The Social Costs of Keystone Species Collapse: Evidence From The Decline of Vultures in India

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High biodiversity losses raising concerns

Cumulative extinctions ▲

Source: Ceballos et al. (2015)

▷ Abundance 25% ↓
  – (Dirzo et al. 2014)

▷ Functional diversity ↓
  – Broodie et al. 2021
How do we prioritize conservation resources?

Tyger Tyger, burning bright,
In the forests of the night;
What immortal hand or eye,
Could frame thy fearful symmetry?
-William Blake, The Tyger, 1794
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“Disgusting”

-Charles Darwin, 
Observing a vulture 
off the deck of the 
Beagle in 1835
Keystone species are not always charismatic

“...we define a keystone species as one whose impact on its community or ecosystem is large, and disproportionately large relative to its abundance.”
- Power et al. 1996

Losing keystone species can:
- Generate damages the extend beyond the ecosystem
- Costly to substitute
- Costly to reverse the loss

Q: How do keystone species affect human well-being?
Vultures as environmental sanitizers

**Setting:** Decline of vultures in the Indian-Subcontinent:
- Vultures remove carrion and crowd out other scavengers
- Special importance due to social norms in India
- Decline was unexpected, due to chemical pollution

**Data:** Vulture habitat ranges, and health outcomes:
- Habitat ranges from BirdLife International
- Map to mean vulture suitability
- Annual district all-cause death rates

**Strategy:** Vulture die-offs as a natural experiment:
- High to low vulture-suitable-districts
- High to low livestock agriculture at baseline
- Before and after vulture population collapse

Main finding: on average, death rates increased by \(\approx 4\%\).
Importance of vultures as scavengers

Vultures have evolved as extremely effective scavengers:

- Consume a cattle carcass in under 40 minutes
- Stomach acidity 10-100 times that of humans
- Terminal stop for bacteria and pathogens

Farmers in India rely on vultures to remove carrion:

- Historically, lack of disposal infrastructure
- Animal landfills on the outskirts of population centers
- Critically important in India due to social norms
  - Hindus do not consume cows
  - Muslims only consume animals killed according to halal
Animal landfills & packs of feral dogs

Source: CBS News (2013)

Source: Open Magazine (2011)

GURUGRAM NEWS
Do not dump animal carcasses in open, forest dept tells MCG

The forest department has sent a proposal to the Municipal Corporation of Gurgaon (MCG) to establish an incinerator at Bandhwari or any other suitable site within three months.

Hindustan Times | By Ipsita Pati, Gurgaon
UPDATED ON MAR 02, 2016 01:48 AM IST
Ecologists highlight two channels (Ogada et al. 2012, Moleón et al. 2014):

Vultures↓ ⇒ Carrion↑ ⇒ Dogs & rats↑ ⇒ Animals bites & infectious diseases↑

Vultures↓ ⇒ Carrion↑ ⇒ Bacterial load↑ ⇒ Pathogens in drinking water↑
Vultures were ubiquitous across India

Source: Saving Asia’s Vultures From Extinction (2011)
Vultures declined by 95-99% in the 1990s

India’s Vanishing Vultures

By Meera Subramanian

Before the recent species collapse, vultures were a vital part of India's sanitation, cleaning carcasses and, as here, scavenging human remains left at the ghats on the banks of rivers.

Can the world's fastest growing nation restore its prime scavenger before there are untold human consequences?

Source: Subramanian (2011)
Vultures declined by 95-99% in the 1990s

Limited survey data on vultures.

Pre-collapse populations:
- Tens of millions
- Estimates of 30-50 millions

Collapse occurred quickly.

Source: Pain et al. (2008)

In 2000, the three affected species were listed as

CRITICALLY ENDANGERED
“Without tigers and elephants, the ecology can still work, their role has been taken over, mostly, by humans. But nobody can take over the role of the vulture. They are very efficient scavengers. Nothing will ever be able to fill that niche”
- Dr. Vibhu Prakash, former Bombay Natural History Society PI, founder of the Pinjore Vulture Conservation Breeding Center.

“They’re gone. They’re gone. They’re gone... There were so many vultures then that you can’t even think they could decline ... Now there are dogs. They eat anything, live or dead. There are dogs on the ground but the skies are empty.”
- Dr. Asad Rahmani, Director of Bombay Natural History Society.

Source: Subramanian (2011)
Decline caused by painkiller residue in carrion

The cause was unknown until 2004.

Oaks et al. (2004) established diclofenac as the cause:
- Diclofenac previously used as a painkiller for humans
- Use in livestock started after its patent expired in 1993
- Price ↓ (generic versions), with wide adoption by 1994

Diclofenac is lethal to vulture species of the gyps genus:
- Vultures would digest diclofenac residue in carrion
- Would develop kidney failure and die within weeks
- Feeding on a single contaminated carcass is sufficient

In India, veterinary use (ineffectively) banned since 2006.
Price ↓ and sales ↑ during the 1990s

Injectable Diclofenac Price & Quantity Sold (1993 = 1)

- Price
- Quantity Sold

Reports of decline in vultures

Year

Price

Quantity Sold

Diclofenac generic approved
Affected vultures observed less post-1996

Observation Share of Vultures in GBIF Records in India (1993 = 1)

- Diclofenac generic approved
- Reports of decline in vultures
Data on the presence of vultures in India

Distribution range maps ⇒ District-vulture-suitability:

- Range maps from BirdLife International
- Calculate overlap of range for each district-species
- Take the mean of the three overlap scores
- Assign high or low suitability

Similar approach to Alsan (2015) TseTse suitability score:

- However, less reliant on functional form
- Here, we focus on separating high from low suitability

To this, we add data on livestock agriculture:

- Using data from pre-collapse years
- Assign districts as high or low livestock agriculture
Distribution of vultures across India

High suitability for vultures, and high baseline livestock ag.
Mortality data at the district level

Civil Registration System (CRS) data on mortality:
- Established in 1969
- Designed to become the source of vital statistics data
- Deaths are reported for all causes, for all ages
- Reported for urban and rural areas
- Reporting shifted from rates to counts in 1988

Population-Weighted All-Cause Death Rates (1993=1)

- Diclofenac generic approved
- Reports of decline in vultures

Year:
- 1985
- 1986
- 1987
- 1988
- 1989
- 1990
- 1991
- 1992
- 1993
- 1994
- 1995
- 1996
- 1997
- 1998
- 1999
- 2000
- 2001
- 2002
- 2003
- 2004
- 2005

Vulture Suitability:
- High
- Low

Reports of decline in vultures
Diclofenac use as a natural experiment

Ideally, randomly assign or manipulate vulture populations:
▶ In practice, distribution = f(environmental conditions)
▶ However, onset of diclofenac use ⇒ natural experiment

Diclofenac induced die-offs ⇒ Shock to sanitation function:
▶ Approximates for random variation in vulture levels

Difference-in-differences research design:
▶ Compare high and low vulture-suitability districts,
▶ before and after the collapse in vulture levels

Triple-differences research design:
▶ Use the baseline livestock classification
Estimating the effects of vulture die-offs

\[ y_{daszt} = \sum_{\tau \in \{T, ..., \bar{T}\}} \beta_{\tau} (\text{High Vulture Suitability})_{d} \times 1\{t = \tau\} + \]
\[ \lambda_{da} + \delta_{zt} + X_{dast} \theta + \varepsilon_{daszt} \]

- All-cause death rate: \( y_{daszt} \)
- Treatment: High Vulture Suitability (HVS)
- \( \beta_{\tau} \): Estimate dynamic response relative to 1993
- Controlling for:
  - District-by-area fixed effects, \( \lambda_{da} \)
  - Zonal council-by-year fixed effects, \( \delta_{zt} \)
  - Weather controls, \( X_{dast} \)

- Observations are population-weighted
- Standard errors clustered at the district level

\( d \), urban or rural area \( a \), in state \( s \), zonal council \( z \), year \( t \)
Additional 0.91 deaths per-1,000 people

Diclofenac generic approved

Reports of decline in vultures

All-Cause Death Rate (per-1,000 People)

Year


Reports of decline in vultures
Mortality effect also evident with state trends

![State-Linear Time Trends](chart1)

![State-by-Year FEs](chart2)

On average, death rates are \(\approx 4\%\) higher during 2000-2005
Sanitation is crucial for public health

- Geruso and Spears (2018) estimate a 28%↓ in IMR
  - From lowering open defecation prevalence from 66% to 33%
- Galiani et al. (2005) estimate a 8%↓ in child mortality
  - From water quality improvements following privatization
- Cutler and Miller (2005) estimate a 46%↓ in IMR
  - From water quality improvement in US cities around 1900
  - From +1σ in sanitation, in Paris during 1880 to 1914
- Bhalotra et al. (2021) find 45%↓ in child mortality
  - After water chlorination ↑ from 58% to 90% in Mexico
Higher livestock agriculture ⇒ Larger effect

<table>
<thead>
<tr>
<th></th>
<th>Combined Sample</th>
<th>Urban Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>HVS × Livestock × Post-1994</td>
<td>0.60</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td>(0.31)</td>
<td>(0.45)</td>
</tr>
<tr>
<td>HVS × Diclofenac</td>
<td>0.49</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>(0.26)</td>
<td>(0.34)</td>
</tr>
<tr>
<td>Livestock × Post-1994</td>
<td>0.05</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td>(0.24)</td>
<td>(0.36)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.74</td>
<td>0.66</td>
</tr>
<tr>
<td>N</td>
<td>2,754</td>
<td>2,790</td>
</tr>
<tr>
<td>Clusters</td>
<td>153</td>
<td>155</td>
</tr>
</tbody>
</table>

DDD Results for All-Cause Death Rate ($\bar{Y} = 10.7$)
High livestock and high suitability $\Rightarrow$ Mortality↑

Decomposing the DDD Results by Vulture Suitability

<table>
<thead>
<tr>
<th>Sample: Livestock×Post-1994</th>
<th>High Suitability</th>
<th>Low Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined</td>
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<tr>
<td>Livestock×Post-1994</td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td></td>
<td>0.62</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>(0.23)</td>
<td>(0.31)</td>
</tr>
</tbody>
</table>

| $R^2$ | 0.828 | 0.765 | 0.68 | 0.60 |
| N     | 1,350 | 1,386 | 1,404 | 1,404 |
| Clusters | 75     | 77     | 78     | 78     |
**District balance pre-vulture collapse**

<table>
<thead>
<tr>
<th>Vulture Suitability:</th>
<th>Group Means</th>
<th>Difference</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Low</strong></td>
<td><strong>High</strong></td>
<td></td>
</tr>
<tr>
<td>Death Rate (1988-1993)(^1)</td>
<td>5.3 (1.8)</td>
<td>4.2 (1.8)</td>
<td>-1.2 (0.32)</td>
</tr>
<tr>
<td>Number of Livestock (1987, 1992)</td>
<td>1,632 (874)</td>
<td>1,615 (731)</td>
<td>-17 (158)</td>
</tr>
<tr>
<td>Degree Days Above 30°C (1988-1993)</td>
<td>54 (43)</td>
<td>66 (35)</td>
<td>12 (6.8)</td>
</tr>
<tr>
<td>Precipitation in mm·km(^{-2}) (1988-1993)</td>
<td>.25 (.42)</td>
<td>.12 (.18)</td>
<td>-.12 (.044)</td>
</tr>
<tr>
<td>Hospitals &amp; Health Centers (1991)(^2)</td>
<td>1.7 (1.7)</td>
<td>2.4 (2.5)</td>
<td>.66 (.35)</td>
</tr>
<tr>
<td>Doctors &amp; Health Workers (1991)(^2)</td>
<td>8.6 (7.6)</td>
<td>9.8 (8.6)</td>
<td>1.2 (1.6)</td>
</tr>
</tbody>
</table>

\(^1\) Per-1,000 people  
\(^2\) Per-100,000 People
DD Results for Observable Characteristics of Districts

- Hospitals per-10,000 People: 0.139
- Health Centers per-10,000 People: 0.101
- Doctors per-1,000 People: 0.083
- Healthcare Workers per-1,000 People: 0.115
- Share of Villages with Medical Facilities: 0.389
- Share Literate: 0.490
- Employment Rate: 0.383
- Agriculture Emp. Share: 0.236
- Services Emp. Share: 0.695
- Manufacturing Emp. Share: 0.280
- Share of Villages With Electricity: 0.753
- Share of Villages With Communications Facilities: 0.434
- Share of Villages with Education Facilities: 0.715
- Share Irrigated Land: 0.288
- Share of Villages with Roads: 0.909

Dep. Var. Mean

-0.1 -0.05 0 0.05 0.1 0.15
Suggestive evidence for mechanisms

We find a break from trend for sales of rabies vaccines

2012 cross-section, feral dogs corr. with vulture suitability

Degradation in water quality, mostly in highly populated areas
Additional tests

Long-differences allows us to use more districts

No pre-trends when sample covers 1981 to 2005

Similar results when using an alternative suitability score

Not driven by a specific district or state (leave-one-out)

Permutation inference to address spatial clustering of SEs
Concluding remarks

Following vulture die-offs, all-cause mortality increased:

- In 2000-2005, by 0.48 deaths per-1,000 people (≈4%) – Relative to a nationally representative mean of 10.7
- On average, 104,386 additional deaths per year – $69.4 billion per year using Nair et al. (2021) VSL

Should we restore vulture populations to previous levels?

- Health estimates suggest the benefits would be large – Even w/o morbidity and cultural role of vultures in burial rites
- However, non-trivial costs and feasibility constraints – Vultures recover slowly: 5 years to maturity, 1 offspring a year

Substituting for vultures is both capital and labor intensive:

- Burying dead livestock is privately costly
- Incinerators might be required now, but expensive
- Ongoing rabies vaccination programs (for dogs)

Substituting keystone species can be prohibitively expensive
Thank You!

YOU KNOW, WE PLAY A CRUCIAL ROLE IN THE ECOSYSTEM.

PEOPLE SEE US AS MONSTERS, EATING THEIR DEAD. BUT IT'S IMPORTANT THAT WE DO.

YEAH

IMPORTANT AND TASTY!

ESPECIALLY THE EYEBALLS. I LOVE EYEBALLS!

MMMMMM EYEBALLS...

HANK -