K)} \qquad \text{---------------(4)}$$

Where; N_t and N_{t+1} are the population sizes respectively at times t and t+1, r_{max} is the intrinsic rate of population growth (max rate under ideal conditions), and K is the (constant) carrying capacity at which realized r=0.

We define commensalism in C.*splendens* as dependence on anthropogenic food source. Commensalism of C.*splendens* on anthropogenically generated organic surplus can be accounted for by the case in which carrying capacity increases exponentially with time at a fixed rate (Banks, 1994, pp. 241–245; Wu et al., 2009, pp. 413–412). Thus the equation for the resource increase can be written as:

$$K_{t+1} = K_t \, e^{\, a} \qquad \text{----------------------------(5)}$$

where; we consider K_t and K_{t+1} as organic surpluses generated by human populations at times t and t+1, and a is the rate of increase of this surplus. If we assume that one human produces the surplus equivalent of food for "X" C.*splendens* assuming a uniform rate of consumption over the life span as well as absence of altruism (inclination to reduce consumption to accommodate increasing population), then K can be directly related to human population numbers, so that:

$K_{ht} = XN_{pt}$ ------------------(6)

Where, N_{pt} is the human population at time t and $X > 0$.

Eq (5) can be written as:

$K_{h(t+1)} = \lambda X N_{pt}$ ------------------------------(7)

where K_{ht} and $K_{h(t+1)}$ are anthropogenic or commensal carrying capacities of a habitat at times t and t+1, X is the number of C.*splendens* which can be supported by organic surplus generated per human, and λ is the average long term annual growth of human population.

We define omnivorism as use of non-anthropogenic diet by C.*splendens* exclusively or in addition to anthropogenic diet, by introducing a constant K_n or the natural carrying capacity of a habitat with zero anthropogenic impact, such that:

$K_t = K_{ht} + K_n$

Where; K_t is the total carrying capacity of the habitat at time t, compensated for both commensalism and omnivorism, and

$K_{t+1} = \lambda X N_{pt} + K_n$ --------------------(8)

We assume 2009, the year of survey, as the baseline year indicative of typical conditions and near habitat stability in long term dispersion and distribution patterns, due to elapse of thirteen years since the last culling event allowing the population to

stabilize. Assuming no immigration/ emigration or change in distribution and dispersion, we evaluate the four habitats defined for Unguja Island against criteria set in Eqs (4) and (7), on the basis of our hypothesis on population abundance for the base year (Table-1) by considering the applicability of two factors C_s and C_f.

In *Urban habitat*, $C_f \rightarrow 0$ and $C_s > 1$, which implies that K_a or the spatial limit of carrying capacity is already reached. The population at time t already represents the maximum abundance and thus, $K_{tu} = K_a = N_{tu}$ (K_{nu}, the natural carrying capacity of the habitat is already compensated in K_a). In the equation subscript u denotes the habitat type (urban). In this case a simple Ricker model can be applied to show that:

$$N_{(t+1)u} = N_{tu} \text{ -------------------(9)}$$

In Suburban habitat also, $C_f < 1$ and $C_s > 1$, which implies that K_a may have been reached or may be approaching. In this case also the population at time t approximates the maximum abundance and thus, $K_{ts} = K_a = N_{ts}$ (K_{ns}, the natural carrying capacity of the habitat is already compensated in K_a). In this case also simple Ricker model can be applied to show that:

$$N_{(t+1)s} = N_{ts} \text{ -------------------(10).}$$

Now we introduce an Island wide culling event C_e and assume that culling effort is applied in proportion to target population in each habitat.
We can rewrite Eq (4) as general equation for Type-1 habitats (habitats where spatial limit is already reached and food is available in abundance such that there is no competition for food):

$$N_1(t+1) = (N_{1t} - C_{e1}) \, e^{\, r_{max} [1 - (N_{1t} - C_{e1}) / N_{1t}]} \text{ ----------(11)}$$

where, C_{e1} is the proportionate culling effort applied to the habitat, such that, $C_{e1} = C_e * N_{1t}/ (N_{1t} + N_{tc} + N_{ta})$, and N_{1t} is the C.*splendens* population in the base

year (here, 2009). The subscript "1" denotes the type of the habitat in relation to spatial limit and resource abundance.

Eqs (9), (10) and (11) are similar if $C_e = 0$. Also the term **$(N1t – Ce1) / N1t$** in the exponent of Eq (11) is the variable C_s, earlier defined.

For both *Costal* and *Agriculture habitats*, $C_s < 1$ and C_f is approaching 1. But the commensal carrying capacity of these habitats would be increasing in proportion to the rate of growth of human population, irrespective of the value of C_f.

We simultaneously compensate for omnivorism and commensalism for these two habitats by substituting Eq (8) for K. We can write the logistic equation as:

$$N_{(t+1)c} = (N_t)_c \, e^{\, r_{max}[1 - N_{tc}/(\lambda X N_{tpc} + K_{nc})]} \text{---------------------(12)}$$

where; N_{tpc} is the human population in the coastal habitat and K_{nc} is its natural carrying capacity.

and,

$$N_{(t+1)a} = (N_t)_a \, e^{\, r_{max}[1 - N_{ta}/(\lambda X N_{tpa} + K_{na})]} \text{---------------------(13)}$$

where; N_{tpa} is the human population in the agricultural habitat and K_{na} is its natural carrying capacity

The subscripts c and a in Eqs (12) and (13) denote respectively the coastal and agricultural habitats. After introduction of the Culling event and assuming λ to be uniform across both habitats, above equations can be written in the general form for Type-2 habitats as:

$$N_2{(t+1)} = (N_{2t} - C_{e2}) \, e^{\, r_{max}[1 - (N_{2t} - C_{e2}) / (\lambda X N_{tp2} + K_{n2})]} \text{---------------------(14)}$$

where; the subscript "2" denotes the habitat of Type-2 in which we assume that *spatial limit is not applicable* and competition is generated by the situation of food abundance.

We now simplify the impact of omnivorism in Eq (14) in terms of known variables by assuming that z portion of the population in these habitats would be reliant on natural food sources instead of anthropogenic organic surplus. We can write this relationship as.:

$Kn_2 = zN_2t$ ---------------------(15), where; $0 < z \leq 1$

For the present study, we fixed the natural carrying capacity for habitats of Type-2, at z times the population of C.*splendens* in the base year (2009). For coastal habitat, we assumed z=.0.3, and for the agricultural habitat 0..2 due to greater abundance of natural food sources such as invertebrates and wild fruits etc. in the coastal areas.

In general, Eq (14) can be written as:

$$N_2(t+1) = (N_2t - Ce_2)\, e^{\, r_{max}\left[1 - (N_2t - Ce_2)\,/\,(\lambda XNtp_2 + zN_2b)\right]}$$ ---------------------(16)

Where, N2b is the population in the base year considered. Also the term **$(N_2t - Ce_2)\,/\,(\lambda XNtp_2 + zN_2b)$** in the exponent of Eq (16) is the variable C_f, earlier defined.

Eqs (11) and (16) are the generalized equations respectively for Type-1 and Type-2 habitats and have been used in the models. On the room-corridor analogy Eq (11) estimates population in the corridor, while Eq (16) estimates it in the room.

PARAMETER ESTIMATION

Of the unknown parameters in the model, **λ** has been estimated using average annual long term human population growth rate, The overall figure for Unguja Island between 1967 and 2012 is **2.9%** (National Bureau of Statistics, Tanzania, 2014, pp. 13–15).**.** Regional growth rates for the long term are subject to greater variations due to migration to urban areas in recent decades and may not be reflective of the long term

trends, as already limited space in urban areas continues to shrink. We have, therefore, used the average growth rate for the Island, uniformly for all regions. **X** and **z** are arbitrarily selected and their sensitivity can be measured across plausible ranges.

For **r**$_{max}$, we have followed the methodology employed by Brook et al. (2003, p. 812) . Caughley (2005, pp. 54–55) defines it as the potential for growth in the absence of other constraints on growth, We use the Euler-Lotka equation (MacCallum, 2000, pp. 140–146):

$$\sum e^{-rx} F_x l_x = 1$$

where; x is the age of individuals, lx is the age specific survivalship, and Fx is the age specific fertility.

We use maximum annual survivalship rate "$l$max" (93%) calculated by Brook et al. (2003, p. 812) with the first year survival set at 20% lower. We also accept their estimate of maximum achievable reproductive age of Corvids as 14 years and first age of breeding as "3 years".

For maximum fecundity Fmax, we assume Brook et al.'s estimate of a maximum of four breeding events in a year and an even sex ratio among the fledglings, such that,

Fmax = Breeding Success $*$ 0.5 $*$ 4

Observational data on breeding biology on the Island is not available due to absence of any studies on this aspect. We, therefore, compared such data from few other studies conducted at other localities with established C.*splendens* populations to determine variations and adopt a selection strategy for determining breeding success (average number of hatchlings produced per successful nest) on the Island.

Brook et al.(2003, p. 813) recorded it at 2.25 in Singapore (non-native habitat), Allan & Davies (2005, p. 26) reported it at 2.4 in Durban, South Africa (non-native habitat),

Awais et al. (2015, p. 5) reported hatchlings produced per successful nest as 3.2 i.e 64 hatchlings produced from 20 successful nests (out of 29 active nests) near Islamabad, Pakistan (native habitat), and Shimba & Jonah (2017, p. 4) reported it as 2.4 in Dar-es-Salam, Tanzania (non native habitat, only 40 Kms distant from Unguja, Zanzibar). From these observations, we picked the highest for non-native habitat, i.e. 2.4 for which F_{max} was determined to be 4.8 We used Microsoft Excel's "Goal Seek" feature to solve Euler-Lotka equation and determined r_{max} to be 0.474 which is slightly higher than r_{max} = 0.465 determined by Brook et a.l (2003, p. 812).

RESULTS

POPULATION ESTIMATES

 We recapitulate the population hypothesis given in Table-1 to compare findings. We predicted low to moderate abundance in Urban and Suburban areas of Unguja Island at high densities due to operation of the variable which we termed C_s. For Coastal areas we expected high abundance and moderate densities due to moderate food availability and high space availability. For the Agricultural habitat, low abundance and low densities were expected due to food factor C_f.

The estimates are largely in line with the hypothesis. By reinterpreting the available data, we estimated mean C.*splendens* population on Unguja Island in 2009 at **465,377** (409,551-521,735) with mean overall density as 294 crows/Km^2. The least number of C.*splendens* i.e. 16,674 were estimated in the Urban habitat while the most i.e 214,806 in the Coastal habitat. Suburban and Agricultural habitats had moderate abundance at 88,522 and 145,374 respectively. Densities in the Urban habitat were highest at 1078 crows/Km^2 and lowest in the Agricultural habitat at 170 crows/Km$^{2.}$ Suburban and Coastal habitats had moderate densities between these two extremes at 406 and 435 crows/Km^2 respectively. The strongest correlation between C.*splendens* and human

populations was observed in Agricultural habitat with the crow per human inhabitant ratio at approximately 1.0 and the weakest in the Urban habitat at 0.081. In coastal areas, crow/inh ratio was 1.59 indicating reliance on non anthropogenic food in at least part of population. These results with other relevant data are contained in Table-2.

C.*splendens* POPULATION AND DENSITIES, UNGUJA ISLAND							
Habitat	Area	Human Pop	Human Pop Density	Crow Pop	Crow/Inh	**Adjusted Crow Pop**	Crow/Km^2
Urban	15.46	204702	13240.75	5297.261	0.081455	**16674.02**	1078.526
Suburban	217.76	340182	1562.188	69615.67	0.26022	**88522.02**	406.5119
Coastal	493.36	135028	273.6906	207302	1.590829	**214806.5**	435.395
Agricltural	855.92	143109	167.199	137420.7	1.015829	**145374.3**	169.8457
Food Centres	NA	823021		45741.18			
TOTAL	1582.5			465376.8		465376.8	
AVERAGE			520.0765		0.737083		294.077

Table-2 Reconstructed C.*splendens* Abundance – Unguja Island, 2009

MODEL ESTIMATES

Abundance Predictions

Assuming that the variables governing the intrinsic rate of growth are accurately determined, the predictive ability of Equation (11), which is in fact the simple Ricker Model adjusted for culling, with respect to abundance estimates is only as good as the population estimates undertaken at the time of peak abundance, because that is the upper bound which controls the model results. Even then, it is more a useful tool for comparison of field survey results instead of a reliable predictor of abundance. In the present case, the population estimates of Urban and Suburban habitats on Unguja Island derived from 2009 survey seem plausible because the model predicts that by the time this survey was undertaken, sufficient time had elapsed after the first culling event

for abundance to have reached peak values (16,674 for Urban and 88522 for Suburban habitats).

On the other hand, assuming that the fundamental assumption linking abundance with anthropogenically generated organic surplus is sound, Equation (16) has a considerably greater predictive potential as it is mainly bound by a fairly accurately determinable variable i.e. the human population growth rate. We can consider Eq (16) again:

$$N2(t+1) = (N2t - Ce_2) e^{r_{max}[1 - (N2t - Ce_2) / (\lambda X Ntp_2 + z N2b)]}$$

In this equation λ (human population growth rate) and $Ntp2$ (human population at time t for habitat Type-2) are known. Only two, reasonably spaced and fairly accurate population surveys are needed. One to determine the initial state of the habitat, and another to determine $N2b$ (abundance in the base year). Peak abundance is not required as the equation is now controlled by two constants X (number of commensals dependent on organic surplus produced per human) and z (proportion of omnivores dependent on non-anthropogenic food in addition to anthropogenic food in the base year) none of which is linked to peak abundance. X and z are controlled by reasonable assumptions. We fixed X at 1 for the Coastal as well as Agricultural habitats while z was fixed at 0.3 and 0.2 respectively. The reasonability of these assumptions can be tested by comparing with the actual base year survey results for these two habitats.

From the 2009 survey, we estimated mean C.*splendens* abundance for Coastal and Agricultural habitats respectively at **214,806** and **145,374**. The model estimates the respective populations in 2009 at **194,499** and **166,782**. We then carried out a What-If analysis using the GOALSEEK feature of Microsoft Excel to determine how much does one factor vary, if the other is kept constant if the model results were to exactly replicate the survey results for 2009. The results of this analysis are given in Table-3 which indicate that the assumptions made above are not too unreasonable.

COASTAL HABITAT			AGRICULTURAL HABITAT		
WHAT		**IF**	**WHAT**		**IF**
WHAT is	IF		WHAT is	IF	
X?	z is	**N2b**	**X?**	z is	**N2b**
1.1567	0.3	**= 214,806**	**0.8439**	0.2	**= 145,374**
WHAT is	IF		WHAT is	IF	
z?	**X** is		z?	**X** is	
0.3951	**1**		0.052	**1**	

Table-3 What-If Analysis for Model Assumptions

In practical terms, the more likely assumption to go wrong is z and X can be even measured experimentally. Therefore, on the model, we keep X as 1 and change the z values in order to reduce the number of assumptions in the model from two to one, and more accurately depict the base year survey results in the future pathways.

Culling and Recovery

We compared recovery periods on *Culling* and *Non-Culling* pathways in all habitats starting from the first Culling Event in 1996 and including the later Culling Event in 2013. We also simulated additional burst Culling Events on the Culling pathway at equal intervals of 6 years after the second Culling Event, and of the same absolute strength (approximate decimation of 55% of 2009 population) assuming it to be the maximum possible effort which can be generated in a year per one generation of C.*splendens*,

with an average age of 6 years (Madge & Burn, 1994),. For Type-1 habitats (with fixed carrying capacity due to increasing contest for space "C_s" with increase in abundance) we evaluated the results over a fifty year period for the calculated value of $r_{max} = 0.474$ as well as at a lower bound of 0.288 suggested in Brook et al. (2003, p. 812). For Type-2 habitats (with variable carrying capacity due to no limits on space but constrained by contest for food C_f), we evaluated the results over a seventy five year period (1995-2070) to determine long term trends at both values of r_{max}. The results obtained are shown in Figs 8 to 15. In these figures, N_t is the culling pathway while Path 0 is the non culling pathway. The results shown here are only for the Urban and Coastal habitats on Unguja Island.

At $r_{max} = 0.474$, for Type-1 habitats, the post culling full recovery for a 55% decimation was regularly spaced at approximately six years for both Urban and Suburban habitats. We varied the magnitude of culling to lower rates considering 55% to be the maximum possible. At lower rates of decimation the recovery was spaced closer (4-5 years for 20% decimation). The rate of increase for the contest for space factor C_s varies directly with recovery rates. The slope of the recovery curve i.e. the curve of abundance at times immediately prior to culling is zero. This implies that culling needs to be spaced closer to make the slope of recovery curve negative (see Figs 8 and 9).

At $r_{max} = 0.288$, for Type-1 habitats, at time steps of six years, the recovery curve has a negative slope implying that the population recovers to lower than pre-culling levels indicating a reduction in abundance over time. The C_s curve also has a negative slope indicating increase in spatial carrying capacity over time (see Figs 12 and 13). We spaced the culling events wider to evaluate the impact. With culling events spread at approximately 8 years, the slope of recovery curve becomes zero.

For Type-2 habitats (with increasing carrying capacity), the recovery as well as the C_f curves have a positive slope at both rates of intrinsic growth, the only change is the reduction in the steepness of the curve at the lower intrinsic growth rate (see Figs 10, 11, 14 and 15). The C_f on the non-culling path (C_{fpo}) approaches 1 but does not become 1 even in a 75 years evaluation indicating a proportionately greater availability of food than the rate of growth of dependent population.
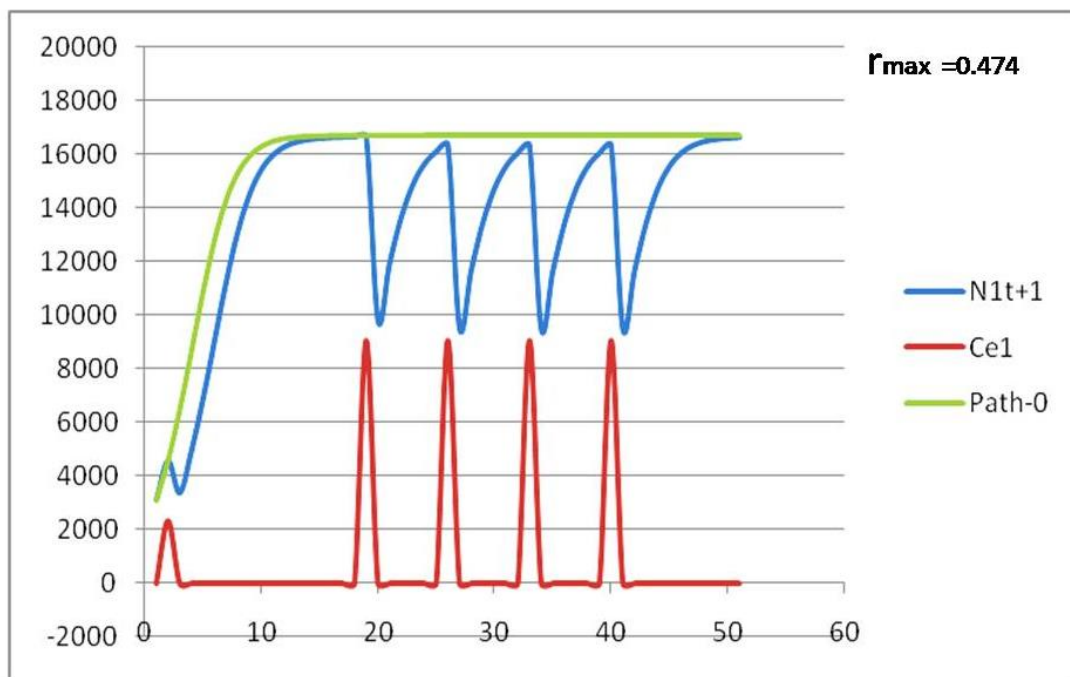

Fig-8 Recovery Periods after Regular Burst Culling (Habitat Type-1)
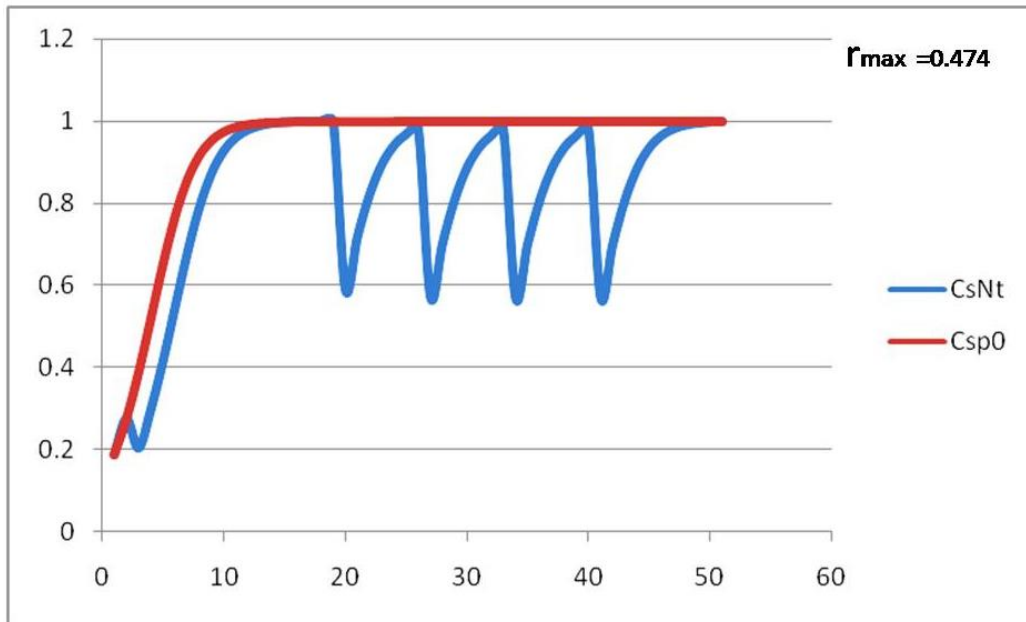
Fig-9 Changes in Cs after Regular Burst Culling (Habitat Type-1)
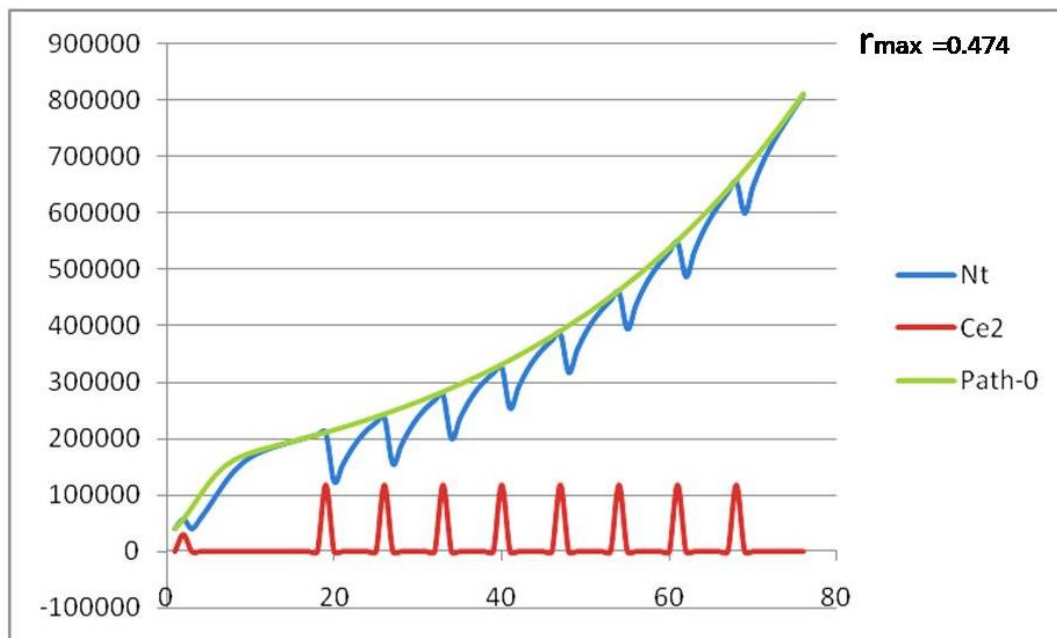
Fig-10 Recovery Periods after Regular Burst Culling (Habitat Type-2)
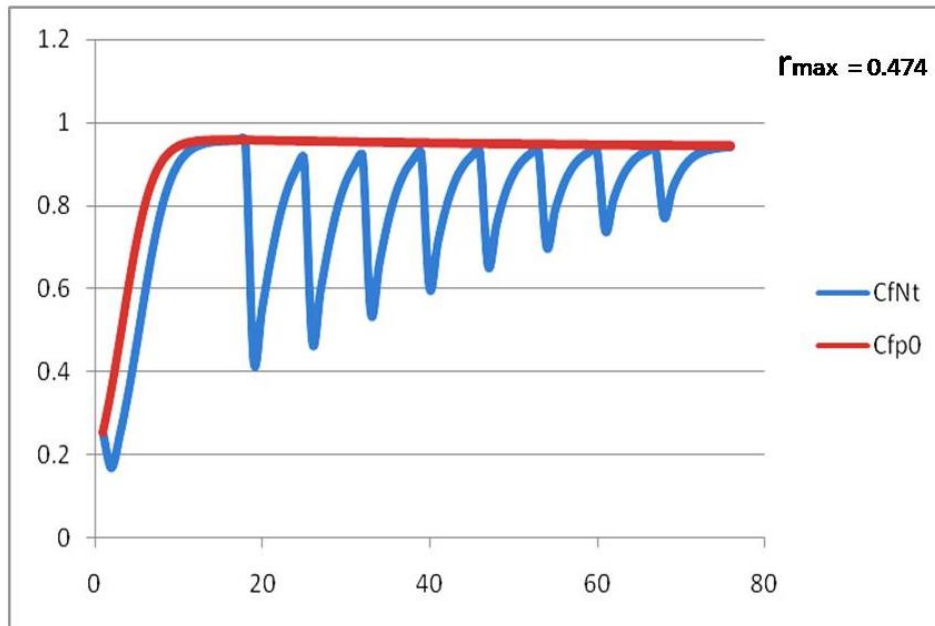
**Fig-11 Changes in Ċf after Regular Burst Culling
(Habitat Type-2)**
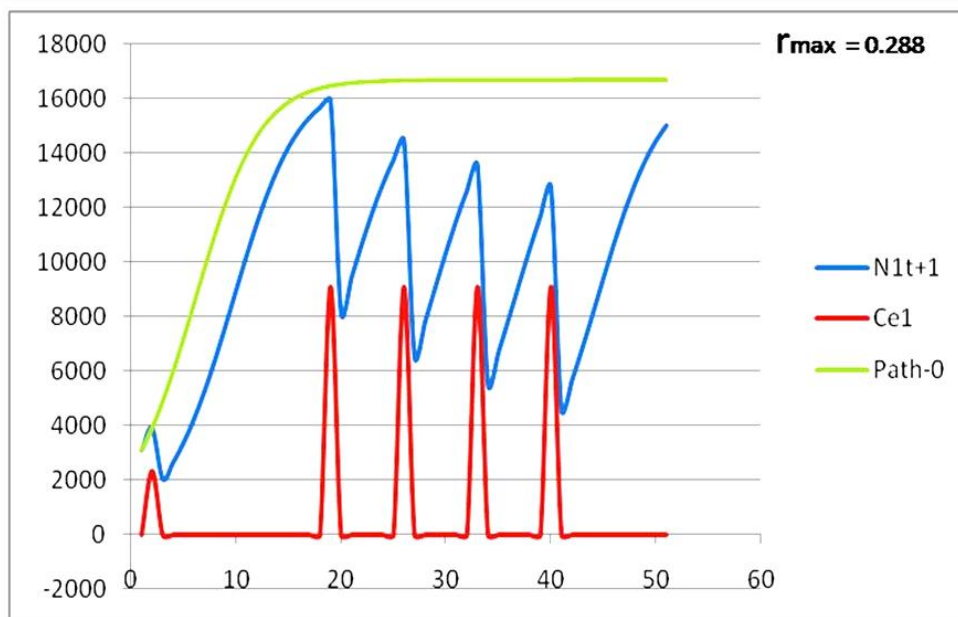
Fig-12 Recovery Periods after Regular Burst Culling (Habitat Type-1)
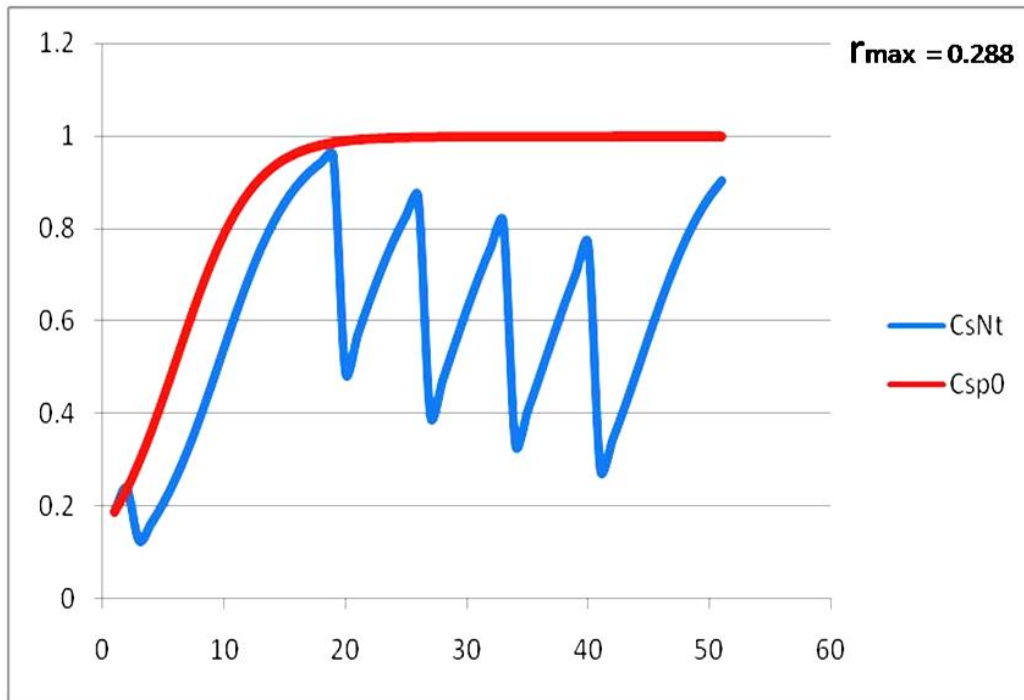
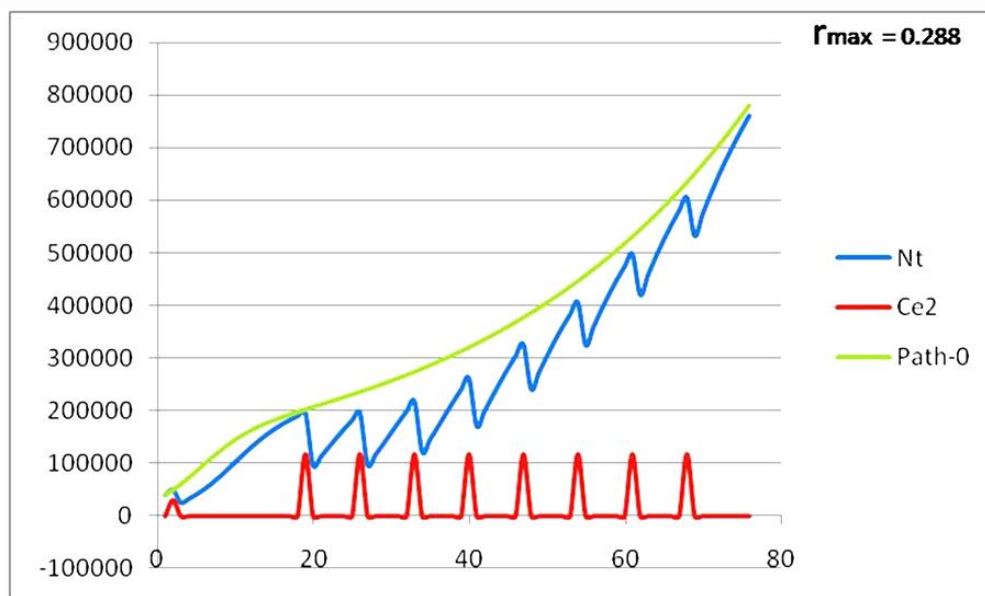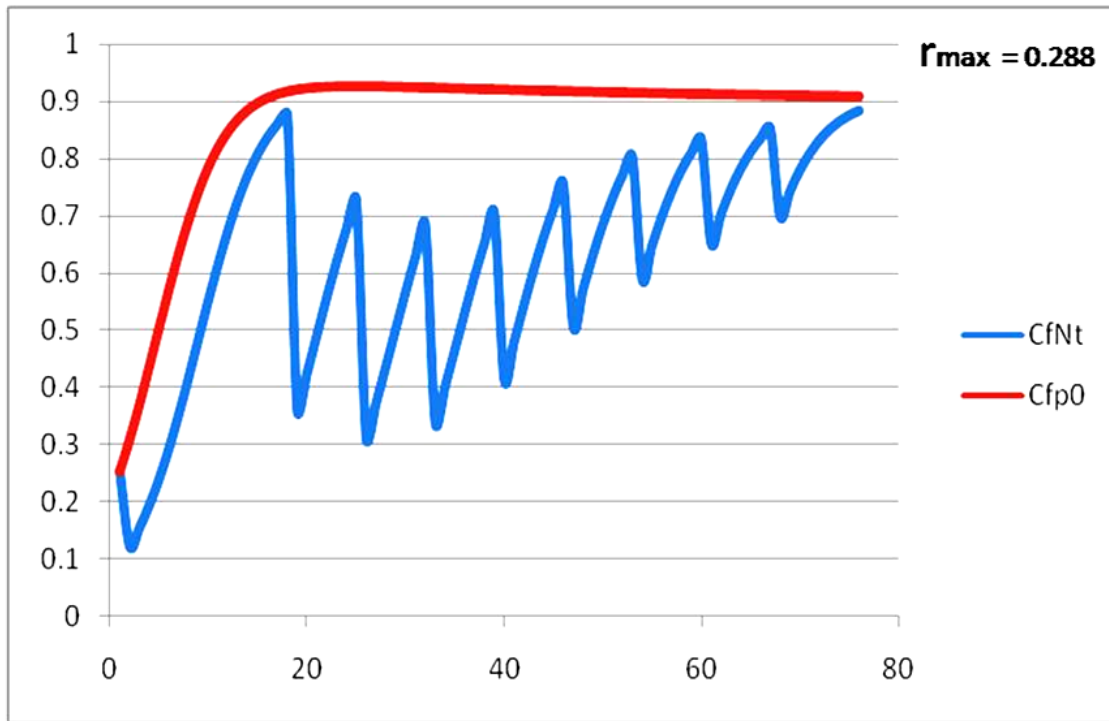**Fig-13 Changes in Cs after Regular Burst Culling (Habitat Type-1)**

Fig-14 Recovery Periods after Regular Burst Culling (Habitat Type-2)

Fig-15 Changes in Ċf after Regular Burst Culling (Habitat Type-2)

DISCUSSION – CONTROL PATHWAYS

The dilemma inherent in burst culling is that it has to be spaced wider to avoid practical difficulties such as escalating finances, effort needed and difficulty of "convincing the target to fall for the repetitious methods", but when it is spaced in this manner, it allows the target population to rebound in relation to the constraining factor i.e. space or food.

Since we do not have control over r_{max}, in the Urban and Suburban habitats which have fixed carrying capacity limited by space, this dilemma can be theoretically resolved by either application of culling at constant lower absolute or proportionately decreasing culling rates i.e constant relative rates. But this has to be a continuous process because the moment it is interrupted, the problem rebounds. The more effective and durable

option is to reduce the access to food, which amounts to constructing a narrow door between the room and the corridor on our analogy.

TYPE-1 HABITATS

We now look at these options as three pathways for Type-1 habitats by considering the Urban and Suburban habitats on Unguja Island. We do not consider constant absolute rates i.e. a fixed number annually as a practicable option. Therefore only three pathways are considered i.e. culling at constant relative rates, reduction of access and a combination of the two. We evaluate the options from the perspective of managing the issue within a ten year framework by considering **target densities** which can be practicably achieved while keeping the longer term perspectives also in view.
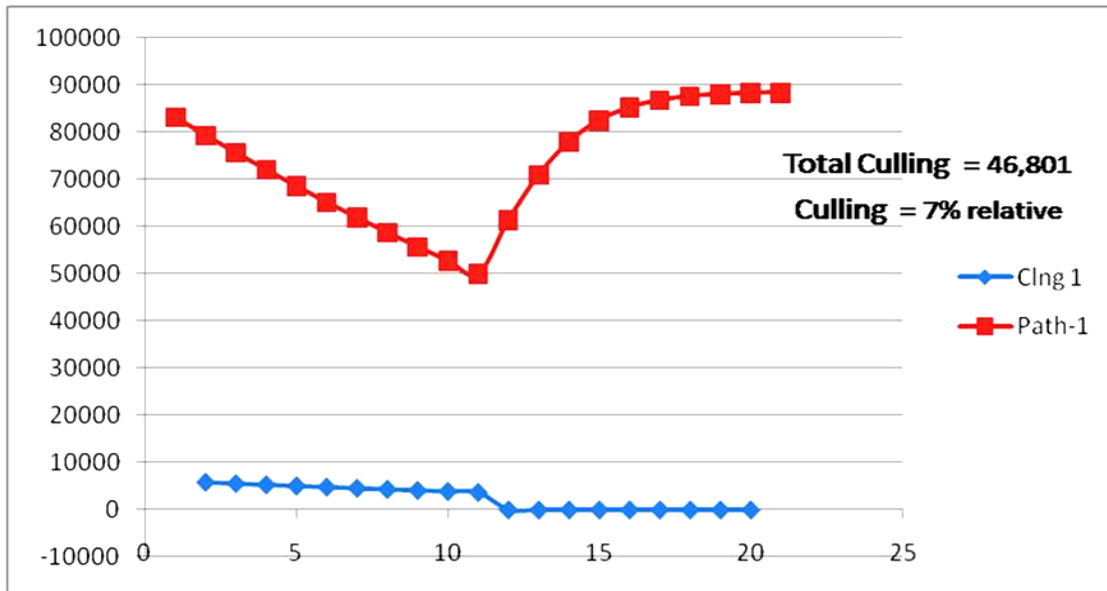
Pathway-1 Constant Relative Rate of Culling

Considering the absolute numbers required to be culled over a ten year period and current population densities of C.*splendens*, we assume that the target densities can be reduced by 75% (from 1013 to 253 crows/sq km) and 40% (from 382 to 229 crows/sq km) respectively in Urban and Suburban habitats. We determine the relative rate of culling required to achieve the target density. We consider the current year (Yr 22 after first Culling Event) as Year 0. Therefore, all remedial actions begin at 23 years after the first Culling Event. We also determine the post-programme implications i.e in the.ten year bracket after the termination of the programme.

In the Urban habitat, we estimate that a relative culling rate of 16% (16% of survivors annually) and total culling of 15,119 birds would be needed to achieve this target. 2526 birds will be culled in the first year and 777 in the tenth. 3911 survivors would be left at the end of ten year period. This population recovers back to pre-culling levels in the 7th year after the programme (Fig-16). In the Suburban habitat a relative culling rate of 7% and total culling of 46,801 birds over ten years would be needed. 5,787 birds would be culled in the first year and 3,666 in the tenth. 49,867 survivors would be left at the end of the programme. This population will recover back to pre-culling levels in the 4th year after the programme (Fig-17)
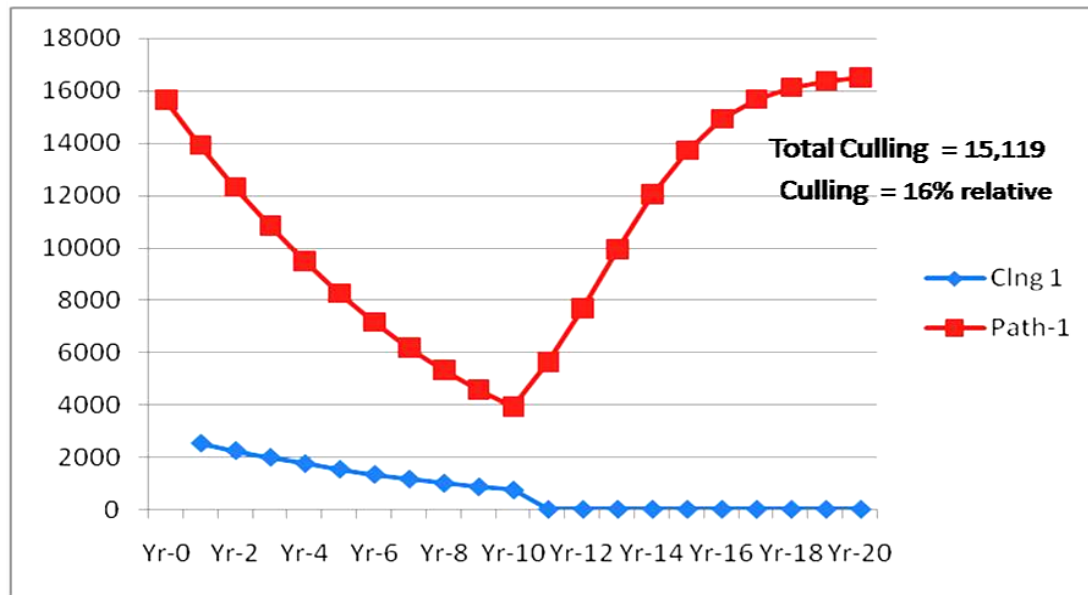

Fig-16 Ten Years Culling Programme at Relatively Constant Rate (Urban Habitat)

Fig-17 Ten Years Culling Programme at Relatively Constant Rate (Suburban Habitat)

Pathway-2 Access Control

We consider this option to be implemented within five years but we look at the ten year and twenty year implications of the programme. We estimate how much access of the maximum levels (i.e. Ka) will have to be reduced within five years, in order to achieve the target densities in the Urban and Suburban habitats. Achieving target densities through this programme will require access reduction through organic waste management plans by 80% in the Urban and 50% in Suburban habitats. The impacts of the programme are permanent, the population does not rebound, and repeat efforts are not needed (Figs 18 and 19).
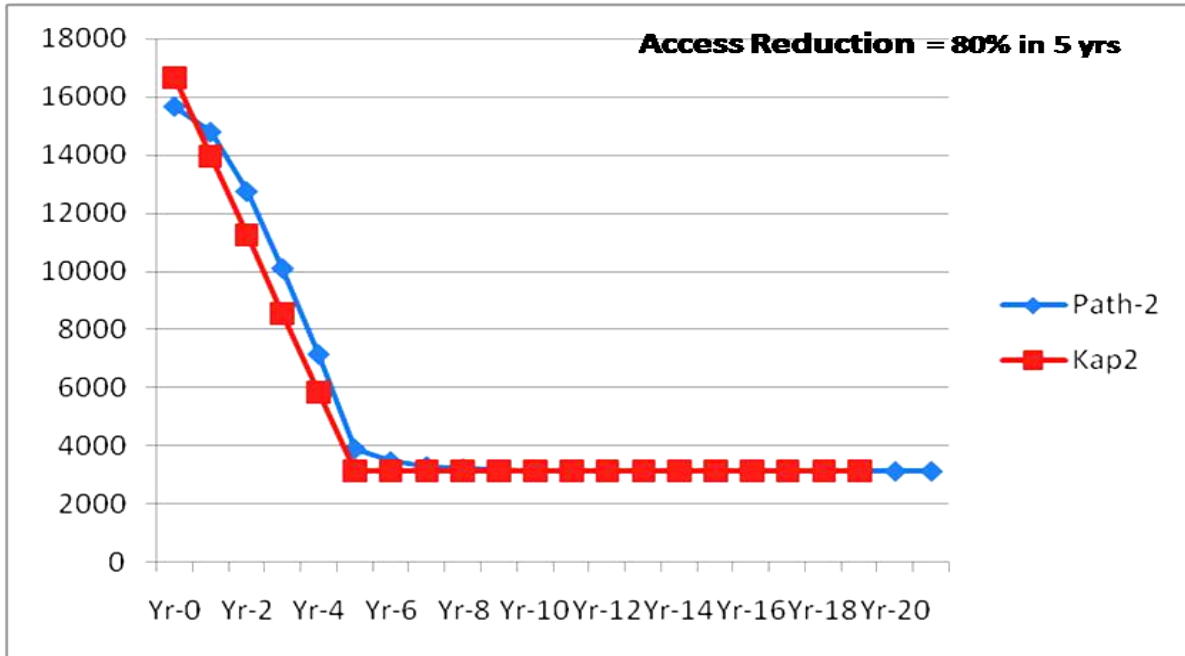
Fig-18 Five Years Access Reduction Programme (Urban Habitat)
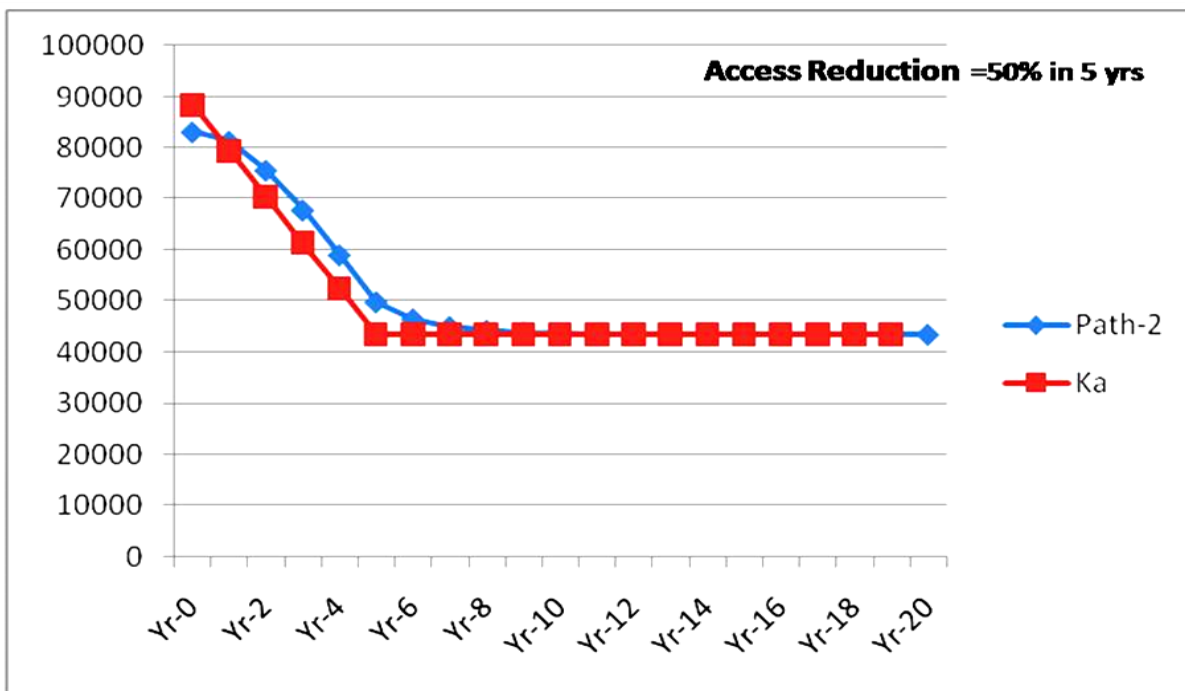
Fig-19 Five Years Access Reduction Programme (Suburban Habitat)

Pathway-3 Combination Control

The discussion on this programme only has an academic value because the culled population will eventually rebound to the carrying capacity set by access control which implies that the effort spent in culling is in fact a wasted effort. With a combination programme of 16% relative culling and access reduction by 80 % the density in Urban habitat can be reduced to 162 crows/sq km. This population recovers back to the density achieved in the access control programme (200 crows/sq km) in the fifth year after termination of the programme. Similarly, in the Suburban habitat the population density levels off at 200 crows/sq km achieved through access reduction programme. The comparison of the three pathways is shown in Figs-20 and 21 in which densities for the three pathways are denoted respectively by D1, D2 and D3.
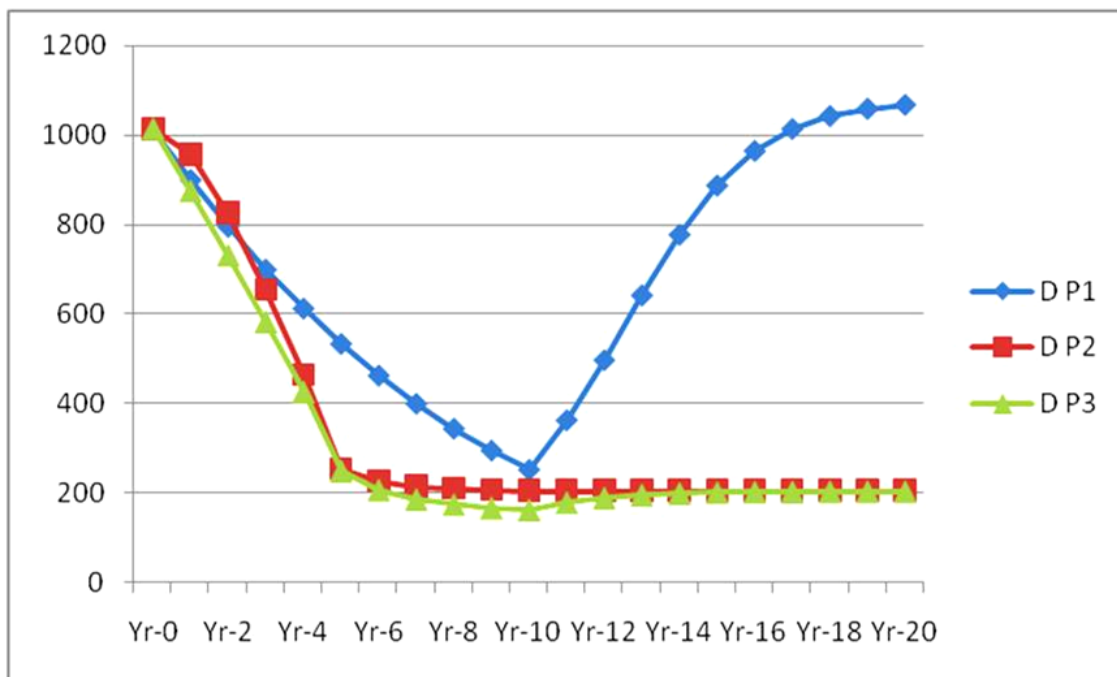

Fig-20
Comparative Density Reduction over Twenty Years for Three Pathways
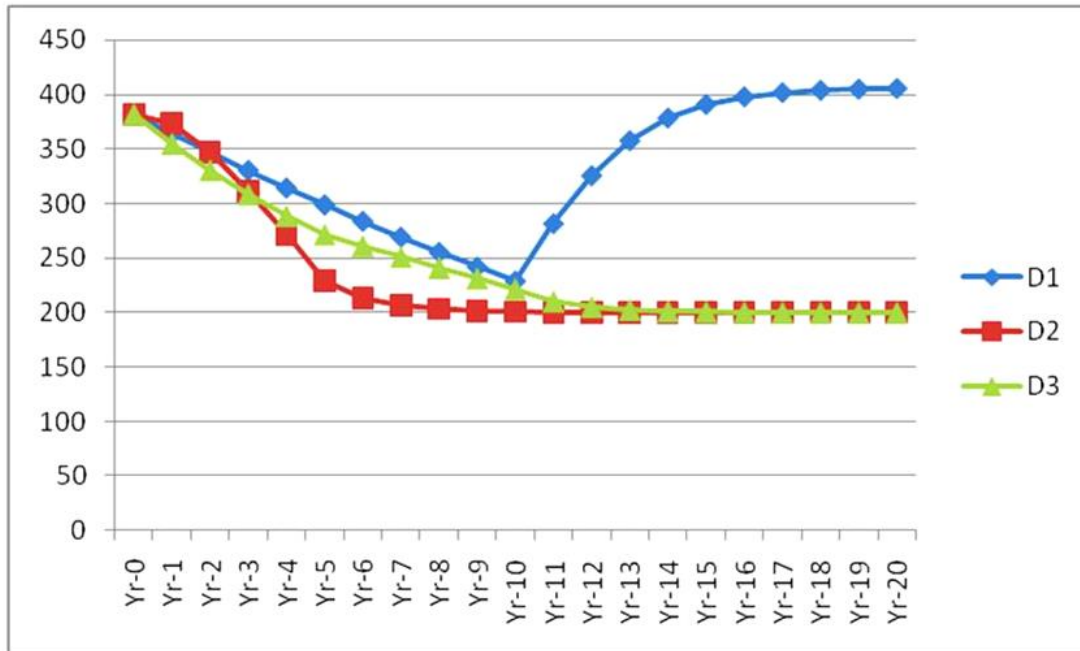**(Urban Habitat)**

Fig-21
Comparative Density Reduction over Twenty Years for Three Pathways
(Suburban Habitat)

TYPE-2 HABITATS

For the Coastal and Agricultural habitats, we evaluate the same pathways as for Type-1 habitats. We set target densities of 219 for the Coastal and 100 for the Agricultural habitats on the Culling pathway at the end of ten years. This is because of the limitations imposed by interplay of the practicably achievable rates of culling and the factor z, which theoretically controls the minimum population even if all anthropogenic influence is removed (the natural carrying capacity). We set the same targets for the access reduction and combination pathways at five years and allowed the minimum possible future densities to be controlled by this change in carrying capacity.

Pathway-1 Constant Relative Rate of Culling

For the Coastal habitat, a 32% constant relative rate of culling is required to achieve the target density. 480, 000 birds will have to be culled in the ten year period with the first year culling requirement of 70,719 and 32,273 for the tenth. At the end of the program, there will be 98,672 survivors and the population will rebound to pre-culling levels in third year after a ten year culling spree. The population will recover to the no-culling pathway levels (Path 0C which presumes no culling or other remedial measures are taken) within the next two years (Fig-22).
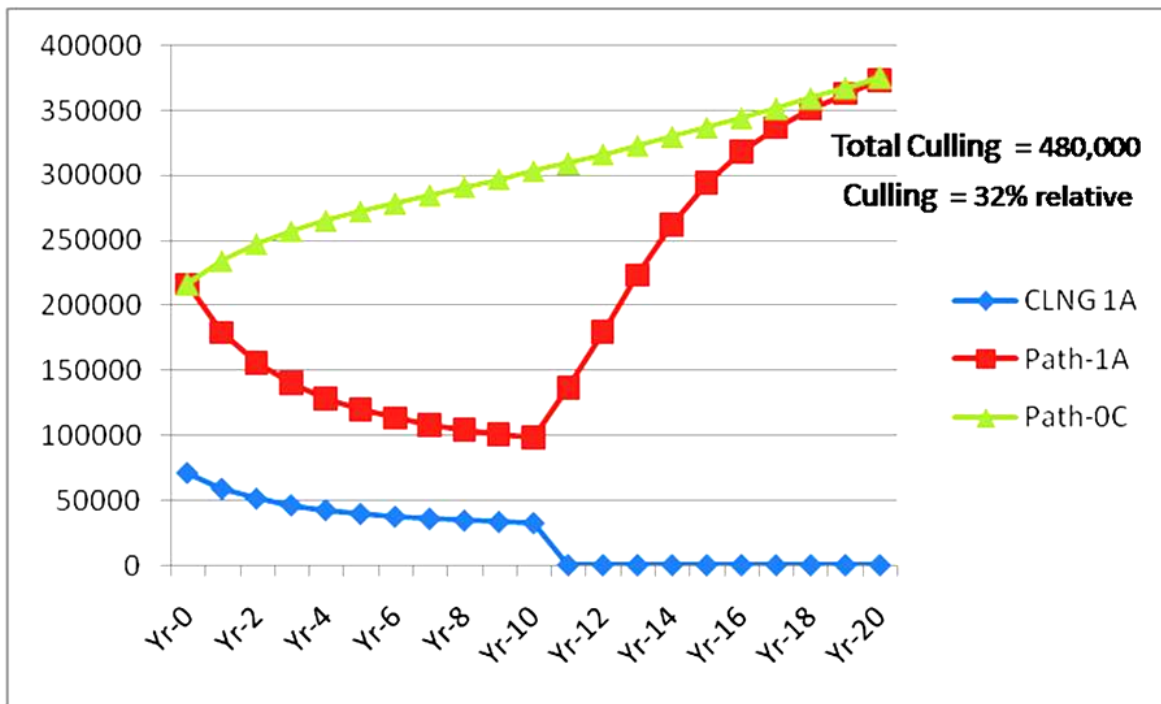

Fig-22
Ten Years Culling Programme at Relatively Constant Rate
(Coastal Habitat)

For the Agricultural habitat, 30% culling rate will achieve the target in ten years. 378, 043 birds will have to be culled over ten years with the first year requirement of 53,994 and tenth year requirement of 27,222. 88,592 birds will survive the event. The population will recover to the pre-culling levels in the third year after the programme and will align with Path-0 in the sixth year (Fig-23).
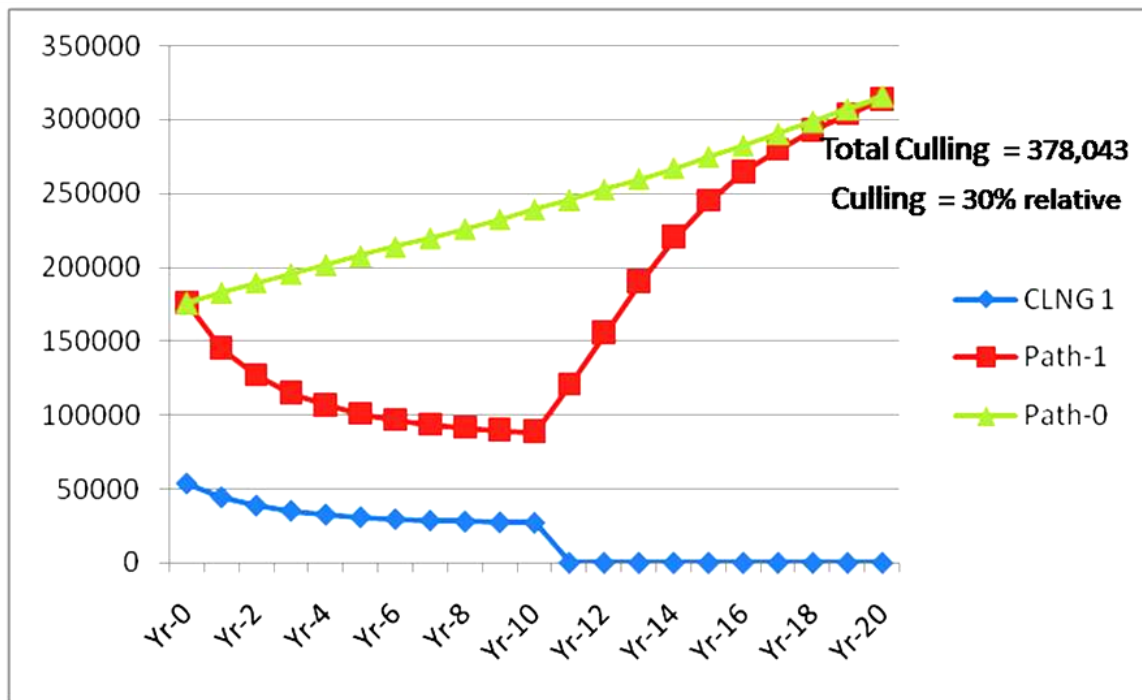

Fig-23
Ten Years Culling Programme at Relatively Constant Rate
(Agricultural Habitat)

Pathway-2 Access Control

On the room-corridor analogy, for Type-2 habitats, this amounts to creation of the corridor connected to the room where none existed before. We estimated the amount of

reduction required in the usable per capita organic surplus (**X**) produced by human population if target densities were to be achieved within five years. For the Coastal habitat, **X** will require an 88% reduction over five years and in the Agricultural habitat 84.5% reduction will be needed. We also capped off the effect of human population growth factor **λ** after the fifth year till the twentieth year implying that this factor will have to be catered for, in any access reduction programme. In the Coastal habitat, the population levels off at the natural carrying capacity by ninth year and is maintained till Year 20, implying that this is the maximum possible achievable density reduction (219 crows/sq km) (Fig-24).
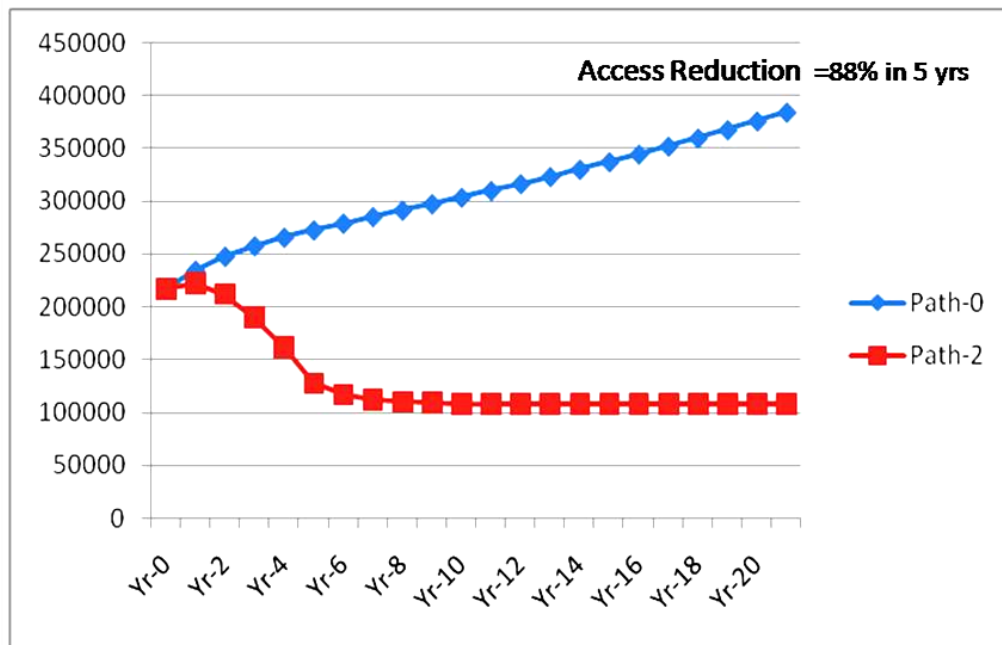

Fig-24
Five Years Access Reduction Programme
(Coastal Habitat)

In the Agricultural habitat the population levels off above the natural carrying capacity at 48 crows/sq km by year six. We conclude that achieving densities lower than this is not practicable due to the practical difficulty of setting **X** further lower as well as the possible error in estimating the effect of natural carrying capacity (Fig-25).
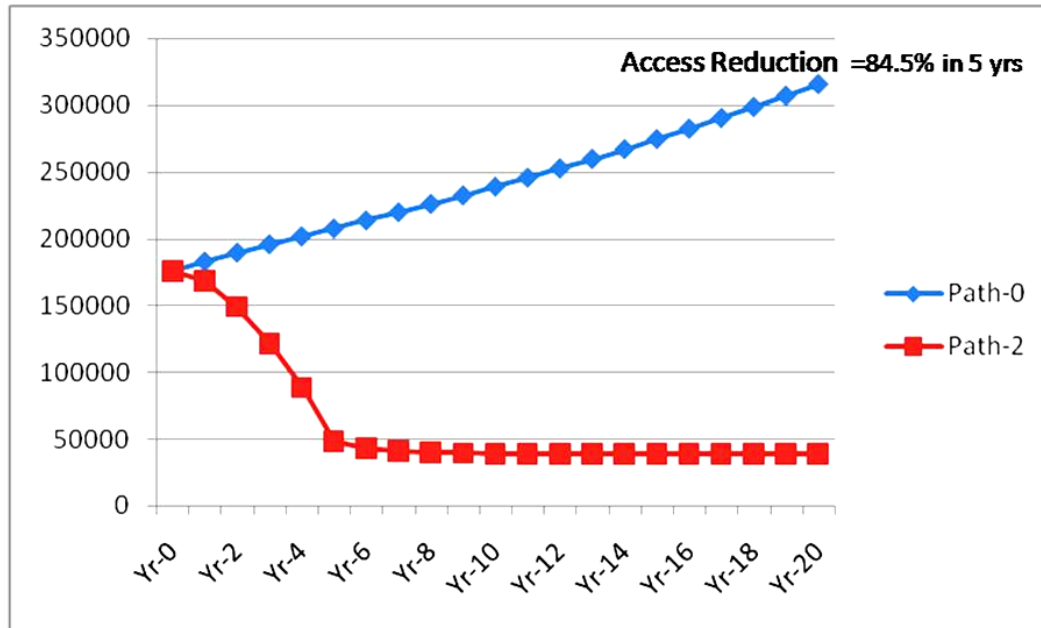
Fig-25
Five Years Access Reduction Programme
(Agricultural Habitat)

Pathway-3 Combination Control

This pathway involves combined application of maximum culling and access reduction as determined for Pathways 1 and 2 respectively. The results are same as for Type-1 habitat but are discussed here in some detail.

In the Coastal habitat, the densities temporarily fall below the natural carrying capacity to as low as 95 crows/ sq km involving a culling effort of 361,558 birds over ten years.

The population recovers to the levels fixed by reduction in carrying capacity in the fifth year after the conclusion of the programme (Fig-26).
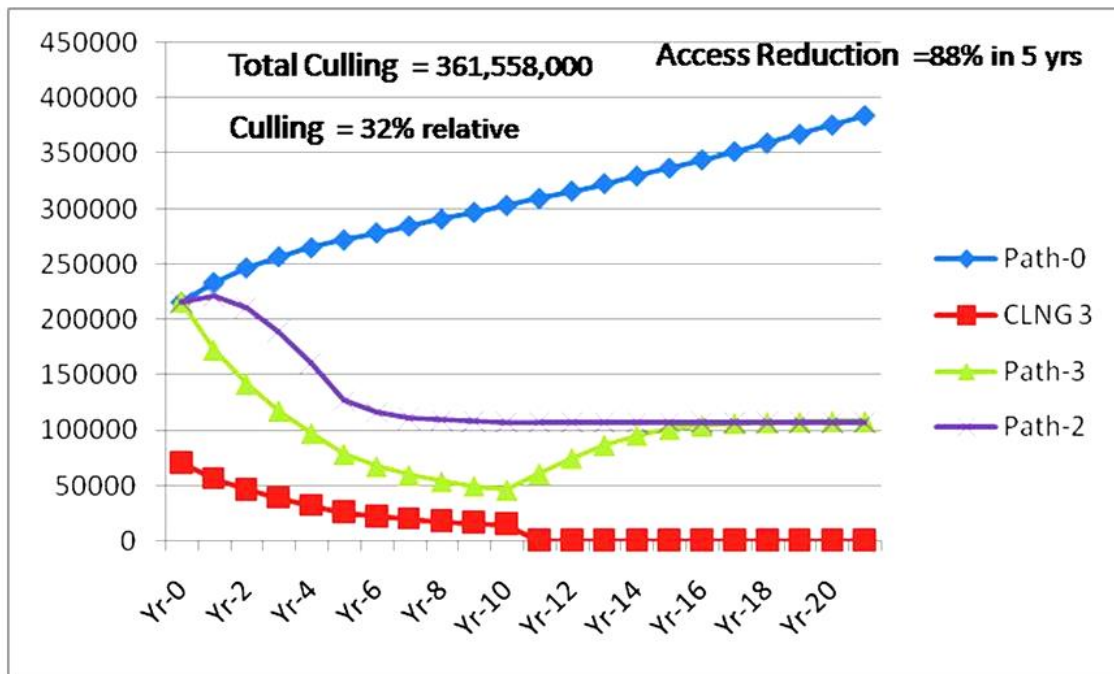
Fig-26
Ten Years Combination Programme
(Coastal Habitat)

In the Agricultural habitat, the density declines to as low as 23 crows/sq km involving a culling effort of 228,998 crows/sq km before recovering to X determined levels in the fifth year after programme's conclusion (Fig-27).
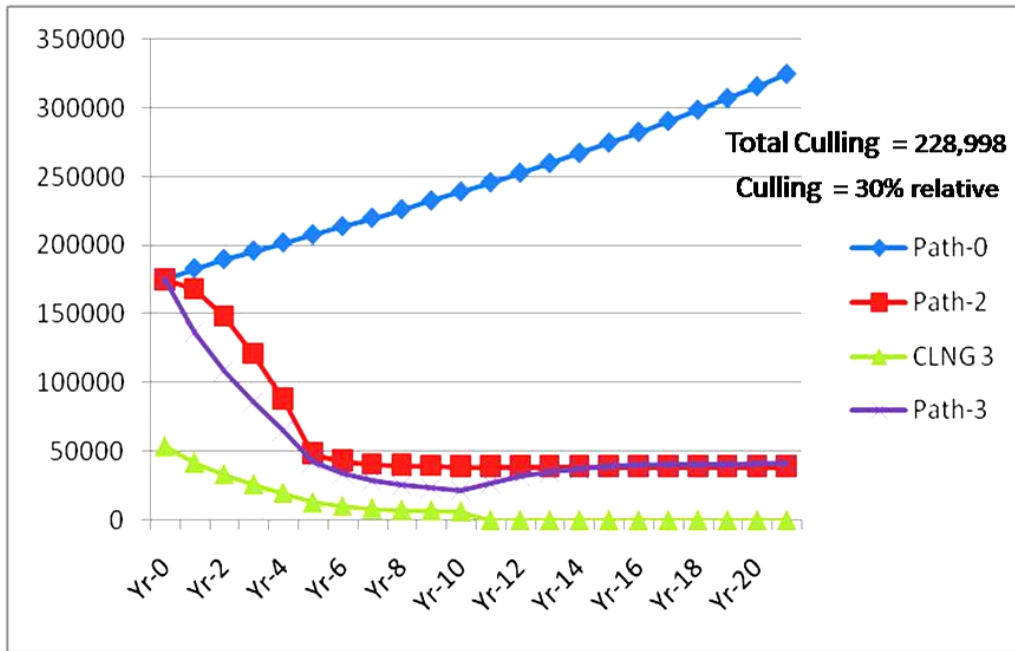
Fig-27
Ten Years Combination Programme
(Agricultural Habitat)

Comparative density reductions over time in both habitats are shown in Figs 28 and 29.
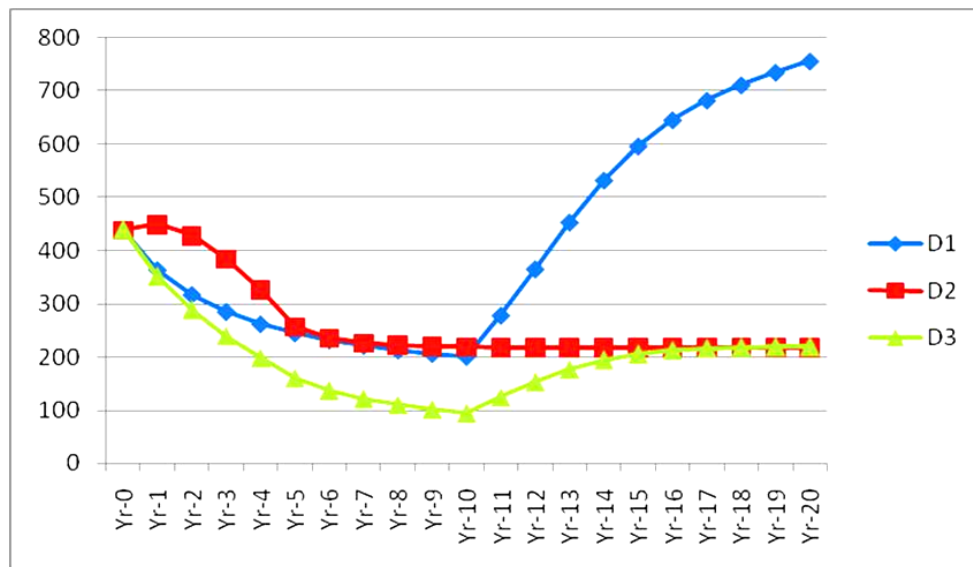
Fig-28
Comparative Density Reduction over Twenty Years for Three Pathways
(Coastal Habitat)
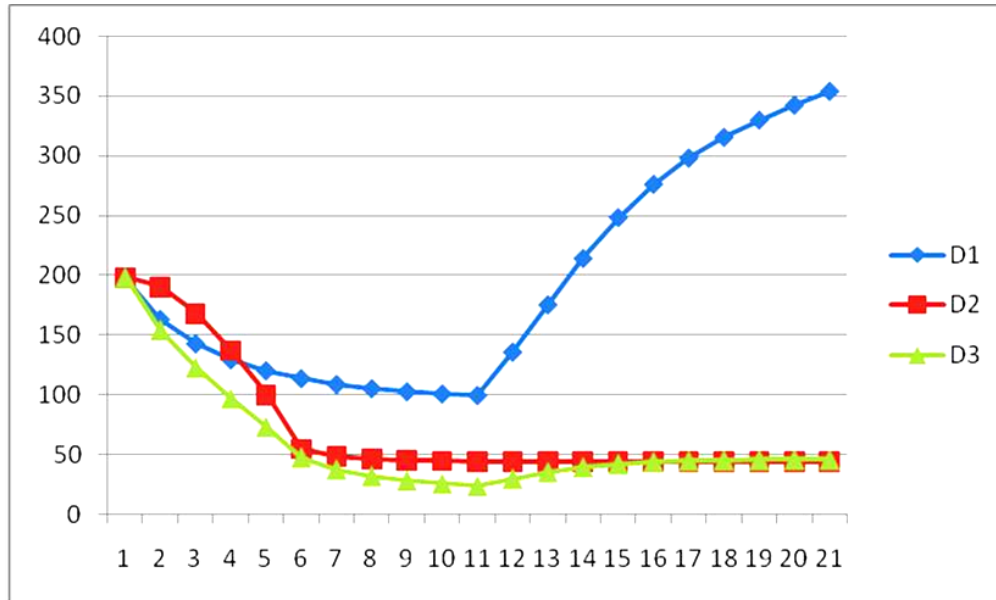
Fig-29
Comparative Density Reduction over Twenty Years for Three Pathways
(Agricultural Habitat)

MANAGEMENT IMPLICATIONS – EFFORT, COSTS AND BENEFITS

Now, we discuss the management implications by measuring cost-benefits versus effort. First we summarize the effort required in terms of two control variables i.e. culling and access reduction $(Ce, \Delta X \text{ and } \Delta\lambda)$ which we have employed in identifying the possible pathways, in order to focus on the larger picture. Table-3 contains this summary. Then we measure the effort required by comparing it with the benefits and associated costs. We, finally recommend the pathway which optimizes this interplay.

EFFORT ANALYSIS

Habitat	Pathway								
	1			2			3		
	Ce	ΔX	$\Delta\lambda$	Ce	ΔX	$\Delta\lambda$	Ce	ΔX	$\Delta\lambda$
Urban	15,119	-	-	-	- 0.2	-	11496	0.2	-
Suburban	46,801	-	-	-	- 0.5	-	44872	0.5	-
Coastal	480,000	-	-	-	0.12	0	361,558	0.12	0
Agricultural	378,043	-	-	-	0.155	0	228,998	0.155	0
Total	**919,963**	**-**	**-**	**-**	**-**		**646,924**	**-**	-

Table-3 Effort Analysis

BENEFITS ANALYSIS

We measure the benefits in terms of proportionate density reduction and the population rebound after the termination of the program. We define R_f, the "rebound factor" as:

$$R_f = D_{t_{max}}/ D_{t_0} \text{----------(17)}$$

where; D_{tmax} is the maximum population density between years 10 and 20 (or any other period considered after the programme), and D_{t0} is the density at Yr 0. $\mathbf{R}_f$ determines the effectiveness of a pathway such that at $\mathbf{R}_f = 1$, the pathway is 100% ineffective and at $\mathbf{R}_f = 0$, it is 100% effective. This factor is calculated for each habitat and the entire Island in Tables 4 to 6.

For Pathway-1 (Culling only) density increases from 310 to 500 with an Rf of 1.61 indicating 161 % wastefulness of the resources employed.

Habitat	Pathway 1				
	N_{to}	N_{tmax}	D_{t0}	D_{tmax}	R_f
Urban	15662	16651	1013	1077	1.06
Suburban	83149	88501	382	406	1.06
Coastal	216216	372943	438	755	1.72
Agricultural	175716	313588	198	354	1.78
Total	**490743**	**791683**	**310**	**500**	**1.61**

Table-4 Benefits Analysis Pathway-1

Habitat	Pathways 2 & 3				
	N_{to}	N_{tmax}	D_{t0}	D_{tmax}	R_f
Urban	15662	3156	1077	203	0.19
Suburban	83149	43516	406	199	0.49
Coastal	216216	107748	438	218	0.5
Agricultural	175716	40601	198	44	0.22
Total	**490743**	**195021**	**310**	**123**	**0.39**

Table-5 Benefits Analysis Pathways-2 & 3

For Pathways 2 and 3, an overall density reduction of 61% (Rf=0.39) is achieved indicating the reduction of original problem by 61%.

COST ANALYSIS

We assume that per capita cost of culling is c and for access reduction it is a. Further, we assume that in the present case, c = a. We also assume that due to increasing resistance to culling over time, the per capita cost increases at the same rate as the relative rate of culling such that the amount spent during first year culling will be required each year to sustain the relative rate of culling. Therefore, the total cost of culling programme can be given as:

C = n $_x$ Ce1 $_x$ Co ------ (18)

where; n is the number of years over which culling is applied, c_o is the per capita cost for the first year of culling and C_{e1} is the population culled in the first year of the programme.

Since 'a' is not affected by the amount of effort put over time, it can be said that it amounts to culling the same number of birds as in Pathway-1 but without the cost penalties over time. We can write the total cost for access reduction as:

$$A = c_o \times (C_{eT} + \Delta N_t) \text{ -------------(19)}$$

where; C_{eT} is the total population culled to achieve the same effects as culling pathway would achieve and ΔN_t is the difference in abundance in the last year (Yr 20) on Path-0 (i.e the path on which neither culling nor access reduction was applied) and abundance in last year on the relevant access reduction pathway (year 5 for pathways-2 and 3), to cater for the effects of capping the impact of λ for t number of years. For Type-1 habitats $\Delta N_t = 0$. Also we take F as the fixed management cost of the programme. C_T, the total cost for a pathway is:

$$C_T = C + A + F \text{ ------ (20)}$$

We calculate c_o from the cost effects available for the latest culling programme in Zanzibar (Mwinyi, 2013) which comes out in US$ terms as 1.05 and F = 123,550 US$ (25% of total cost) for culling programme and US$ 150,000 (43% of 2013 cost) for access reduction due to more extensive effort including surveys and monitoring required to implement the programme. The project report containing state of expenditure is enclosed as Appendix B to this study. Cost effects are calculated in Tables 6 to 7 for Pathways 1 and 2.

Habitat	Pathway 1					
	F = 123550 n=10 Co = 1.05					
	ΔN_t	Ce_T	Ce_1	C	A	C_T
Urban	-	15,119	2,527	26,530	-	**152,0320** **(1.52 million)**
Suburban	-	46,801	5,786	60,750	-	
Coastal	-	480,000	70,719	74,2450	-	
Agricultural	-	378,043	53,995	56,6950	-	
Total	**-**	**919,963**	**133,026**	**139,6770**	**-**	

Table-6 Cost Analysis Pathway-1

For Pathway-1, the cost based on 2013 figures in Zanzibar is estimated as approximately US$ 1.52 million while for Pathway-2 it is estimated as US$ 1.69 million. For Pathway-3, it is the sum of the two plus the difference in culling costs of pathways 1 and 3 (US$ 0.287 million). It comes to US$ 2.92 million.

Habitat	Pathway 2					
	$F = 150{,}000$ $n=5$ $Co = 1.05$					
	ΔN_t	Ce_T	Ce_1	C	A	C_T
Urban	0	15,119	2.527	-	15,875	
Suburban	0	46,801	5.786	-	49,141	**168,8034** **(1.69 million)**
Coastal	268,030	480,000	70,719	-	785,432	
Agricultural	276,801	378,043	53.995	-	687,586	
Total	**544,831**	**919,963**	**133,026**	**-**	**153,8034**	

Table-7 Cost Analysis Pathway-2

RECOMMENDATIONS BASED ON COSTS-BENEFITS COMPARISON

We now perform a cost-benefit comparison for the three pathways analyzed to recommend the optimum pathway as well as proposals for its implementation. Table-8 contains the costs-benefits comparison.

We define the Cost-Benefit factor CB_f as:

$CB_f = [C - (C \times R_f)]/C$,   or $CB_f = 1 - C \times R_f /$, or $CB_f = 1 - R_f$ -----------(21)

where; C is the total cost for the pathway in question and R_f is the rebound factor defined earlier. CB_f determines the beneficial aspect of cost spending on each pathway.

Pathway	Cost (C)	Rebound (Rf)	Cost-Benefit (CBf)
1 (Culling)	US$ 1.52 million	1.61	(-) 0.61
2 (Access Reduction)	US$ 1.69 million	0.39	(+) 0.61
3 (Culling and Access Reduction)	US$ 2.92 million	0.39	(+) 0.61

Table-8 Cost-Benefit Analysis

From cost-benefit comparison, it can be seen that on Pathway-1 US$ 1.52million are spent to aggravate the problem by 61%. On Pathway-2 US$ 1.69 million are spent to ameliorate the problem by 61% and on Pathway-3 same reduction in problem is achieved by spending 70% more than Pathway-2 i.e. US$ 2.92 million. We, therefore, recommend adoption of Pathway-2 i.e. access reduction with no culling in a five year programme.

The most pressing requirement is to institute Coastal and Inland Areas "Organic Waste Management Programmes" besides advising the municipalities in urban and suburban areas on the effective methods of access prevention through existing waste management programmes. Surveys and monitoring are essential for accurate assessment of impacts, we recommend surveys to be conducted at least twice a year to

compensate for seasonal changes in abundance. Communities must be involved in implementation of the programme besides awareness and education. We also recommend that the programme should be managed centrally but operaionalized at the local governments and community levels.

CONCLUSION

On the strength of scientific argument alone, it can be asserted that culling offers no significant benefits in environments similar to Zanzibar where the control over anthropogenically generated organic surplus is poor and C.*splendens* populations are well established. And even if there is a transitory illusion of benefits accruing from culling, it wears off as soon as as there is interruption, as the populations rebound with greater vigor. The efforts, resources and money spent on such programmes are efforts, resources and money wasted.

The problem, as we have seen has anthropogenic origins and therefore, the responsibility also lies with us to control it at the source, instead of externalizing the costs to target species. Capping the carrying capacity which gives rise to the problem in the first place is not only a more durable but also a more humane solution with significant additional developmental benefits for developing countries. Population models are thus invaluable tools in determining the extent of the problem and the remedial measures needed to control the origin of problems.

Besides the wastefulness of culling as a strategy in managing C.*splendens* abundance, the ethical questions which arise from the methods employed also need to be taken into consideration. Corvids are among the most intelligent and sentient bird species, and although the concerns for biodiversity are appreciable but as in all human affairs, a large part of the problem is how it is socially constructed (Marzluf & Angel, 2005, pp.36-79, i-xv) Declaring an "open season" and rousing the passions of entire populations against them, especially on small Island nations like Zanzibar where developmental and educational indices are low, is not even a particularly viable social strategy. We,

therefore, have to focus on optimum pathways in resolving the C.*splendens* problem keeping the long term implications of our actions in view.

APPENDICES

We submit with this study, the following appendices:

Appendix-1: Mwinyi, A & T. A Said,. (2009). *Crows Eradication Programme: Survey on population, distribution and socio-economic impacts of Crows, in Zanzibar, Tanzania.*: Department of Commercial Crops, Fruits and Forestry, Zanzibar, Tanzania.

Appendix-2: Mwinyi, A. (2013). *Completion Report: Crow Eradication Project.* Zanzibar, Zanzibar, Tanzania: Department of Commercial Crops, Fruits and Forestry, Zanzibar, Tanzania

Appendix-3: Excel Work Book – Population Estimates and Bootstrap Approximations

Appendix-4: Excel Work Book – Habitat Conditions, Euler-Lotka Solution and Model Estimates

REFERENCES

Allan, D. G., & G. B.Davies, (2005). Breeding biology of House Crows (*Corvus splendens*) in Durban, South Africa. *Ostrich*, *76*(1–2), 21–31. https://doi.org/10.2989/00306520509485469

Archer, A. L. (1996). Indian House Crow Control in Zanzibar. *Aliens, 3.*

Archer, A. L. (2001). Control of the Indian House Crow Corvus splendens in Eastern Africa. *Ostrich*, *Supplement 15*, 147–151.

Ash, J. S. (1984). *Report of UNEP Ornithologist/Ecologist on the Advice to the Peoples Democratic Reppublic of Yemen on "Combatting the Crow Menace"* (No. NEP/84/0819). UNEP Rep.

Awais, Muhammad, Shabir Ahmed, Sajid Mahmood, Tariq Mahmood & Hanif Alvi. (2015). Breeding Biology of the House Crow Corvus splendens at Hazara University, Garden Campus, Mansehra, Pakistan. *PODOCES, 10*(1), 1;7.

Banks, R. (1994). *Growth and Diffusion Phenomena: Mathematical Frameworks and Applications*. Berlin ; New York: Springer-Verlag.

Brook, B. W., N. S. Sodhi, M. C. K. Soh & H. C. Lim. (2003). Abundance and Projected Control of Invasive House Crows in Singapore. *The Journal of Wildlife Management*, *67*(4), 808. https://doi.org/10.2307/3802688

Chong, Kwek Yan, Siyang Teo, Kurukulasuriya Buddhima, Fei Chung Yi, Rajathurai Subaraj, Chuan Lim Haw, & T. W. Tan Hugh. (2012). Decadal Changes in Urban Bird Abundance in Singapore. *The Raffles Bulletin of Zoology*, S*upplement* no. *25.*

Chongomwa, Mwangome Muye. (2011). Mapping Locations of Nesting Sites of the Indian House Crow in Mombasa. *Journal of Geography and Regional Planning*, *4*(2), 87–97.

Cooper, J. E. (1996). Health studies on the Indian house crow *(Corvus splendens)*. *Avian Pathology*, *25*(2), 381–386. https://doi.org/10.1080/03079459608419148

Caughley, G. (2005). *Analysis of Vertebrate Populations*. Caldwell, N.J: Blackburn Press.

Ryall, C. & Guntram Meier. (2008). House Crow in the Middle East. *Wildlife Middle East News*, *3*(3).

Davenport, T. (2017, May 2). Interview with Country Director Tanzania, Wildlife Conservation Society.

Feare, C. J., & Mungroo, Y. (1990). The Status and Management of he House Crow Corvus splendens (Vieillot) in Mauritius. *Biological Conservation*, *51*(1), 63–70. https://doi.org/10.1016/0006-3207(90)90032-K

Fraser, D., G. Aguilar, W. Nagle, M.Galbraith, & C. Ryall, (2015). The House Crow (Corvus splendens): A Threat to New Zealand? *ISPRS International Journal of Geo-Information*, *4*(2), 725–740. https://doi.org/10.3390/ijgi4020725

ISSG. (n.d.). *Global Invasive Species Database (GISD) 2015. Species profile Corvus splendens*. Retrieved from http://www.iucngisd.org/gisd/species.php?sc=1199

Jennings, M. C. (1992). The House Crow Corvus splendens in Aden (Yemen) and an Attempt at its Control. *Sandgrouse*, *14*, 27–33.

Lim, H. C., N. S.,Sodhi, B. W. Brook, & M. C. K. Soh, (2003). Undesirable Aliens: Factors Determining the Distribution of Three Invasive Bird Species in Singapore. *Journal of Tropical Ecology*, *19*(6), 685–695. https://doi.org/10.1017/S0266467403006084

MacCallum, H. (2000). *Population Parameters: Estimation of Ecological Models*. Oxford: Blackwell Science.

Madge, S., & H.Burn, (1994). *Crows and Jays: a Guide to the Crows, Jays and Magpies of the World*. London: Helm.

Marzluff, J. M., & T. Angell, (2005). *In the Company of Crows and Ravens*. New Haven: Yale University Press.

Marzluff, J. M., & E.Neatherlin, (2006). Corvid Response to Human Settlements and Campgrounds: Causes, Consequences, and Challenges for Conservation.

Biological Conservation, *130*(2), 301–314. https://doi.org/10.1016/j.biocon.2005.12.026

Meier, G. G., & C. Ryall. (2007). The House Crow (Corvus splendens): An Invasion without Limits. *Aliens*, *24/25*.

Mwinyi, A. (2013). *Completion Report: Crow Eradication Project.*Zanzibar *Tanzania.*Department of Commercial Crops, Fruits and Forestry, Zanzibar, Tanzania..

Mwinyi, A., & T. A. Said,. (2009). *Crows Eradication Programme: Survey on population, distribution and socio-economic impacts of Crows, in Zanzibar, Tanzania.*Department of Commercial Crops, Fruits and Forestry, Zanzibar, Tanzania.

Mustafa, I., N. Arif, S. M. Hussain, I. U. Malik, A. Javid, Muhammad Irfan Ullah, &Haroon Ahmed. (2015). Population Dynamics of House Sparrow (Passer domesticus) and House Crow (Corvus splendens) in Punjab (District Sargodha), Pakistan. *Pakistan Journal of Zoology*, *47*(4), 1147–1155.

National Bureau of Statistics, Tanzania. (2014). *Basic Demographic and Socio-Economic Profile, Tanzania Zanzibar*. Zanzibar, Tanzania: National Bureau of Statistics Ministry of Finance, Tanzania and Office of Chief Government Statistician, Ministry of State, President Office, State House and Good Governance Zanzibar.

National Bureau of Statistics, Tanzania (2016a.). *Basic Demographic and Socio-Economic Profile, Mjini Maghribi Region*. Zanzibar, Tanzania: National Bureau of Statistics Ministry of Finance, Tanzaniar and Office of Chief Government Statistician Ministry of State, President Office, State House and Good Governance Zanzibar.

National Bureau of Statistics, Tanzania. (2016b.). *Basic Demographic and Socio-Economic Profile, Kaskazini Unguja Region*. Zanzibar, Tanzania: National Bureau of Statistics Ministry of Finance, Tanzaniar and Office of Chief Government Statistician Ministry of State, President Office, State House and Good Governance Zanzibar.

National Bureau of Statistics, Tanzania. (2016c). *Basic Demographic and Socio-Economic Profile, Kusini Unguja Region*. Zanzibar, Tanzania: National Bureau of Statistics Ministry of Finance, Tanzaniar and Office of Chief Government Statistician Ministry of State, President Office, State House and Good Governance Zanzibar.

National Bureau of Statistics, Tanzania. (2017, February 4). Tanzania: Zanzibar (Districts and Wards) - Population Statistics in Maps and Charts. Retrieved May 11, 2017, from https://www.citypopulation.de/php/tanzania-zanzibar-admin.php

Nyari, A., C. Ryal, & Peterson. A. Townsend (2006). Global Invasive Potential of the House Crow Corvus splendens based on Ecological Niche Modelling. *Journal of Avian Biology*, *37*(4), 306–311. https://doi.org/10.1111/j.2006.0908-8857.03686.x

Paul, L. A. E., & J. Seys, (1995). *Census of Roosting Indian House Crows (Corvus splendens) on Mombasa Island*. Kenya Wildlife Service.

Prendergast, M. E., H. Rouby, P. Marchant, R. Punnwong, , A. Crowther, N. Kourampas & N. L. Boivin. (2016). Continental Island Formation and the Archaeology of Defaunation on Zanzibar, Eastern Africa. *PLOS ONE*, *11*(2), e0149565. https://doi.org/10.1371/journal.pone.0149565

Reaume, T. (2013). *The American Crow, Naturally, Open WorldCat*.

Ryall, C. (1994). Recent Extensions of Range in the House Crow Corvus Splendens. *Bull. B.O.C.*, *114*, 90–100.

Ryall, C. (1995). Additional Records of Range Extension in the House Crow Corvus Splendens. *Bull. B.O.C.*, *115*, 185–187.

Ryall, C. (2002). Further Records of Range Extension in the House Crow Corvus Splendens. *Bull. B.O.C.*, *122*, 231–240.

Sakai, H. F., & J. R. Carpenter. (1990). The Variety and Nutritional Value of Foods Consumed by Hawaiian Crow Nestlings, an Endangered Species. *The Condor*, *92*(1), 220–228. https://doi.org/10.2307/1368403

Shimba, M. J., & F. E. Jonah (2017). Nest success of the Indian House Crow "Corvus splendens": an Urban Invasive Bird Species in Dar es Salaam, Tanzania. *Ostrich*, *88*(1), 27–31. https://doi.org/10.2989/00306525.2016.1223766

Sinclair, A. R. E., J. M. Fryxell & G. Caughley.. (2006). *Wildlife Ecology, Conservation, and Management* (2nd ed). Malden, MA ; Oxford: Blackwell Pub.

State Government Queensland. (2016). *Invasive Animal Risk Assessment: Indian House Crow (Corvus splendens)*. Department of Agriculture and Fisheries.

The Star, Kenya. (2017, February 6). Plans to Wipe Out Invasive Indian Crow. Retrieved May 5, 2017, from http://www.the-star.co.ke/news/2017/02/06/plans-to-wipe-out-invasive-indian-crow_c1500744

Ricker, W. E. (1954). Stoch and Recruitrnentl. *Journal of the Fisheries Research Board of Canada*, *11*, 559–623.

Wilson, R. F., D.,Sarim, & S.Rahman, (2015). Factors Influencing the Distribution of the Invasive House Crow (Corvus. splendens) in Rural and Urban Landscapes. *Urban Ecosystems*, *18*(4), 1389–1400. https://doi.org/10.1007/s11252-015-0448-6

Wu, H., A., Chakraborty, B..L. Li & C. M. Kenerley, (2009). Formulating Variable Carrying Capacity by Exploring a Resource Dynamics-based Feedback Mechanism underlying the Population Growth Models. *Ecological Complexity*, *6*(4), 403–412. https://doi.org/10.1016/j.ecocom.2008.11.002