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Assessment of economic burden of lumpy skin disease in India using stochastic modeling

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This study assessed the farm-level economic loss due to LSD in India and at disaggregate (state) level by collecting data from 2351 cattle farms covering seven states. Data were analyed using descriptive statistics and stochastic modeling with Monte Carlo simulations. Gujarat state reported the highest milk loss, with a median reduction of 74, 90, 60, 45, 15, 15, and 8 L per animal in Rajasthan, Gujarat, Tamil Nadu, Karnataka, Madhya Pradesh, Assam, and Odisha, respectively. Crossbred cattle experienced more milk loss per animal, ranging from USD 0.0 to 237.8. The median mortality loss per animal varied between USD 12.2 and 1,084. The substantial national loss was due to decreased milk production, followed by the loss of draught power, treatment cost, and vector management cost. Stochastic modelling estimated economic loss due to LSD in cattle in India was USD 2440.29 million (90% CI 2162.55–2716.15) / (INR 202,544.07 million (90% 179,491.65—2,225,440.45) during 2022 & 2023 with a highest loss of USD 314.18 million (90% CI 279.10–349.34)) in Rajasthan state.

Keywords LSD, Economic burden, Stochastic modelling, India

Lumpy Skin Disease (LSD), caused by the lumpy skin disease virus of the genus *Capripoxvirus* in the family *Poxviridae*, poses a severe threat to the global cattle industry. The virus spreads mainly through arthropods[1]. LSD was first described in southern Africa in the 1920s, since then spread across continents, reaching the Middle East, Israel, Turkey, and many regions of Europe[2]and since 2019, it has been reported in many countries in Asia including India. LSD is characterized by fever, nodular lesions on the skin, mucous membranes, and lymphadenopathy[3], has been linked to significant economic consequences such as reduced milk production, temporary or permanent sterility, weight loss, inability to provide draught power, abortion, and hide damage[4–6].

In India, LSD was reported in 2019 from Odisha state and quickly spread to all other states, posing a significant threat to the livestock sector[7,8]. The cattle movement within and across states in India is continuous, mainly for trade and grazing. During 2022–23, around 0.18 million cattle died to LSD in India[9]. Assessing the economic burden of the disease is a pre- requisite exercise to understand the burden per se and to evaluate the cost-effectiveness of various control options[10]. Further, it helps the policy makers to reorient the disease control and planning options that are in placce to achieve sustainable development goals, contributing to zero hunger, better nutrition, good health and economic growth as envisaged by the United Nations(https://animalhealthmetrics.org/).

In India, various research studies on LSD have focused on pathogen biology, and vaccines[8,11–14]. All India economic burden estimates are available for other livestock diseases like Foot-and-Mouth Disease (FMD) and Haemorrhagic Septicaemia[15–19]and there is a scarcity of evidence of LSD economic burden at national level and

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disaggretated level, except a pilot study from Punjab state covering 100 LSD infected farms and extrapolated to pan India[20]. Empirical studies on disease burden with appropriate sample procedures covering various regions/states are vital for planning the control programmes that benefits various stakeholders in the livestock value chain. Further, larger country like India with 28 states and 8 union territories and abode to 536 million livestock population[21], the economic burden estimates are needed at disaggregated level. Furthermore, in the federal country like India, where agriculture including livestock is a state subject, the disaggregated economic burden assessment provides evidence for the policy makers for implementing appropriate state specific policies.

Deterministic disease burden assessment models provide point estimates and estimates depend on the specific input parameters whereas stochastic/probabilistic models predict outcomes under variable conditions. Deterministic estimates are based on the disease incidence, disease cost and the susceptible population, while probabilistic models provide range of outcomes considering uncertainty in the input parameters.Hence, to address the gap, the present study comprehensively assessed the economic burden due to mortality, milk reduction, opportunity cost of labour, management cost associated with the LSD at national and disaggregated (state) level using stochastic/probabilistic models.

Materials and methods

Study states

The study was undertaken in seven states out of 28 states covering six regions in India (North, West, South, Central, East, North East). The details of the surveyed states (Rajasthan, Gujarat, Tamil Nadu, Karnataka, Madhya Pradesh, Odisha and Assam) is presented in Fig. 1. As per the livestock census, 2019, the total cattle population in the surveyed states was 80.85 million [indigenous cattle (60.14 million) and crossbred population (20.71 million)] out of 193 million total cattle population in India [indigenous cattle (143 million) and crossbred cattle (50 million)].

Sample size

The sample size for the primary survey in the study states was based on Cochran (1963), as below

$$n = D * \frac{Z^2 * (P) * (1 - P)}{d^2}$$

where,

n = Estimated sample size per state.

Z = Area under normal curve corresponding to the desired confidence level (e.g. 1.96 for 95% confidence level).

P = Proportion of rural households rearing cattle to total households.

d = Margin of error (0.07).

D = Design effect (1.6).

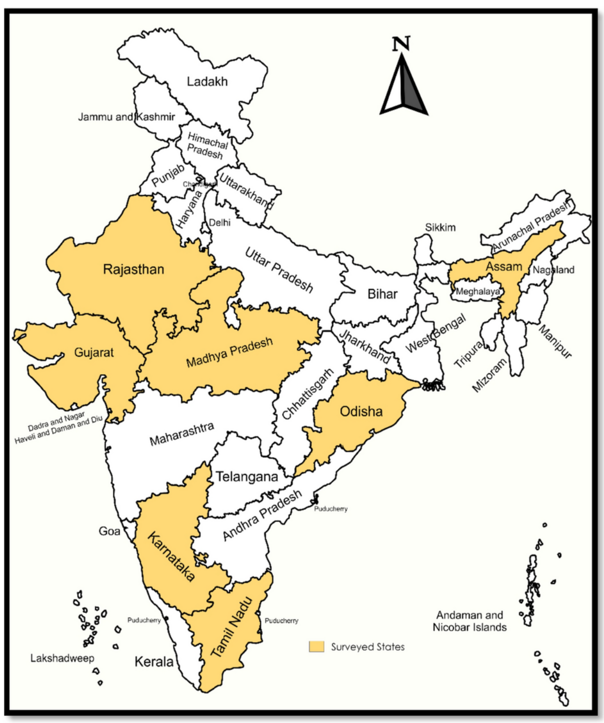

Fig. 1. Represents the surveyed states in India.

The Z value was 1.96 (for 95% CI) and p values was 0.32, 0.43, 0.5, 0.53, 0.52, 0.68 and 0.50 for Rajasthan, Gujarat, Tamil Nadu, Karnataka, Madhya Pradesh, Odisha and Assam states, respectively. At the margin of error of 0.07% and the assumed design effect of 1.6, the estimated sample size was 273, 307, 314, 312 ,313, 273 and 313 cattle farms in Rajasthan, Gujarat, Tamil Nadu, Karnataka, Madhya Pradesh, Odisha and Assam states, respectively.

Sampling procedure

A multistage random sampling procedure was adopted for the primary survey and the details of sampling criteria in each stage is presented in Supplymentary Table S1.

LSD loss estimation

To estimate the various losses, the data on the pre- and post-LSD milk yield, number of days reduction in milk, farm gate price of milk, draught power cost, number of days draught power unavailability, value of the healthy animals across breed-,sex-and age, treatment cost that includes modern and ayurvedic treatrment, cost incurred for vector management and opportunity cost of labour was collected from the sample farmers using the pre-tested questionnaires. The milk yield and mortality values were collected at animal level whereas treatment cost, opportunity cost of labour was collected at farm-level and converted to per animal. Majority of the farmers do not maintain farm-records, hence milk yield data was triangulated with the daily milk sale record maintained by some farmers and in some cases, from the digital milk procurement records of the farmers maintained by the milk cooperative societies, where farmer supplies milk. In case of value of different breeds across age- and sex- groups, besides opinion of the farmers, triangulated with the village level key informants and jurisdictional veterinarian. The treatment cost incurred in managing the disease was triangulated with the jurisdictional veterinarian and para-veterinarian.

Various farm-level losses per animal was calculated as below.

Milk reduction loss

A case-crossover design was used to estimate the effect of LSD on the transient milk yield reduction loss per animal as given below

$$\mathrm{MT} = \frac{1}{n}\sum_{i=1}^{n}(M_{ai} * DP * P)$$

where,

MT- Milk loss per animal (USD).

Ma- Difference in pre- and post LSD milk yield (ltr/day).

DP- Duration of infection in the LSD affected animal (number of days).

P- Farm gate milk price (USD/ltr).

n- Number of LSD affected in-milk cattle (No.) i = 1,2, 3,….n

Milk loss per animal in indigenous and crossbred cattle was calculated independently.

Mortality loss

Mortality loss for crossbred cattle were calculated as below

$$ML = \frac{1}{n}\sum_{j=1}^{6} Ij * Vj$$

where,

ML = Mortality loss per crossbred animal (USD).

j = Category of crossbred animals, viz. male below 1.5 years (j = 1), male draught animals (j = 2), female up to 2 years (j = 3), female in-milk (j = 4), female dry (j = 5) and female not calved once (j = 6).

Ij = Number of crosbred animals died due to LSD in different categories (j).

Vj = Farm gate value of the died crossbred animals (healthy condition value) (USD).

N = Number of crossbred animals died due to LSD.

Similarly, the loss per animal for the indigenous cattle was calculated.

Draught power unavailability

$$D = \frac{1}{n}\sum_{i=1}^{n}(DIi * adj) * Bh$$

where,

D = Draught power loss/animal(USD).

DIi = Duration of infection in the LSD affected bullock (number of days).

Bh = Bullock Hiring charges / day (USD).

N = Number of LSD affected bullocks (1 = 1,2,…n).

adj = Draught power adjustment factor.

Draught animals are not engaged round the year and hence effective number of days lost due to LSD was calculated using an adjustment factor[22]. Further, the calculation assumed the LSD affected animals are unavailabe for the complete disease duration.

Allopathic treatment cost (modern medicine) The cost associated the modern medicine treatment for LSD control is calculated as below

$$\mathrm{T} = \frac{1}{n}\sum_{i=1}^{N}(V_i + D_i + O_i)$$

where,
T = Treatment cost per LSD affected animal (USD).
V = Veterinarian/Para-veterinarian fee paid during LSD outbreak in the farm (USD).
D = Cost incurred on drugs for LSD treatment in the farm (USD).
O = Other costs associated in treatment (transaction cost).
N = Number of farms (i = 1,2,3….)
n = Total number of LSD infected animals across all N farms.
The cost was calculated per-farm and converted to per animal based on the number of animals treated in the farm.

Ayurvedic treatment cost (traditional method) The cost associated with the traditional method was calculated as below

$$\mathrm{T} = \frac{1}{n}\sum_{i=1}^{N}(D_i * d_i)$$

where,
T = Ayurvedic treatment cost per LSD affected animal (USD).
D = Cost of ayurvedic products applied per day in the LSD affected farm (USD).
d = Number of days of ayurvedic treatment in the farm.
N = Number of farms (i = 1,2,3….)
n = Total number of LSD infected animals across all N farms.
[@]Ayurvedic treatment refers to the traditional remedies adopted by the farmers mainly to treat the nodules on the skin (eg. topical application of turmeric paste (*Curcum longa*) or application of betel leaves (*piper betle*) or application of neem leaves paste (*Azadirachta indica*) or combination of one or the other natural products along with the clarified butter.

Vector management cost
The vector management cost was calculated per farm and converted to per animal cost as below

$$\mathrm{VT} = \frac{1}{n}\sum_{i=1}^{N}(C_i + A_i + E_i)$$

where,
VT = Vector management cost per animal (USD).
C = Disinfectant cost for vector management in the farm (USD).
A = Application cost (USD).
E = Equipment hiring charges incurred (USD).
N = Number of farms.
n = Total number of animals in the farm.
In the study region to manage the vectors, chemicals like Sodium hypochlorite (2%) were applied in the farm premises and Cypermethrin (2 ml/litre) and herbal tick repellents (herbal spray) were applied to control the ecto-parasites.

Opportunity cost of labour
Farmers spend considerable time to manage the LSD affected animals and forbade their regular income during this period. The opportunity cost of extra labour hours spent for managing the diseased animals are calculated as below

$$L = \frac{1}{n}\sum_{i=1}^{N}((IL_i * D * MW) + (ILF_i * D * FW))$$

where,
L = Opportunity cost of labour (USD/animal).
IL = Incremental male labour hours spent compared to pre-LSD (hours/day).

ILF = Incremental female labour hours spent compared to pre-LSD (hours/day).
D = Duration of infection (days).
MW = Wage Rate / day for male labour (USD).
FW = Wage Rate / day for female labour (USD).
i = 1…N, represents number of farms.
n = number of LSD affected animals.
The conversion rate used was 1 USD = 83 INR (during 2024).

Stochastic model projections and sensitivity analysis

Before the simulation exercise, the cattle population was grouped into two broad categorie viz., indigenous and crossbred cattle. Indigenous cattle were further classified into male and female categories. The male population was further classified as draught (above 1.5 years) and non-draught animals (below 1.5 years). Indigenous females were grouped as in-milk (above 2 years and lactating animals), dry (non-lactating animals), not calved once and female calves (below 1.5–2 years). Similarly, the crossbred cattle were also grouped into different categories based on sex-and age.

For simulating the LSD infected population in indigenous and crossbred cattle, the in-milk, draught and other animal categories (female and male animals under < 2 years, dry, and not calved once) were considered except for crossbred males (as crossbred males were not oserved among the surveyed samples). For simulating the died animal population in various age- and sex- groups, all the above animal categories were considered.

The population of different categories were parameterized using normal distribution with a standard deviation of 10% of its population size. The population parameters were simulated with respective to incidence and mortality rates of sample data, along with Monte Carlo simulation model. The optimistic, pessimistic and most likely scenarios of mortality and incidence were simulated at 90% confidence Interval (CI). The parameterized details are presented in Supplementary Table S3. The analysis was carried out in Python Jupyter Notebook software (https://jupyter.org/). The model was run for 150,000 iterations to ensure convergence[23,24].

The median loss of various components viz., milk loss, draught power loss, opportunity cost, mortality loss, modern and traditional treatment cost and vector management cost were calculated from the survey data and used for economic loss simulation for indigenous and crossbred cattle (Supplementary Table S3). The overall loss of each component for indigenous and crossbred cattle, as well as the pooled economic loss in each of the surveyed states, were simulated based on Monte Carlo simulation with Latin Hypercube sampling technique with PERT in Python Jupyter Notebook software (https://jupyter.org/).

For projecting the loss in the non-surveyed states and Union Territories (UTs), the target population of the particular non-surveyed state/UT and the incidence, mortality and economic parameters of the reference state was considered. The reference states were identified based on geographical contiguity of the borders, similar rearing patterns and availability of the disease and economic data. The projection was not undertaken for five UTs (Andaman and Nicobar Islands, Chandigarh, Dadra and Nagar Haveli and Daman and Diu, Lakshadweep and Ladakh) due to negligeble cattle popultion. The details of the reference states for the non-surveyed states is presented in supplementry Table S2. The model was run for 10,000 iterations to ensure convergence.

A sensitivity analysis was carried out to quantify the influence of different losses and expenditures to the total loss in each of the surveyed states. The rank order correlation depicting the contributing factors for the total loss is presented using tornado graphs as recommended by World Organisation for Animal Health (WOAH)[23,24].

Results

The primary data was collected from 343, 264, 417, 350, 312, 323 and 342 cattle farms in Rajasthan, Gujarat, Tamil Nadu, Karnataka, Madhya Pradesh, Odisha and Assam states, respectively. The less sample collection in Gujarat than the planned size (307) was due to non-participation of some of the farmers in the survey.

Estimated milk reduction (litres)

The estimated the median transient milk reduction (from the infection to recovery period) in indigenous cattle (in litres per animal) during the LSD incidence was 74,90,60,45,15, 8 and 15 in Rajasthan, Gujarat, Tamil Nadu, Karnataka, Madhya Pradesh, Odisha and Assam state, respectively. The maximum loss was observed in Rajasthan followed by other states. In crossbred cattle, the loss ranged between 0 and 371 L per animal with wide variation between the states. The details of milk loss per animal in indigenous and crossbred cattle are provided in Table 1.

Estimated median loss per animal

The various components of farm-level loss due to LSD in the surveyed states are presented in Table 2. In Indigenous cattle, the milk loss per animal ranged between USD 0.0 and 182.9 with a highest median milk loss of USD 54.8 in Gujarat followed by Rajasthan (USD 51.5), Tamil Nadu (USD 23.1), Karnataka (USD 16.2), Assam (USD 8.13), Madhya Pradesh (USD 7.22) and Odisha (USD 4.6). In crossbred cattle, the milk loss per animal ranged from USD 0.0 to 237.8 with highest median milk loss in Rajasthan (USD 237.8). A significant difference in median milk loss between the Indigenous and crossbred cattle population was observed in all the study states (Table 2). The median mortality loss per animal varied between USD 12.2 and 1084 and USD 24.4 and 1084, in indigenous and crossbred cattle, respectively. A highest median mortality loss per animal of USD 481.9 and 542.1 was observed in indigenous and crossbred cattle, respectively in Madhya Pradesh state. No significant difference in the median mortality loss per animal was observed in the study states except Rajasthan (median test statistic, 6.3 ($p < 0.05$)). The median draught power loss per animal varied between USD 13.5 and 534.7 with highest loss per draught animal (USD 95.1) in Karnataka. The median treatment cost (with modern medicine) varied between USD 8.4 and 60 per animal without significant difference between the indigenous and crossbred cattle across the study states except in Rajasthan (median test statistic, 4.9 ($p < 0.05$)). The median treatment cost

State	Rajasthan		Gujarat		Tamilnadu		Karnataka		Madhya Pradesh		Odisha		Assam		Pooled	
Species	IC	CC	IC	CC	IC	CC	IC	CC	IC	CC	IC	CC	IC	CC	IC	CC
Transient loss (median)	74 (25–480)	140 (30–360)	90 (15–300)	150 (45–300)	60 (22–225)	101 (101–371)	45 (35–165)	112 (15–288)	15 (3.5–40)	30 (7.5–80)	8 (0–30)	40 (0–240)	15 (0–50)	7 (0–40)	60 (0–480)	90 (0–371)

Table 1. Estimated transient milk reduction per animal (litres). IC-Indigenous cattle; CC-Crossbred cattle.

State	species	Total Milk loss	Mortality loss	Draught power loss	Treatment cost	Ayurveda treatment cost	Vector management cost	Opportunity cost of labour
Rajasthan								
	Indigenous	51.5 (19.8–75.6)	146.3 (12.2–548.8)	NO	27.9 (7.9–146.3)	2.1 (0.6–15.5)	1.8 (0.3–14.0)	9.7 (2.3–24.4)
	crossbred	91.4 (20.1–237.8)	365.8 (24.4–609.8)	NO	42.8 (8.8–150)			9.1 (1.5–41.2)
	Median test	**21.1*** **	**6.3** **		**4.9** **	**0.21^{NS}**	**0.0072^{NS}**	**0.78^{NS}**
Gujarat								
	Indigenous	54.8 (7.3–182.9)	365.8 (48.8–731.7)	54.12 (13.5–162.4)	30.5 (30–304.9)	4.6 (0.6–13.1)	NO	6.8 (2.1–18.3)
	crossbred	54.8 (32.9–164.6)	235.3 (73.2–294)	NO	46.7 (20.3–116.8)			10.2 (6.9–13.7)
	Median test	**4.92** **	**0.00^{NS}**	**0.18^{NS}**	**0.01^{NS}**	**0.00^{NS}**		**2.03^{NS}**
Tamil Nadu								
	Indigenous	23.1 (9.6–67.4)	210.8 (60.2–722.8)	59.4 (17.8–267.3)	42.1 (6–120.4)	0.36 (0.07–21)	1.20 (0.09–18.6)	10.5 (4.5–58.7)
	crossbred	46.2 (9.6–101.2)	180.7 (30.1–722.8)	NO				
	Median test	**9.98*** **	**0.01^{NS}**	**0.14^{NS}**	**0.25^{NS}**	**0.38^{NS}**	**0.55^{NS}**	**0.06^{NS}**
Karnataka								
	Indigenous	16.2 (12.6–59.6)	240.9 (60.2–1084.3)	95.06 (17.8–534.7)	39.1 (13.2–144.5)	3.5 (0.07–34.4)	1.8 (0.24–36.1)	18.07 (4.5–112.9)
	crossbred	50.2 (10.8–110.8)	180.7 (30.1–722.8)	NO	60 (18.0–138.5)			42.9 (4.0–135.5)
	Median test	**3.89** **	**0.22^{NS}**	**0.00^{NS}**	**2.04^{NS}**	**0.00^{NS}**	**0.56^{NS}**	**0.08^{NS}**
Madhya Pradesh								
	Indigenous	7.22 (3.4–21.6)	481.9 (271–542.1)	47.6 (36.1–67.7)	18.07 (7.22–36.1)	3.51 (0.31–8.4)	1.5 (0.28–2.21)	14.0 (2.8–26.5)
	Crossbred	12.1 (3.4–33.7)	542.1 (180.7–722.8)	NO	18.07 (7.22–36.1)			14.0 (2.8–27.1)
	Median test	**5.22** **	**2.18^{NS}**	**0.00^{NS}**	**0.05^{NS}**	**0.11^{NS}**	**0.019^{NS}**	**0.05^{NS}**
Odisha								
	Indigenous	4.6 (0–14.4)	361.4 (120.4–1024.09)	NO	8.4 (0.84–61.4)	1.8 (0.18–4.21)	0.60 (0.12–3.73)	7.2 (1.27–23.04)
	Crossbred	19.2 (0–115.6)	512 (96.3–1000)	NO	12 (1.2–36.1)			6.5 (1.2–16.64)
	Median test	**16.8*** **	**0.29^{NS}**	-	**3.18^{NS}**	**28.1*** **	**0.83^{NS}**	**0.10^{NS}**
Assam								
	Indigenous	8.13 (0–21.6)	376.5 (30.1–692.7)	90.3 (67.7–135.5)	18.07 (4.8–90.3)	0.8 (0.18–3.8)	10.73 (2.45–42.94)	10.7 (2.4–42.9)
	Crossbred	4.5 (0–24.1)	481.9 (72.2–626.5)	NO	17.6 (4.2–38.5)		10.73 (2.2–42.9)	10.7 (2.2–42.9)
	Median test	0.61^{NS}	0.2^{NS}	0.00^{NS}	0.67^{NS}	0.008^{NS}	0.5^{NS}	0.01^{NS}
Pooled								
	Indigenous	38.31 (0–183)	365.8 (12.2–1084.3)	50.8 (17.8–534.7)	20.08 (0.84–305)	1.38 (0.073–34.4)	1.7 (0.086–36.1)	10.8 (1.28–113)
	Crossbred	57.3 (0–238)	365.8 (24.4–1000)	NO	30.1(1.2–150)			9(1.2–135.5)
	Median test	**9.26*** **	**0.76^{NS}**	**0.016^{NS}**	**19.24*** **	**0.00^{NS}**	**0.00^{NS}**	**1.15^{NS}**

Table 2. Estimated median loss per animal in the surveyed states (in USD). *** Significant at 1%, ** significant at 5%, NS- non significant; NO- particular loss component was not observed among the surveyed samples.

incurred for traditional medicine varied from USD 0.6 to 1.8 per animal with an overall cost ranged between USD 0.09 and 36.1. The opportunity cost of labour for managing the sick animal varied from USD 1.27 to 112.9 and 1.2 to 135.5 per animal with the highest cost in Karnataka The details of other costs associated with the LSD is presented in Table 2.

LSD loss in different states of India

Among the surveyed states, the estimated cost in stochastic modeling for Indigenous and Crossbreed cattle was highest in Rajasthan [USD 314.18 million (90% CI 279.10–349.34)] followed by Gujarat [USD 225.35 million (90% CI 204.06 –246.13)], Assam [USD 182.7 million (90% CI 163.7 –201.6)], Madhya Pradesh [USD 176.11 million (90% CI 159.00–192.90]), Tamil Nadu [USD 172.15 million (90% CI 147.45–196.61)], Karnataka [USD

116.49 million (90% CI 101.86–130.90)] and Odisha [USD 84.24 million (90% CI 75.31–92.98)]. Among the various cost components simulated [Supplementary Table S4 and Fig. 3(A)] highest loss was due to mortality with 42.5%, followed by modern treatment cost (26.5%), milk loss (13.7%), opportunity cost of labour (10.8%), draught power loss (3.7%), traditional (ayurvedic) treatment cost (1.7%) and vector management cost (1.1%). The probability distribution of mean loss is presented in Supplementary Figure S 1 and the simulated loss of various cost components for each surveyed state are presented Fig. 2 and supplementry Table S4. The probability

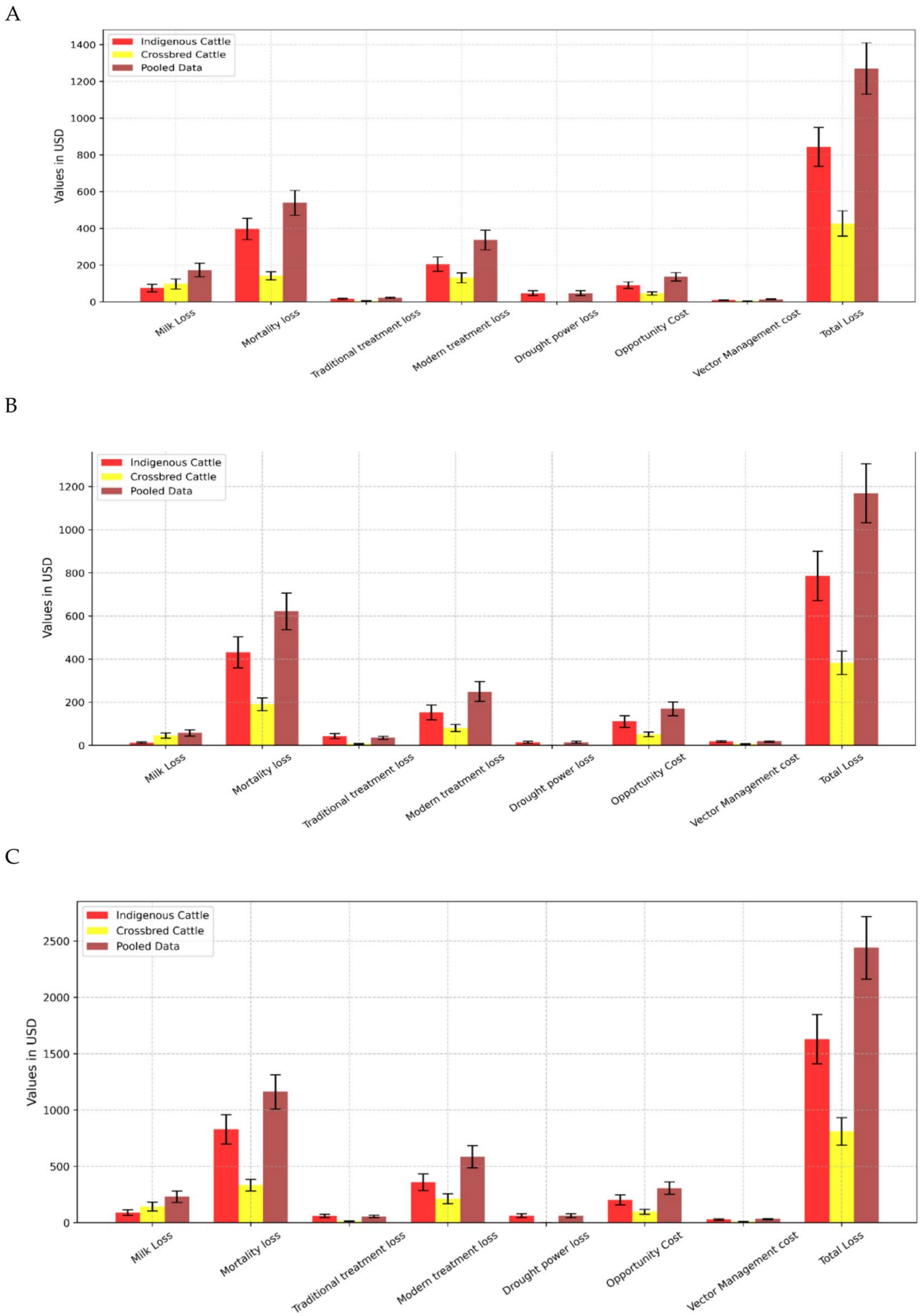

Fig. 3. Simulated total losses in **A**) Surveyed States, **B**) Non-Surveyed States, **C**) All India (Surveyed + Non-Surveyed).

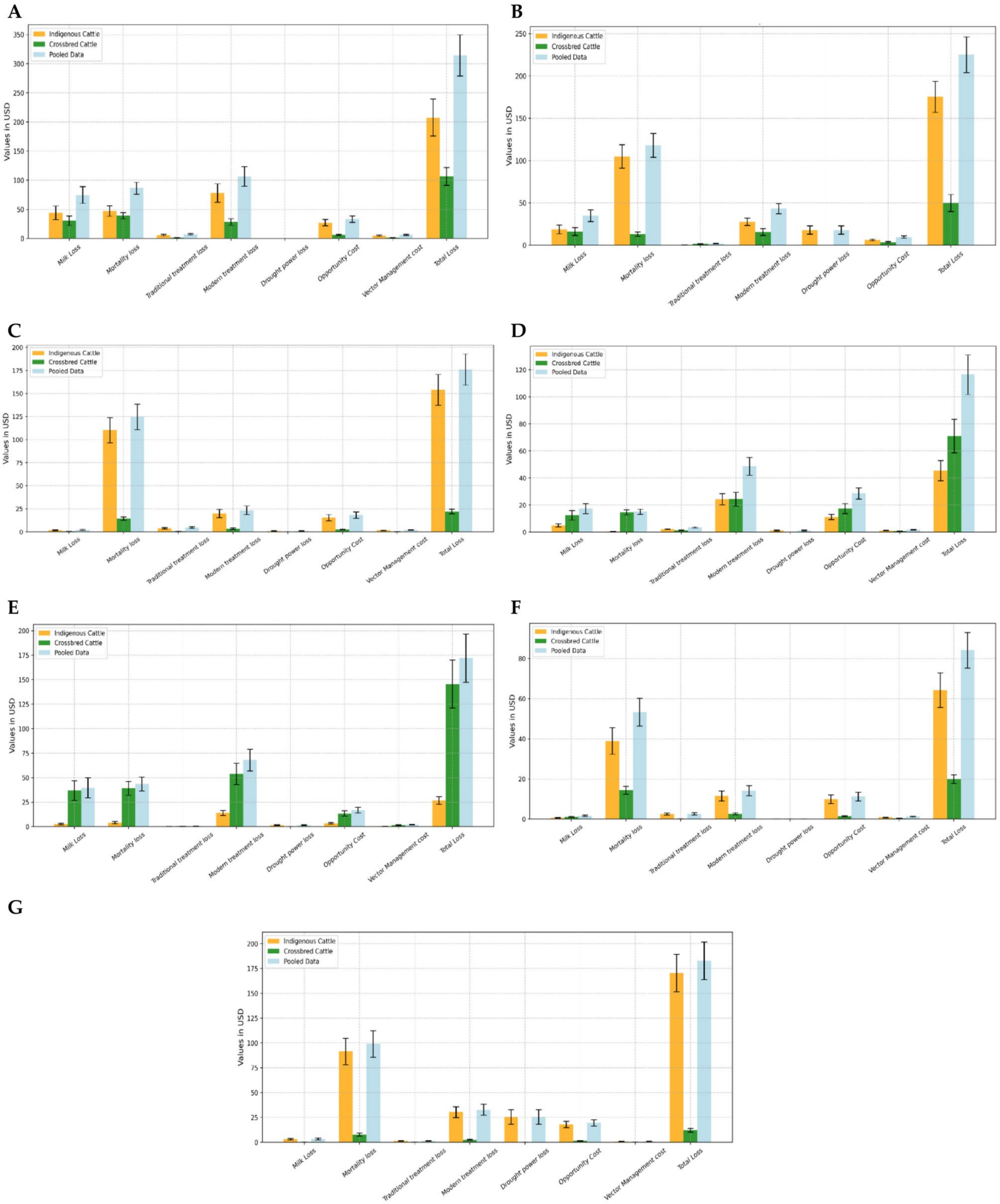

Fig. 2. Simulated various losses in surveyed states [(**A**) Rajasthan**,** (**B**) Gujarat**,** (**C**) Madhya Pradesh, (**D**) Karnataka, (**E**) Tamil Nadu, (**F**) Odisha and **(G)** Assam] (million USD).

distribution of mean loss due to LSD and the simulated cost of various cost components in the non-surveyed states/ UTs at disaggregate level is presented in Supplementary Table (S5), Fig. 3(B) and supplementary figure (S3).

Among the non-surveyed states/UTs, the highest loss was in Bihar [USD 197.74 million (90% CI 177.25–218.65)] followed by Assam USD 182.79 million (163.77—201.61) and other states. The total projected loss due to LSD in cattle in India was [USD 2440.29 million (90% CI 2162.55–2716.15)] / (INR 202,544.07 million (90% 179,491.65—2,225,440.45) during 2022 and 2023 (Fig. 3(C) and Supplementary Table S6).

The sensitivity analysis of total projected loss in Rajasthan state showed a high correlation coefficient (0.88) for the treatment cost, vector management cost and opportunity cost of labour implying these costs were the important influential parameters. In Gujarat, the important influential parameters (correlation coefficient of 0.71) in the total projected loss were modern treatment cost and opportunity cost of labour. In Madhya Pradesh, Karnataka, Odisha and Assam the mortality loss is the most influential parameter in the total project loss with a correlation coefficient of 0.82, 0.98, 0.78 and 0.70, respectively. The details of the sensitivity analysis for various surveyed states is presented in Supplementary Figure (S2).

Discussion

In India, the economic impact studies for important diseases viz Foot and Mouth Disease (FMD) and Haemorrhagic septicaemia (HS) in cattle and buffaloes[15,22,25,26], are available, but not on the recently reported LSD, a deadly transboundary disease in bovines. As per our knowledge, this is the first national level study addressing the farm-level economic impact of LSD based on one of the largest surveys (n = 2351 farms) covering seven Indian states during 2023.

The incidence of LSD in various states of India ranged from 11.9% to 44.8% and 14.3% to 45.9% and mortality rates ranging from 0.9% to 16.3% and 2.5% to 8.4% in indigenous and crossbred cattle, respectively. The variation between the Indian states might be due to variation in composition of at-risk population, breed charecteristic, farm management practices and factors related to the host-environment-pathogen-vector interactions. High incidence or mortality rates in milch animals indicates a significant reduction in the current milk production levels of 221.1 million tonnes (https://www.nddb.coop/information/stats/milkprodindia) in the coming years, alongside a a potential decline cattle population.

In the study states, among the indigenous cattle, a transient reduction in milk yield of 60 L per animal while in crossbred cattle, the reduction was one- and- a-half-times greater and it corroborates with[27,28] reported a mean reduction of 1.5 L per farm per day for farms keeping indigenous cattle and 9.9 L for farms with exotic breeds of cattle. In monetary terms, a considerable difference in median milk loss per animal was observed between indigenous (USD 38.3) and crossbred cattle (USD 57.3), as well as within the indigenous and crossbred cattle in different states. The varying levels of milk reduction loss was due to differences in the productivity levels of various native and crossbreds reared in different states. The milk productivity of native breeds like *Gir* (2110 kg per lactation, with approximately 4.5% fat around 7 L/ day for 300 days) (https://en.wikipedia.org/wiki/Gyr_cattle) are comparable to that of Holstein Friesian (HF) cross or Jersey crosses. In contrast, some other native breeds, such as *Malwi*, *Deoni* and *Tharparker milk* yields range between 2 and 3.5 kg/day. Hence there is variation in milk reduction loss within and between breeds as well as across the study states.

The median mortality loss per animal in crossbred cattle is higher than indigenous cattle in Rajasthan, Madhya Pradesh, Odisha and Assam whereas it is lower than in indigenous cattle in Gujarat, Tamil Nadu and Karnataka. The wide range in the estimated mortality loss per animal in different states can be attributed to valuation differences across age-, sex-, breed-, lactation and productivity levels. In western and central region states, such as Gujarat and Madhya Pradesh, there is greater preference for indigenous cattle breeds like '*Gir,*' as these breeds are high yielders and comparable productivity levels with crossbreds. Hence the valuations of indigenous breeds are higher than crossbreds like Holstein Friesian cross or Jersey cross in these states[29]. reported a mean mortality loss per affected animal in Kenya ranged between USD 0.1–1.0 and USD 5–189 for indigenous and crossbred cattle, respectively.

In developing countries, the important crop operations like sowing, intercultural, harvesting and post-harvest operations depend on the draught power. During the LSD infection, the availability of animals for farm operation decreases, and hence the cost of agricultural operations increases considerably. The estimated median draught power loss per animal in the study states varied between USD 47.6 to 95.1 whereas[30] reported a loss of USD 5,743. The wide variation in draught power loss depends on the severity and duration of infection, the season of the infection, the extent of usage and the cost of the bullock power in the respective states.

LSD is a viral disease, and hence prevention is better than cure. However, in the event of outbreaks, the symptomatic palliative treatment is necessary to avoid secondary bacterial complications. In addition to modern treatment with antibiotics and supportive therapy, farmers adopted traditional methods mainly to treat the nodules on the skin (eg. topical application of turmeric paste (*Curcum longa*) or application of betel leaves (*piper betle*) or application of neem leaves paste (*Azadirachta indica*) or combination of one or the other natural products along with the clarified butter).The mean cost of modern treatment and traditional method varied between USD 8.4 to 60 and USD 0.36 to 4.6, respectively. However[31], reported a cost of Rs. 1,749.10 (USD 21.07) for traditional treatment with ethnoveterinary remedies to protect from LSD. The variation in treatment cost across the states and breeds depend on the severity of infection and the treatment regimen adopted by the respective jurisdictional veterinarian, as well as traditional methods adopted by the farmer. LSD is a vector borne disease, hence considerable amount was invested by the farmers for vector control. Farmers in all the surveyed states expended in vector control except Gujarat, where it was conspicuous by its absence due to lack of awareness about the need of vector control.

The total projected loss due to LSD was highest in Rajasthan state with USD 314.18 million followed by Gujarat (225.35 million), and other states. There is considerable variation in the total projected loss across different states due to factors such as the demography of cattle population, proportion of the crossbred and indigenous cattle, incidence and mortality rates, milk reduction, the stage and number of lactations, duration of infection, animal health status, milk prices, labour wages, value of the animals, farm management factors and differences in treatment cost for managing the LSD. Further, the projected loss in the non-surveyed states and UTs was influenced by population demography, epidemiological parameters and economic values in the reference states. The sensitivity analysis showed higher correlation coefficient for few components viz treatment cost, opportunity cost and vector management cost despite less contribution of these components in the total projected loss.

At the national level, the projected loss due to LSD in cattle during 2022 and 2023 was USD 2440.29 million (90% CI 2162.55–2716.15)/ (INR 202,544.07 million (90% 179,491.65—2,225,440.45) implies the devastating economic burden of the diseases in the short term. However, if medium to log term impacts—such as long-term milk reduction within and subsequent lactations, conception delay, reproduction failures, and the loss of animal asset (e.g., future animals not born due to the current death of animals)—are considered, the impact would be even higher. In the coming years, the milk production in India is expected to decline due to current LSD infection and deaths unless urgent disease mitigation measures are initiated.

To control the LSD spread, the state governments have initiated ring vaccination with the goat pox vaccine (103 TCID 50/ml) and advocated the biosecurity measures adoption at the farms such as isolation, vector management and quarantine. However, the survey observed that the vaccination was sometimes administered after the LSD outbreaks possibly due to non- availability of the vaccines. Further, vector management practices was limited to a few farms and only during the peak LSD infection period.

The study needs to be viewed with certain limitations: only farm-level short-run impacts were considered, and indirect losses associated with abortions, reproductive failures, sterility in the animals and macro-level impact of LSD on the livestock and associated sectors were not included. Additionally, only seven states from different geographical regions out of 28 states and eight union territories, were surveyed.

Conclusions

Lumpy skin Disease has devastated the cattle sector in India. In addition to short-term reduction in milk production, the medium to long-term impacts are expected due to wide spread death of the cattle population. Furthermore, the current impact will permeate to other actors within the livestock sector and to other sectors, particularly in rural areas. Therefore, to mitigate the effects of LSD, the vaccination efforts need to be intensified, along with the implementation of other bio security measures.

Data availability

The data presented in this study are available in the manuscript and in supplementary files. All datasets supporting our findings are available at Socio-Economic section of ICAR-NIVEDI, Bengaluru on reasonable request from the corresponding author.

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Author contributions
G.G.N: Conceptualization, investigation, resource, project administrating, supervision, writing the original draft, review and editing. R.R.S, and P.R.R; Data collection and analysis. H.G., M.H.D., N.G, and S.G.C.S: Data Collection. P.K.S.N and S.S.P: Analysis. A.K., L.B., J.T., S.A., G.B.M, J.R.B, D.P.B., B.C., Y.R: Coordinated the field surveys in different states. B.R.G: resources and Co-ordination.

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Declarations

Competing interests
The authors declare no competing interests.

Institutional review board
This study was approved by ICAR-National Institute of Veterinary Epidemiology and Disease Informatics (NIVEDI) and ethics committee and approval number is NIVEDI/IAEC/2023/05 dated 01/03/2023. All the methods were performed in accordance with the relevant guidelines and regulations.

Informed consent
Informed consent was obtained from all the survey participants.

Additional information
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