Eco-Epidemiology of Plague in the U.S. and Abroad

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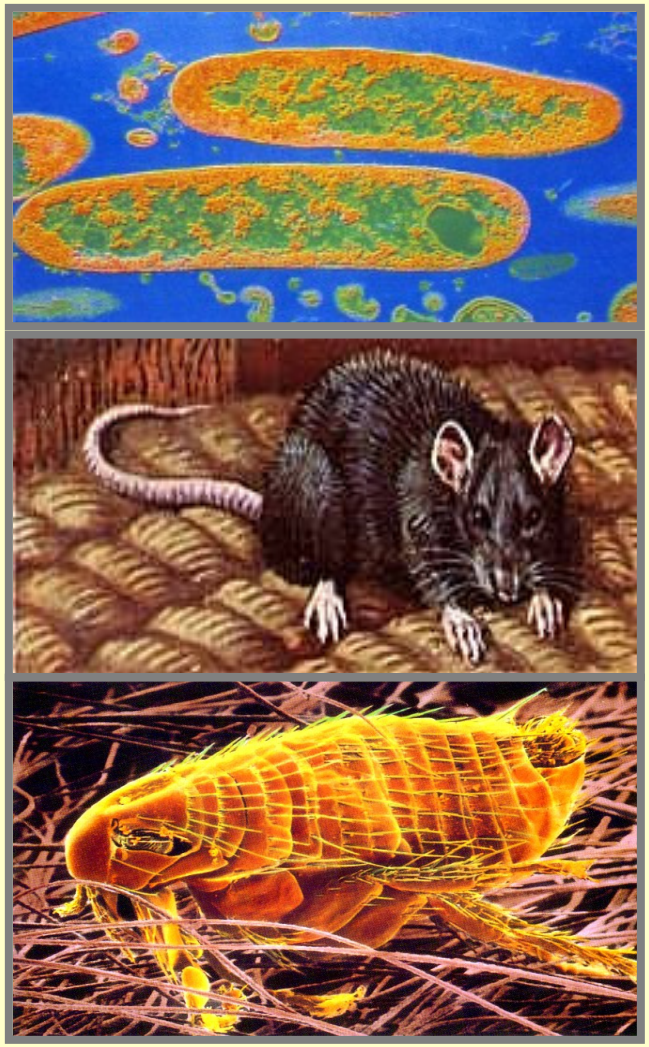
The World's Big Three Plague Stars

- *Yersinia pestis* –
  Extremely virulent gram-negative bacterium
- *Rattus rattus* –
  Widespread commensal rat; highly susceptible to plague
- *Xenopsylla cheopis* –
  Unexcelled plague vector



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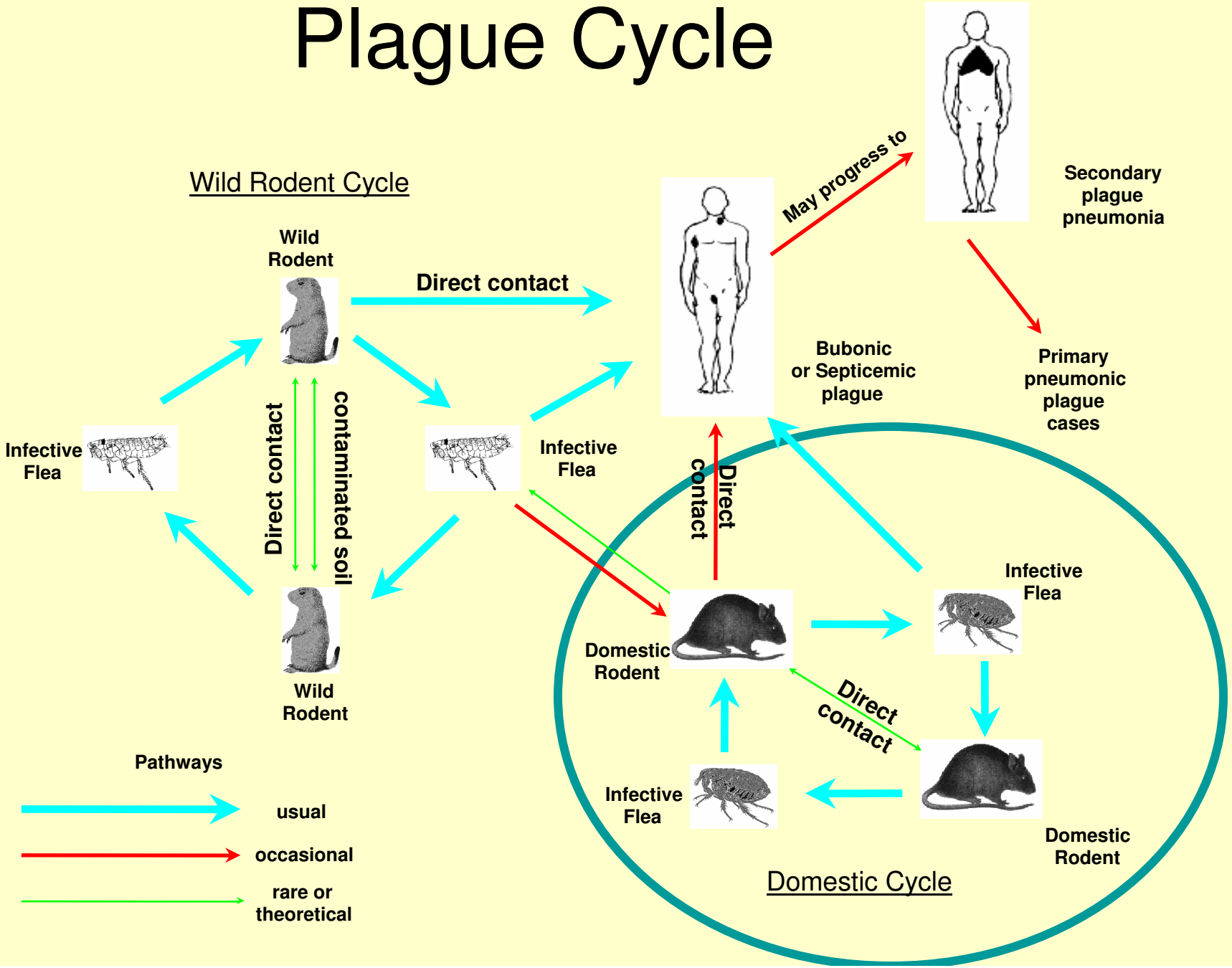
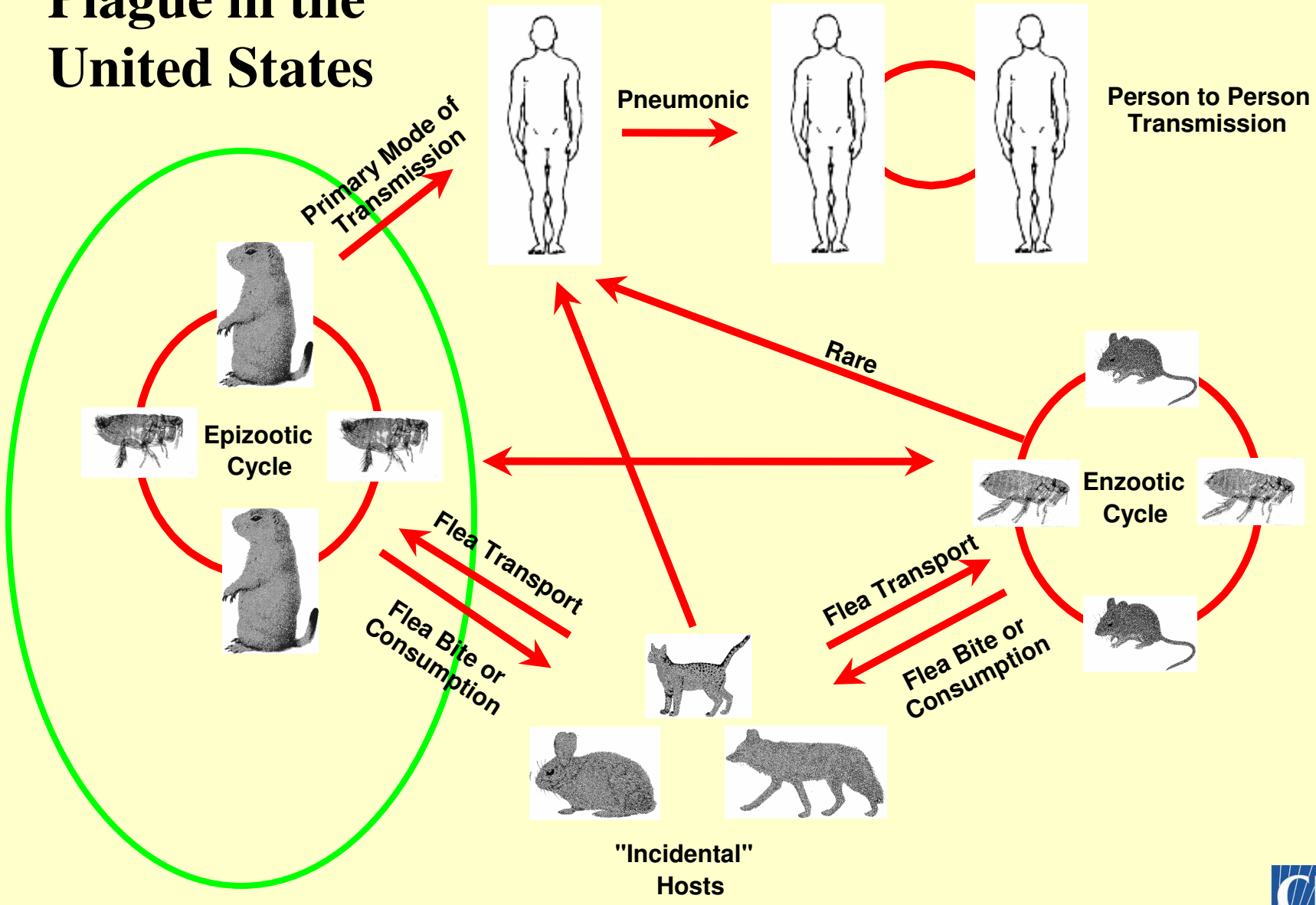
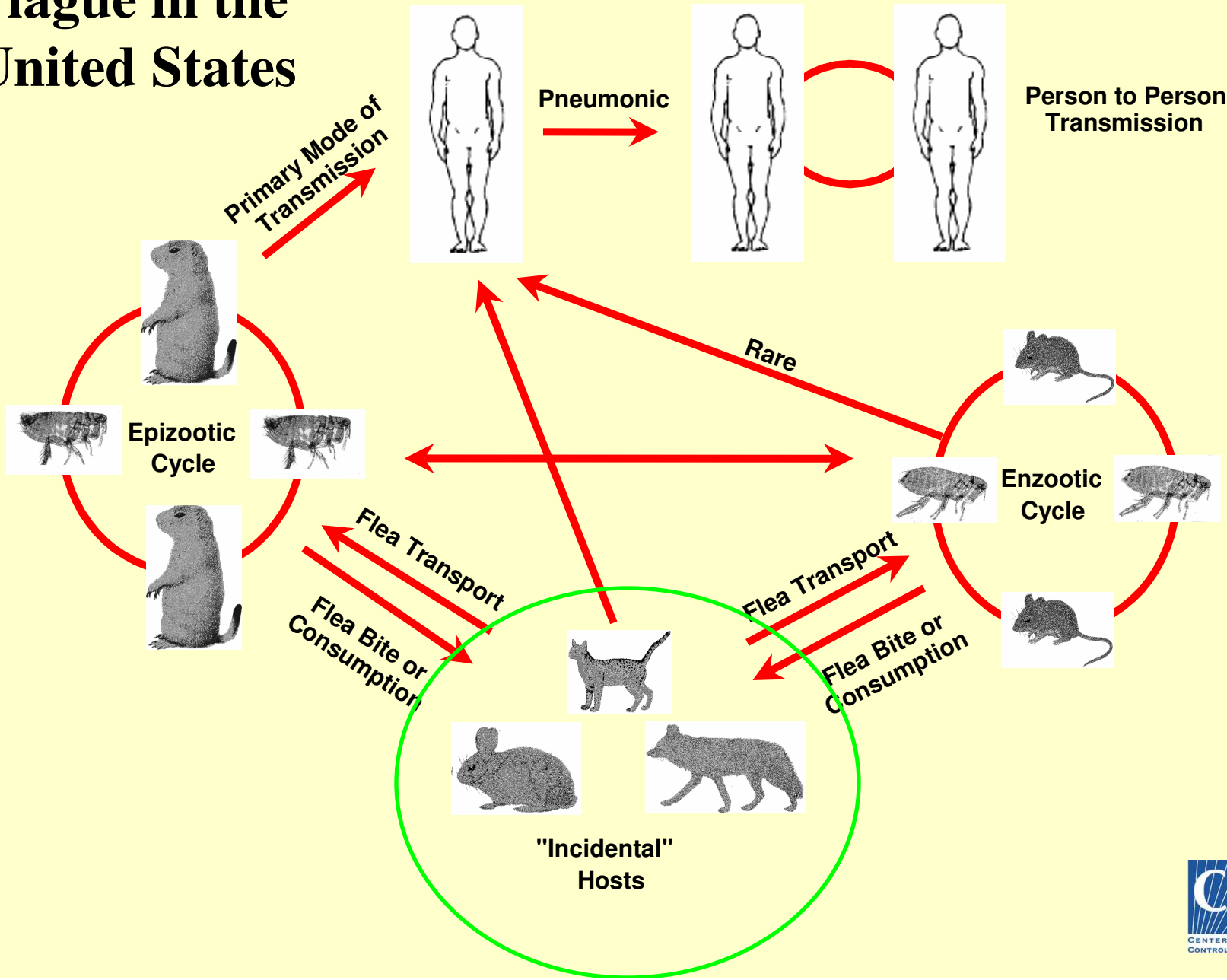
Plague Cycle



Plague in the United States



Plague in the United States



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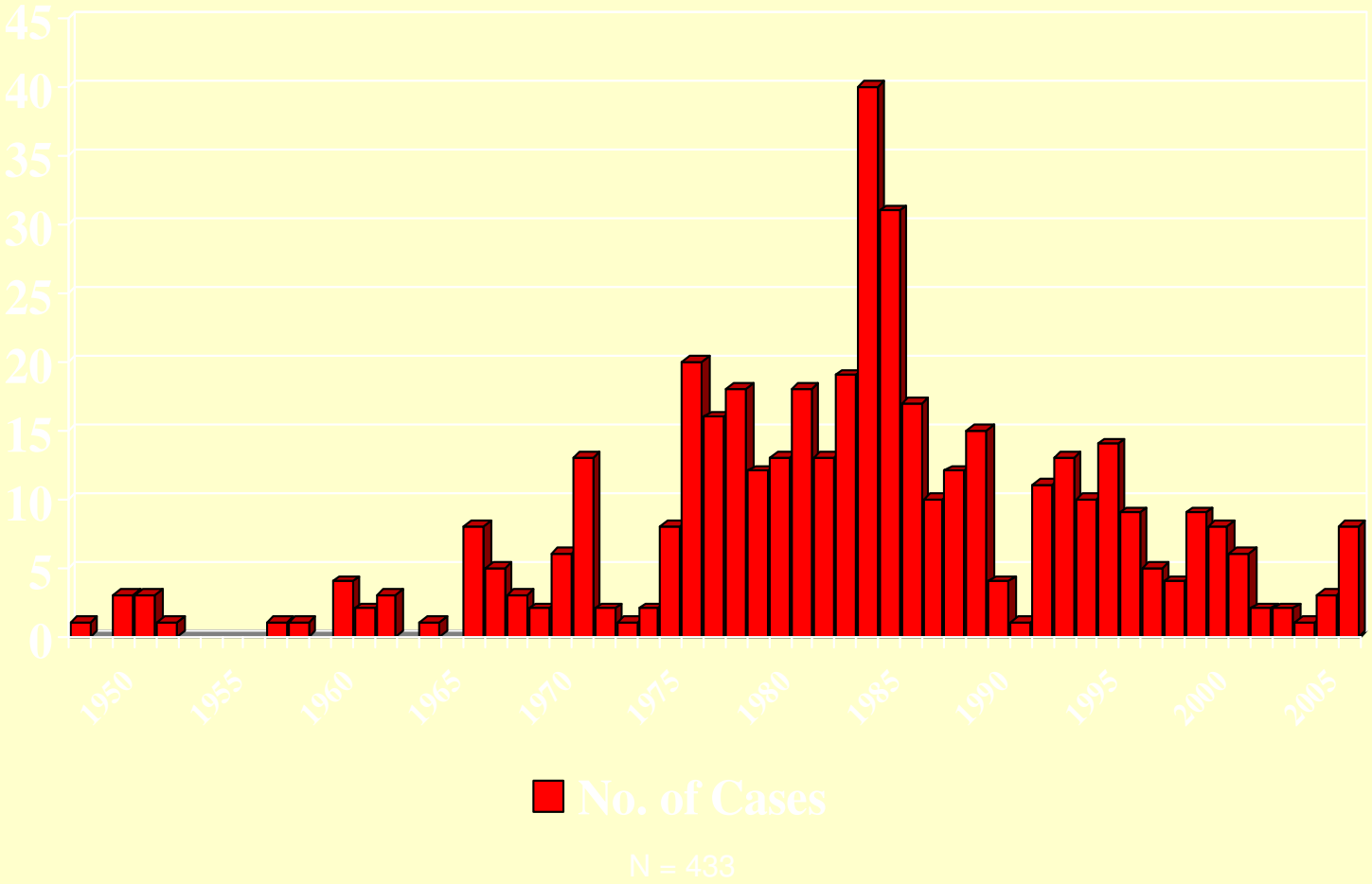
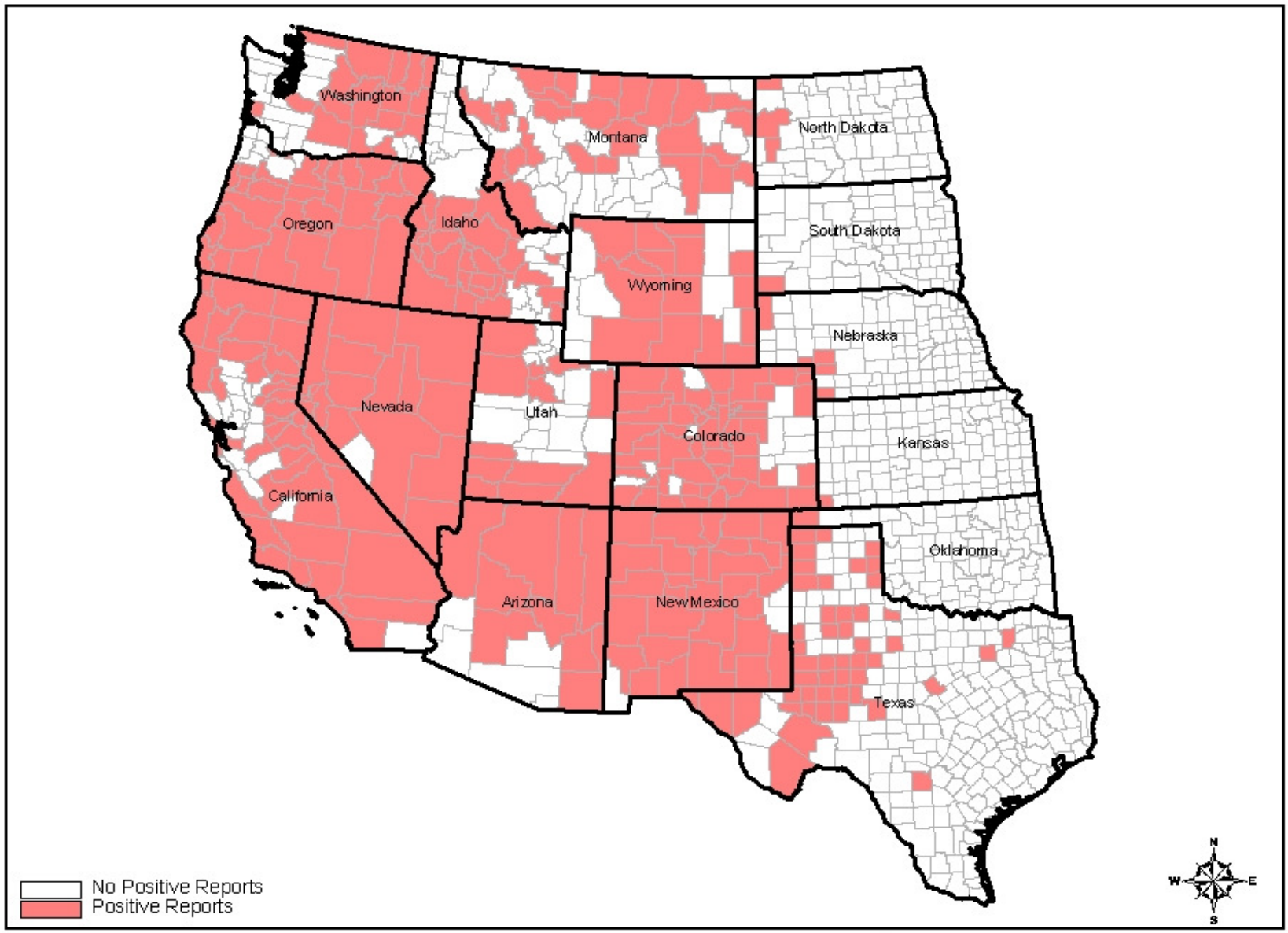
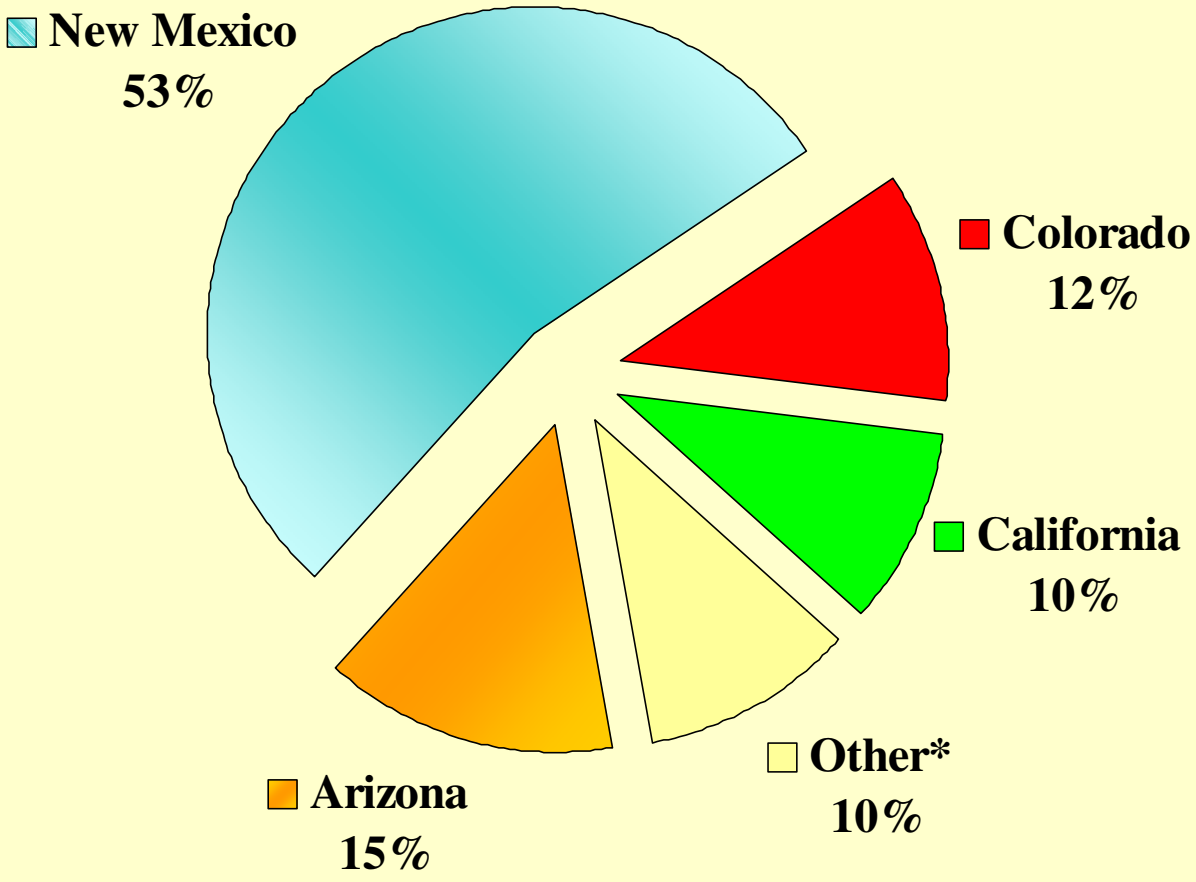
Reported Human Plague Cases By Year-U.S.A., 1947-2005



Western US Counties With Plague Positive Data, 1970 - 2005



Plague Cases by State
1970 - 2005
(n=390)



* UT,OR,NV,TX,ID,WY,MT,OK,WA

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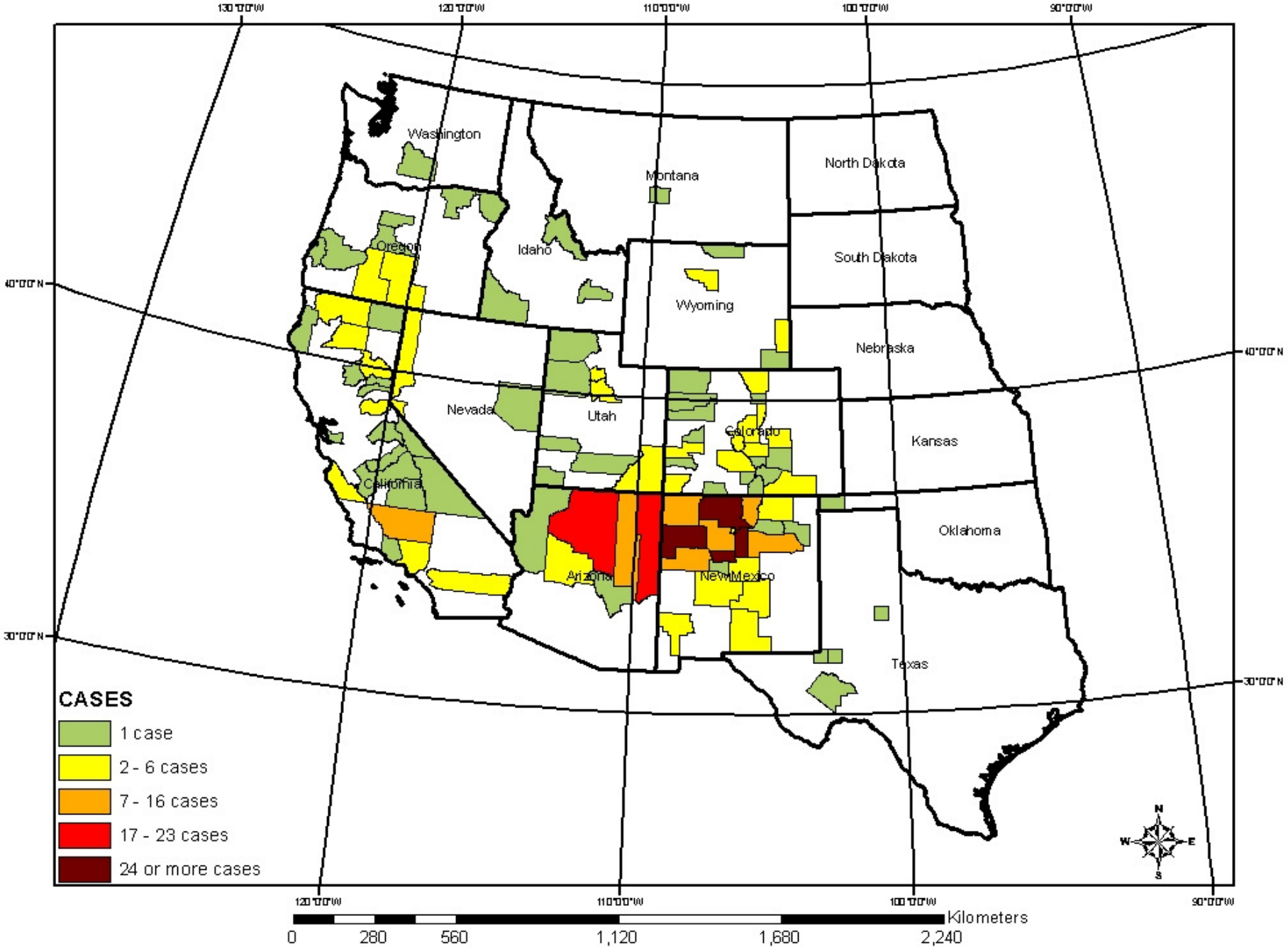
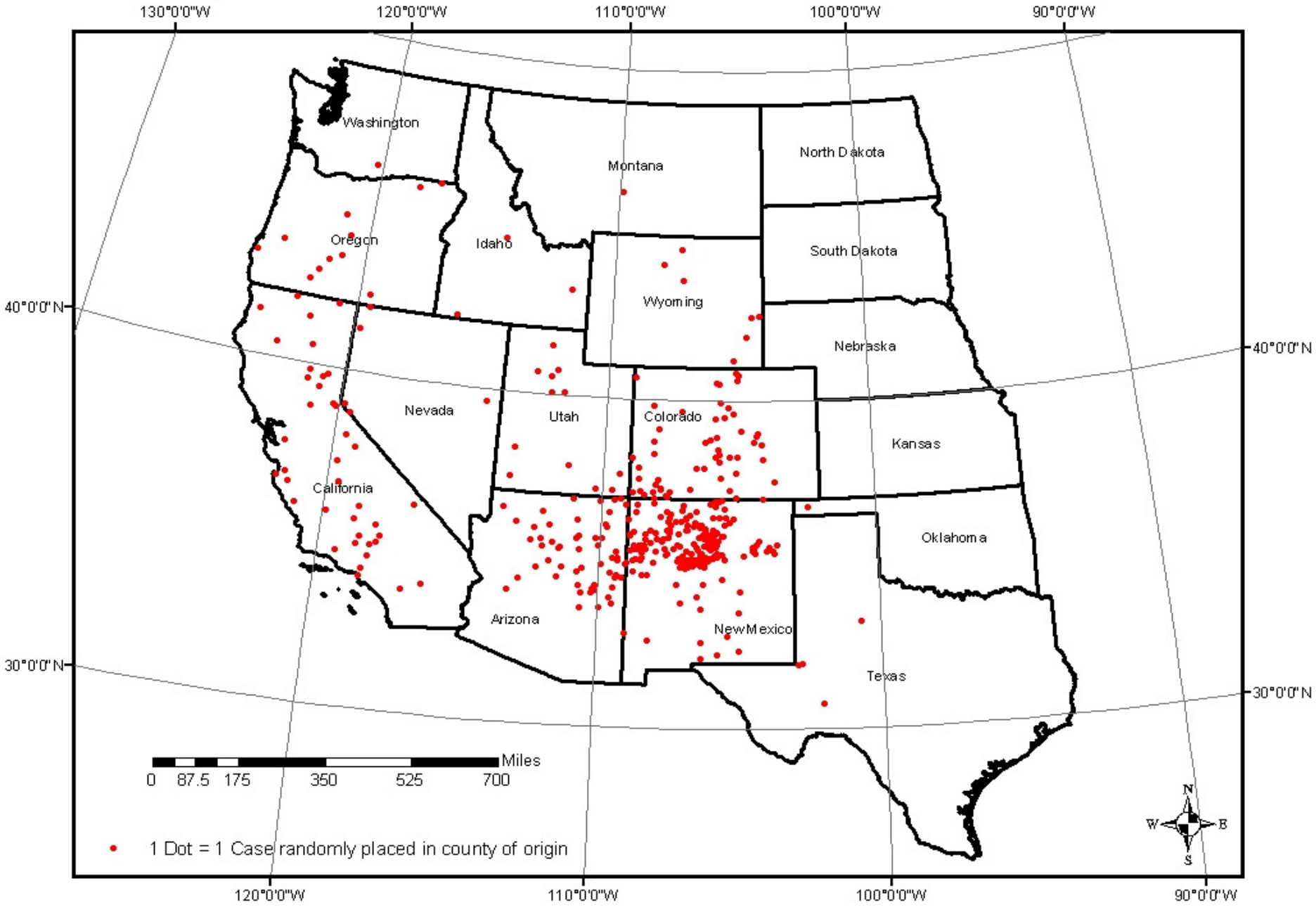
Plague Cases, by county, Western U.S., 1970 - 2005

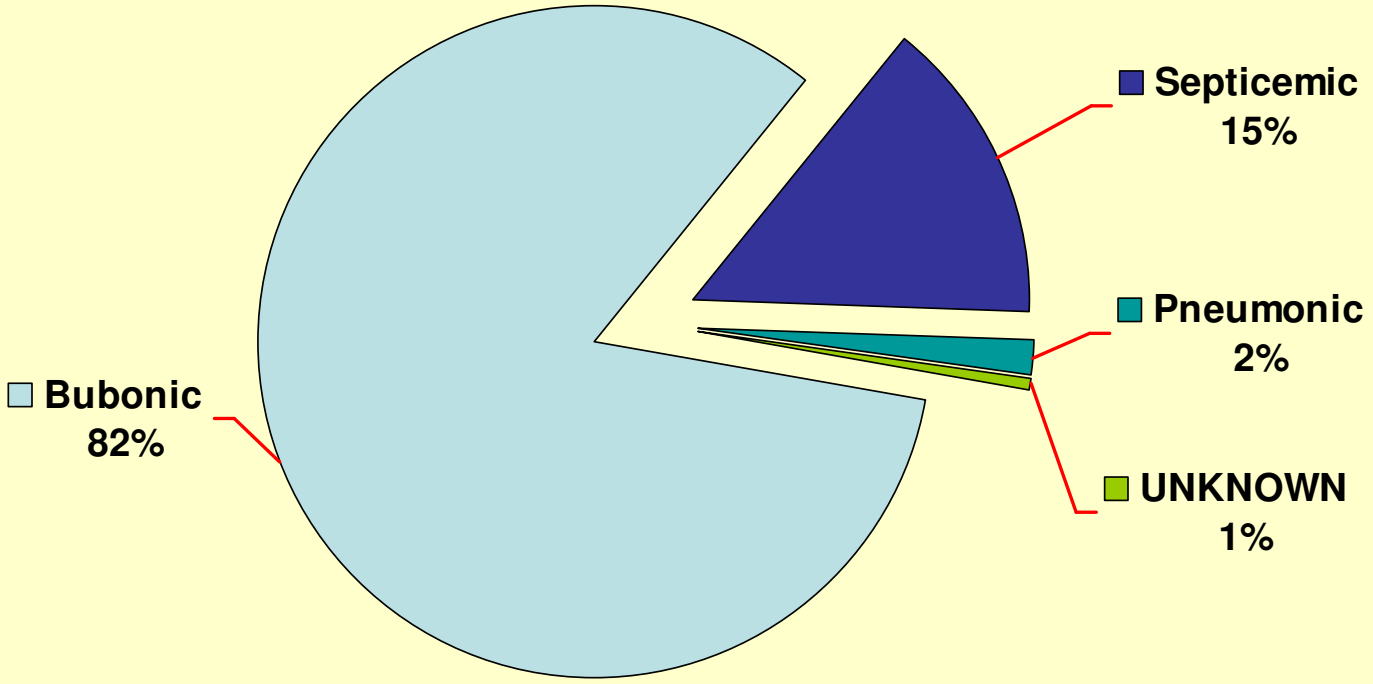


Plague Cases in the Western U.S., 1970 - 2005



Plague in U.S., 1970-2005
Primary Presentation

N = 389



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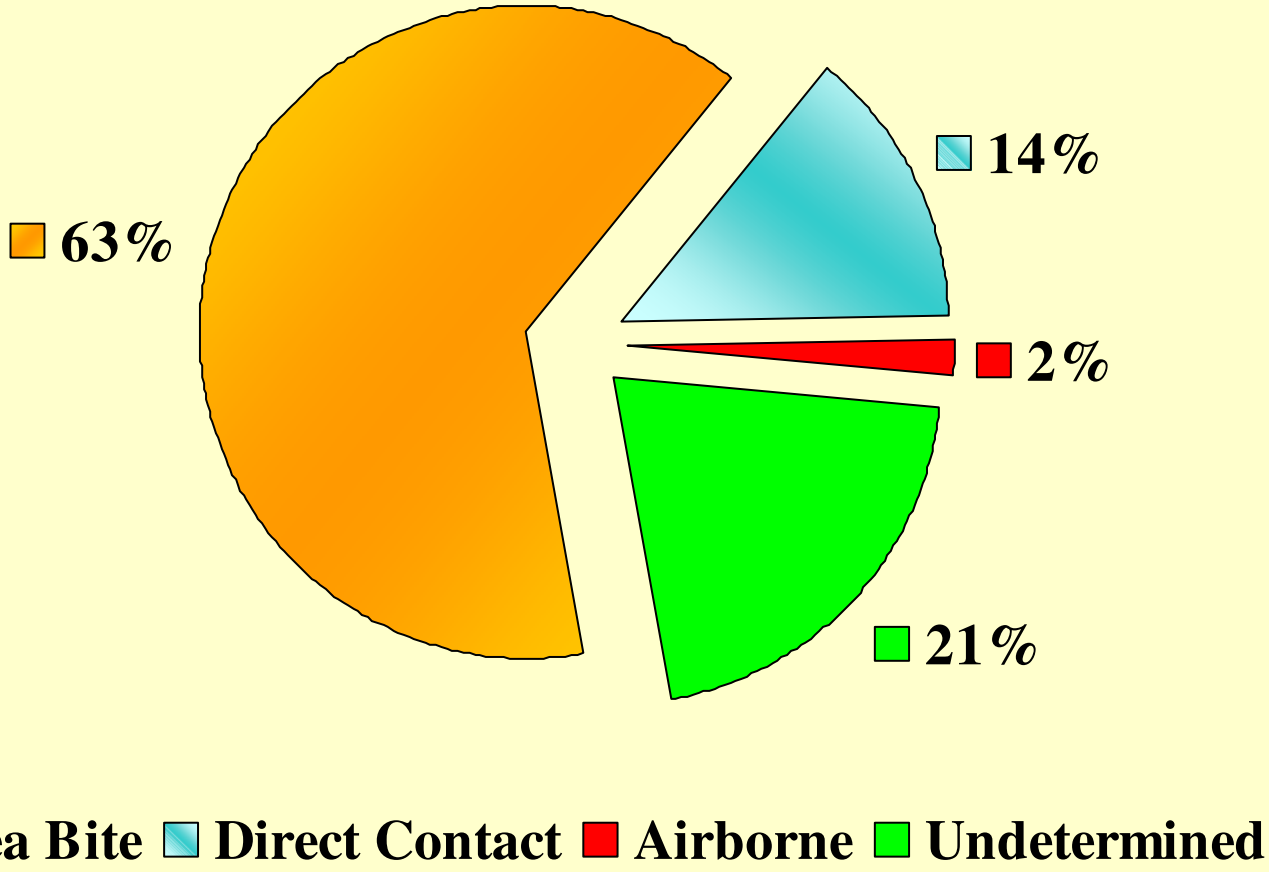
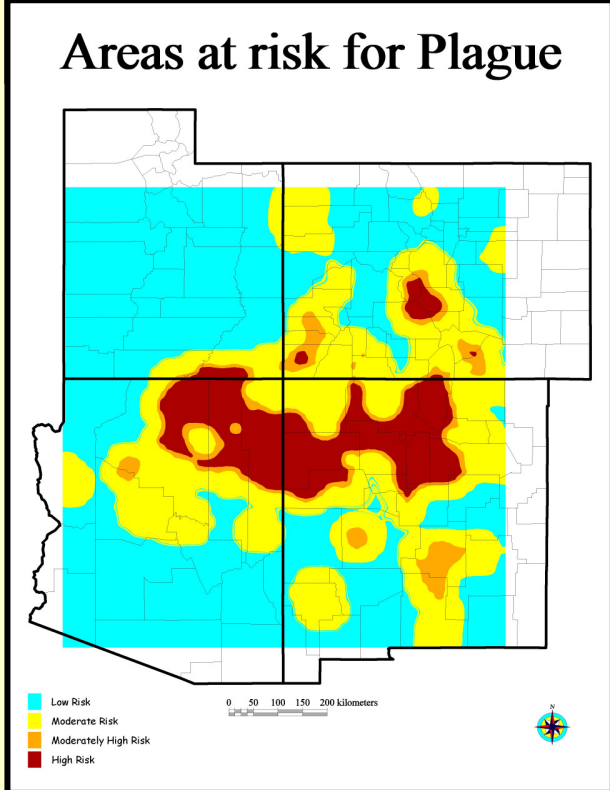
Plague Cases by Mode of Transmission 1970 – 2005

(N = 390)



Human Risks of Plague – U.S.

- Human risks vary by area (SW highest)
- Risks vary over time (partially climate-related)
- Risks highest during epizootics
- Peridomestic environment important risk factor
- Recreational areas also important exposure sites in California and surrounding areas



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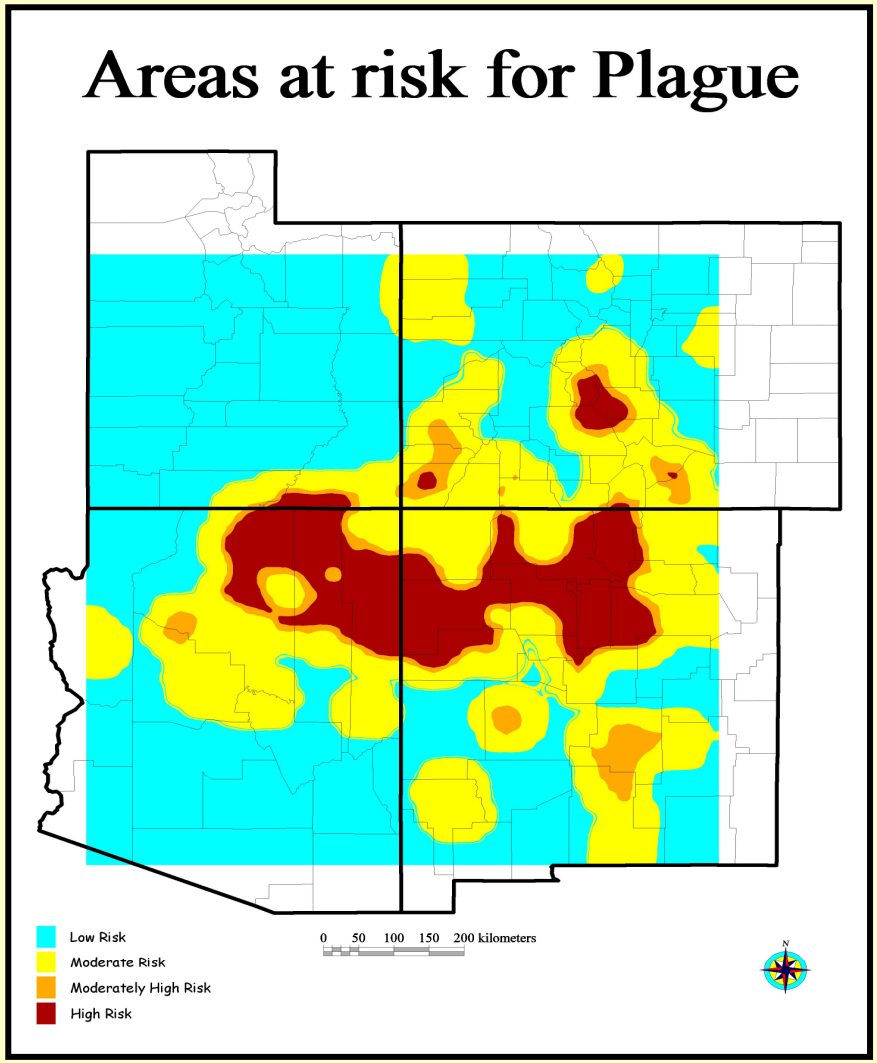
Plague in the Southwest



- **High risk areas (pinon-juniper and nearby areas)**
- **Peridomestic exposures (about 80% of exposures)**
- **Rock squirrels, other ground squirrels, prairie dogs, wood rats, deer mice and their relatives**
- **Acquired via:**
  - **a. Flea bite (~ 80%)**
  - **b. Direct contact with animals (~ 20%)**
  - **c. Inhalation (rare – cats with pneumonic plague)**

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Temporal Changes in Plague Risk

- Strong links between climatic variables and human plague and epizootic activity (Parmenter et al. 1999, Enscore et al 2002, Stapp et al. 2004, Collinge et al. 2005)
- Positive correlations with high winter precipitation
- Negative correlation with excessively high summer temperatures
- Effects most noticeable in areas with strong seasonal climate variations, especially late season winter precipitation peaks (Collinge et al. 2005)
- El Nino events correlated with plague in prairie dogs (Stapp et al. 2004)
- Results appear to have broad applicability but local variations in climatic variables need to be taken into account along with scale of area examine

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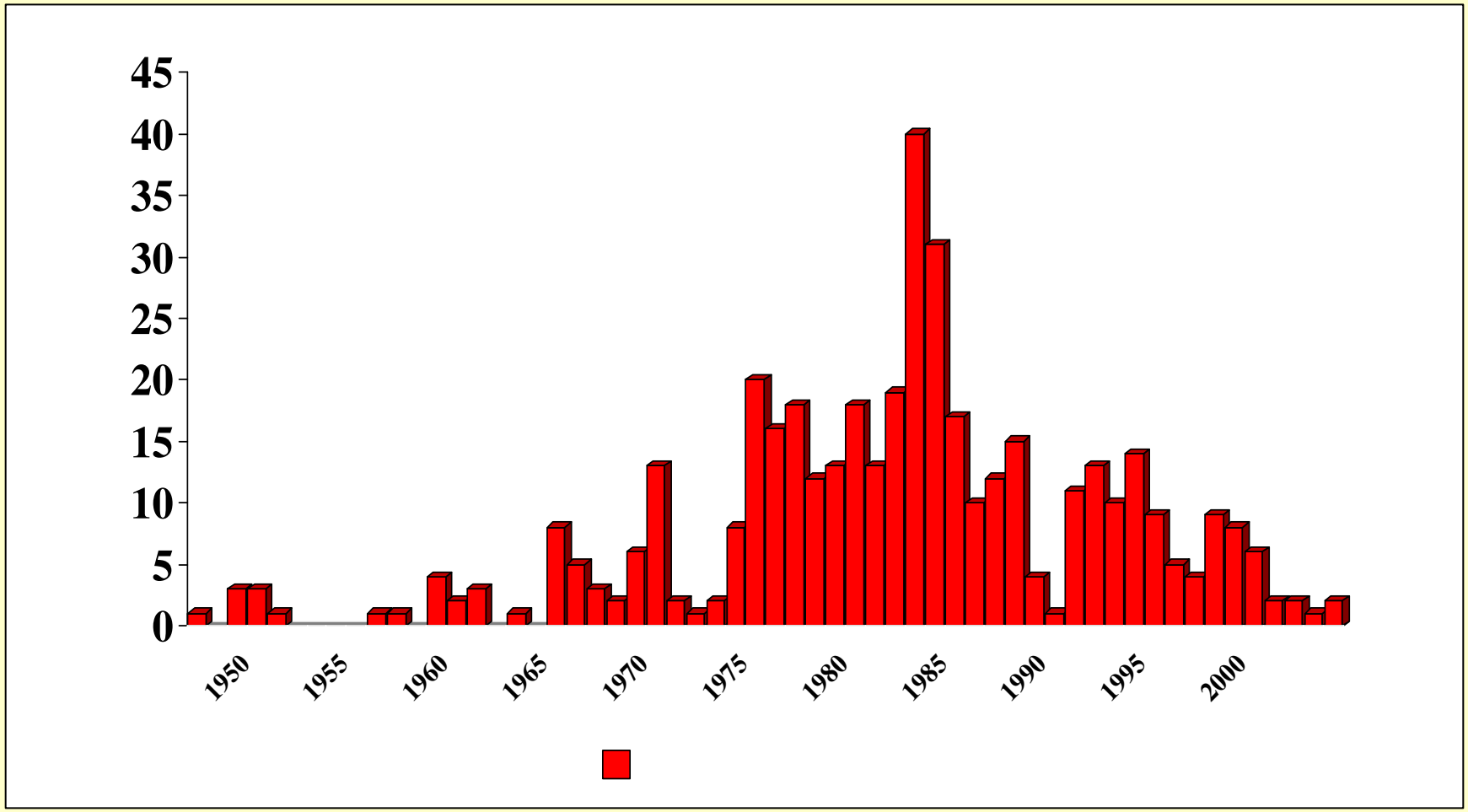
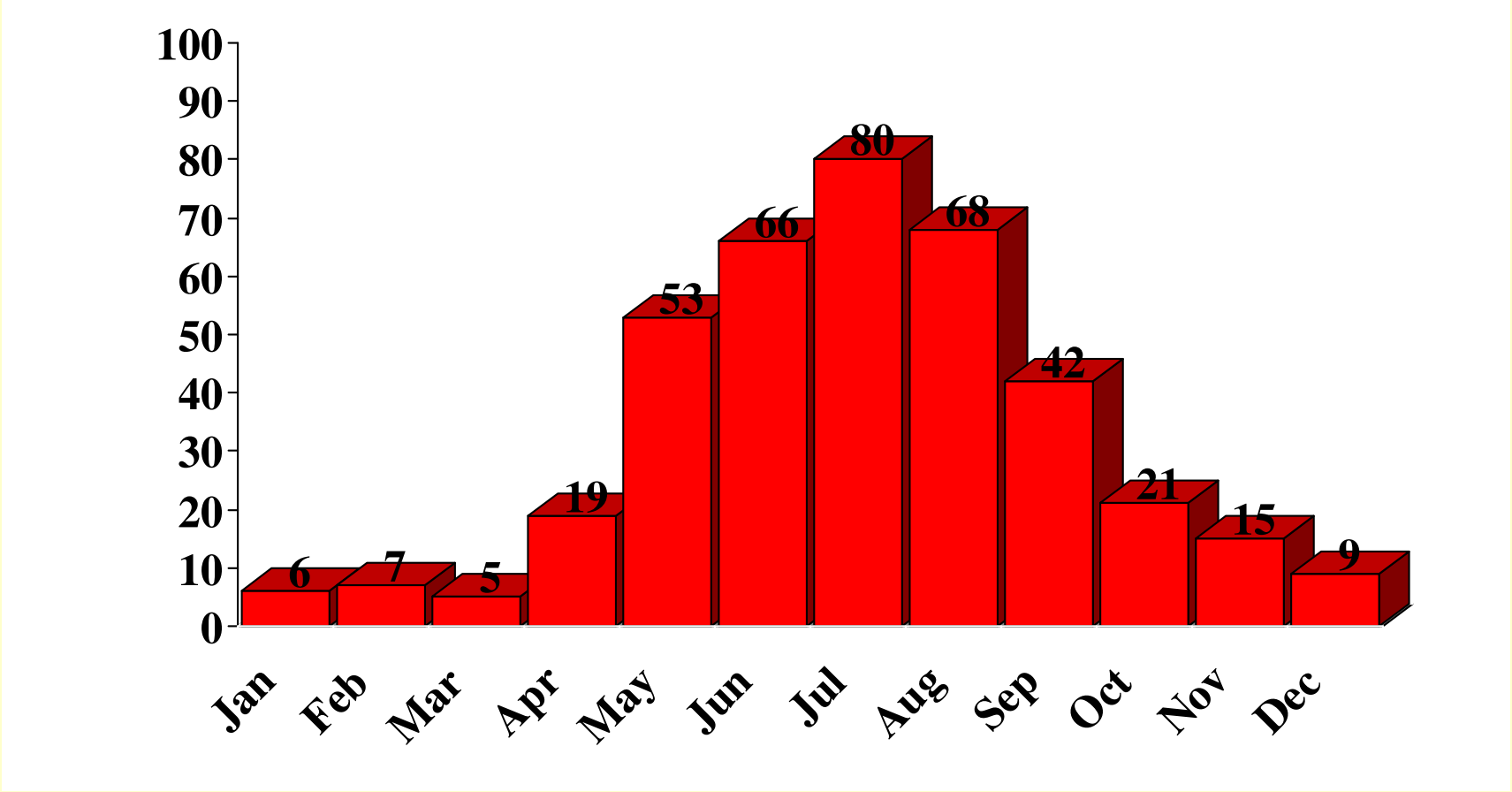
Reported Human Plague Cases By Year-U.S.A., 1947-2004



N = 422

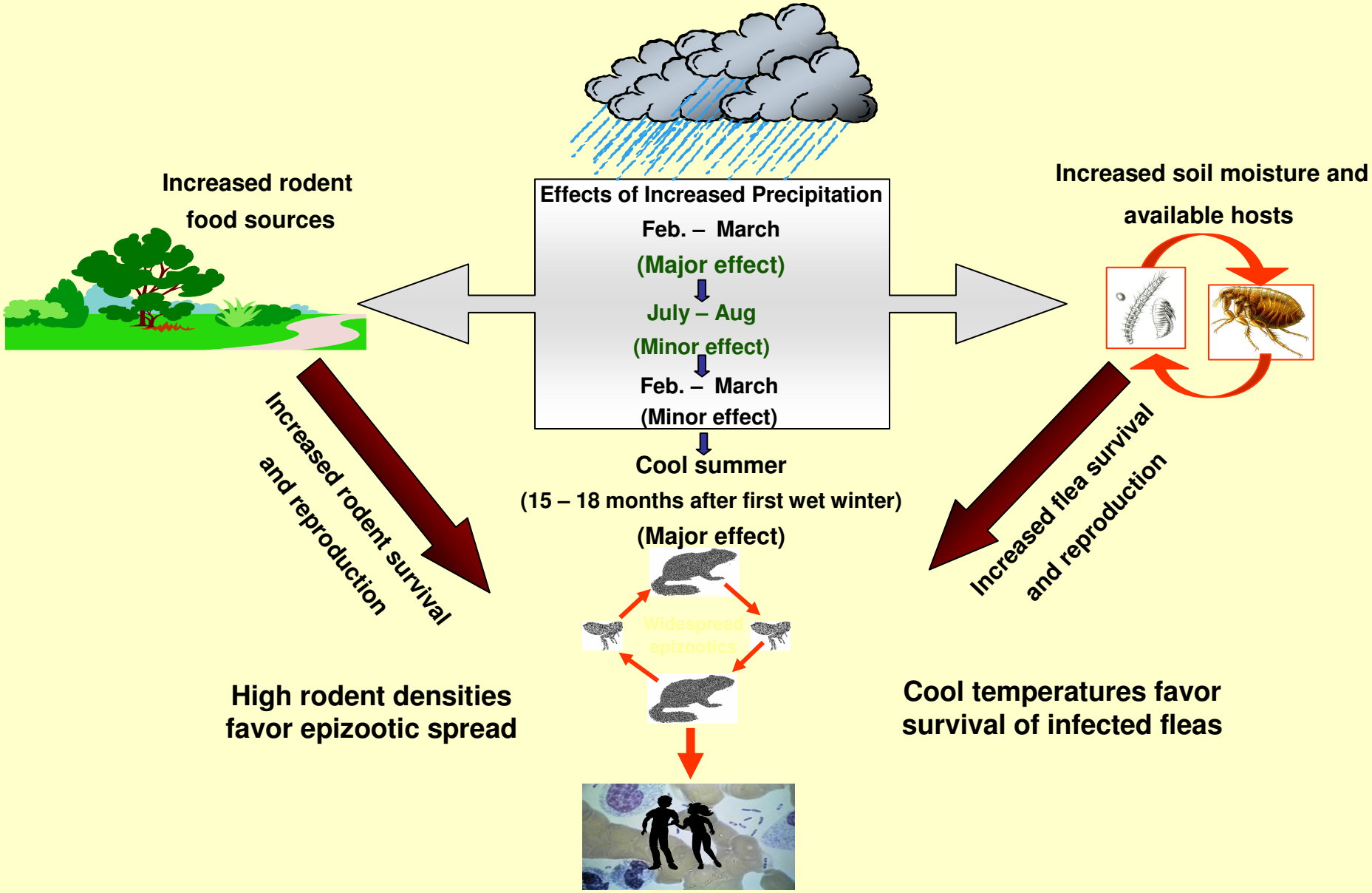
Cumulative Reported Human Plague Cases By Month of Onset, US, 1970 - 2005



N = 390

How Could Climate influence Plague Activity?

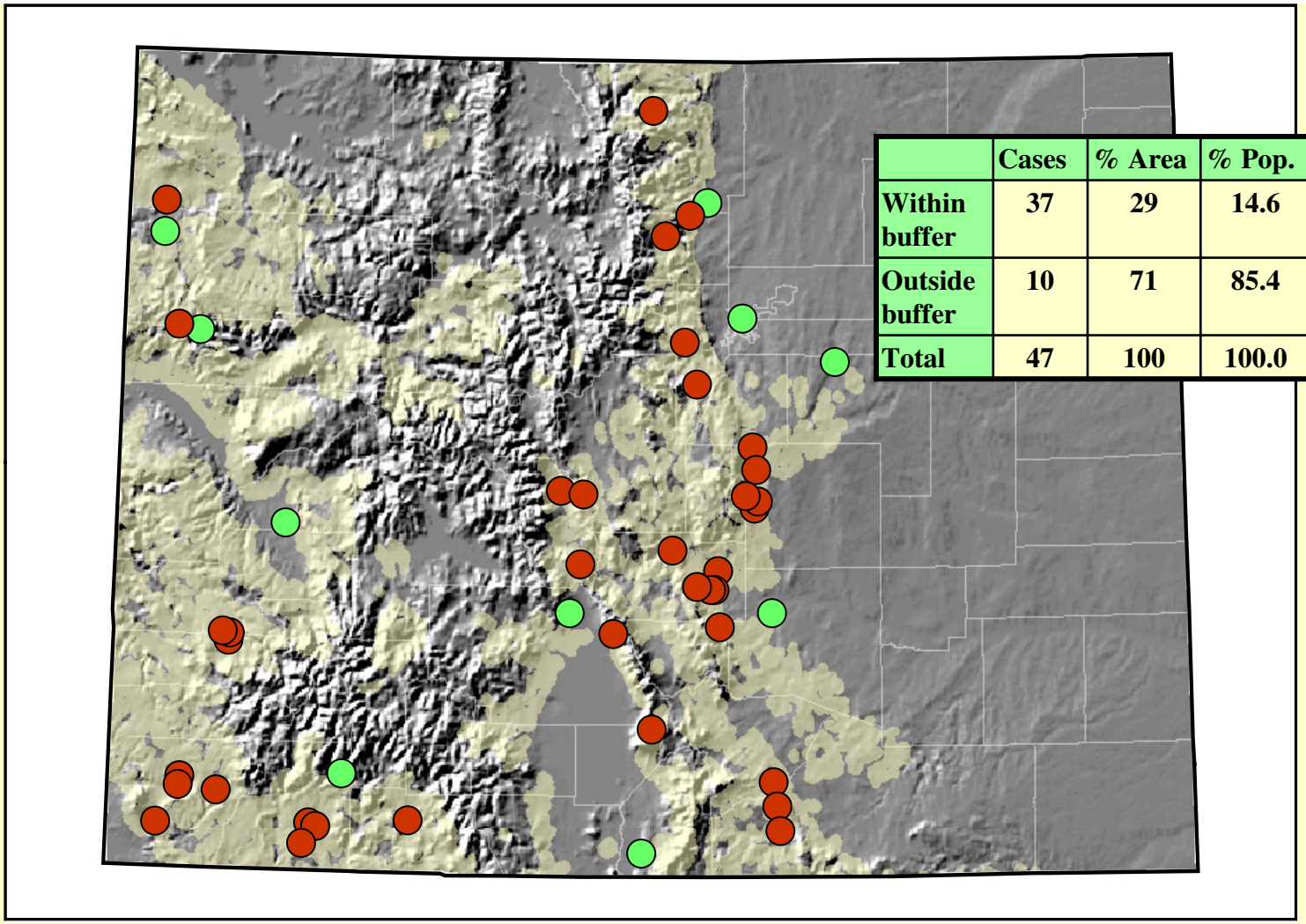
- Seasonality of transmission
- Survival of fleas
- Ability of fleas to transmit and retain infection
- Rodent host and flea vector population dynamics


Increased rodent food sources
Effects of Increased Precipitation
Feb. – March
(Major effect)
July – Aug
(Minor effect)
Feb. – March
(Minor effect)
Cool summer
(15 – 18 months after first wet winter)
(Major effect)
Increased soil moisture and available hosts
Increased rodent survival and reproduction
Increased flea survival and reproduction
Widespread epizootics
High rodent densities favor epizootic spread
Cool temperatures favor survival of infected fleas
Increased human plague risks

Spatial variations in Plague Risk

- Clear habitat associations
- Human risks highest near pinyon-juniper
- Cases not common on public land in NM, CO and AZ (mainly private or tribal lands)
- Human behaviors also contribute significantly to risk

Cases within 2.5 km of Selected Habitat Types (Pinyon-Juniper and Ponderosa Pine)



	Cases	% Area	% Pop.	Rate/10^6
Within buffer	37	29	14.6	1.71
Outside buffer	10	71	85.4	0.08
Total	47	100	100.0	

N
W E
S

0 20 40 80 120 160 Miles

Cases within 2.5 km buffer

Cases outside 2.5 km buffer

Habitat Buff)

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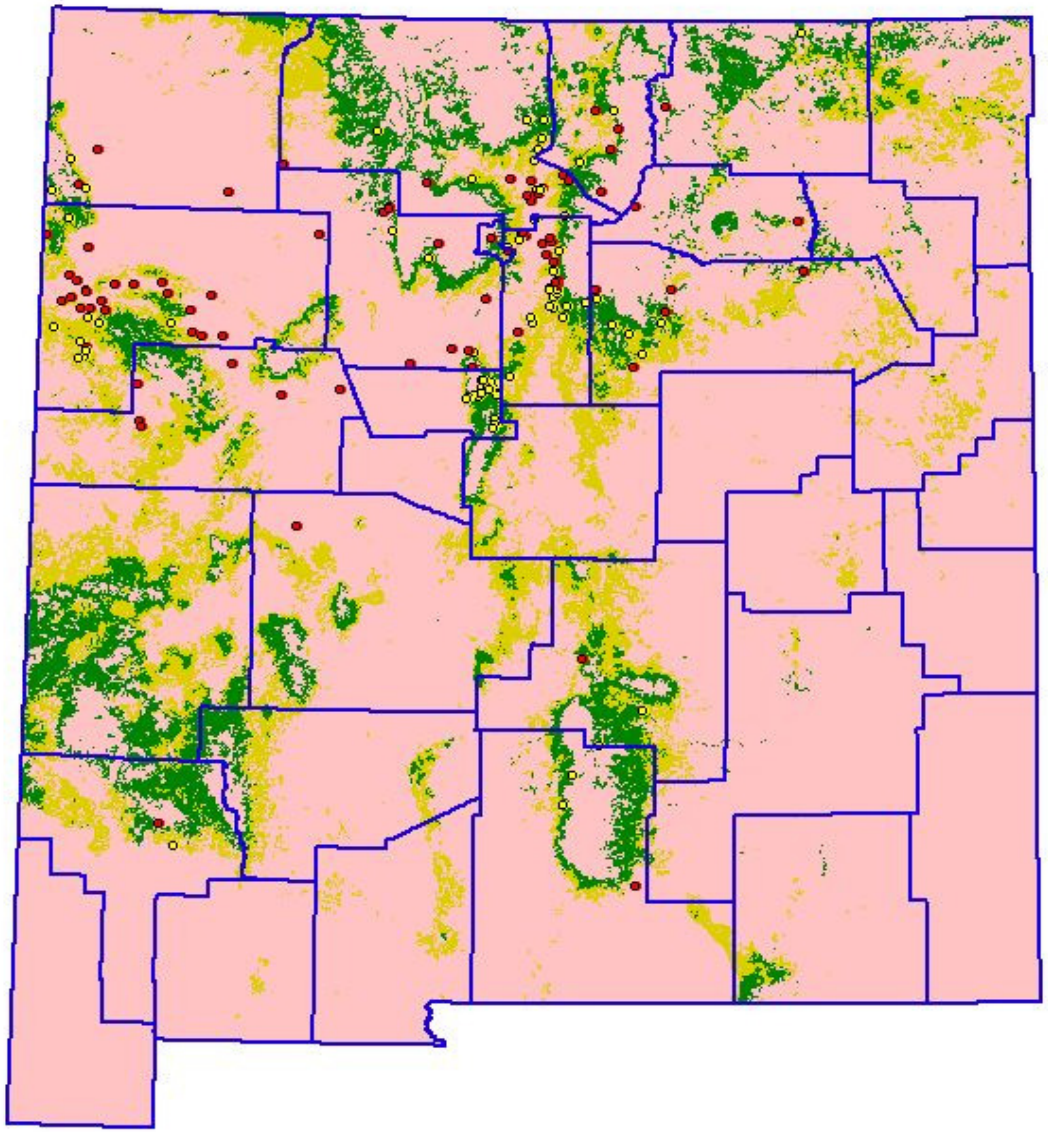
Human Plague Cases within Combined Rocky Mountain Great Basin Open and Closed Coniferous Woodlands



Cases within habitat
(49.2% of cases; 7.2% of population)

Cases outside habitat
(50.8% of cases; 92.8% of population)

County Boundaries

Rocky Mountain Great Basin
Closed Coniferous Woodland

Rocky Mountain Great Basin
Open Coniferous Woodland

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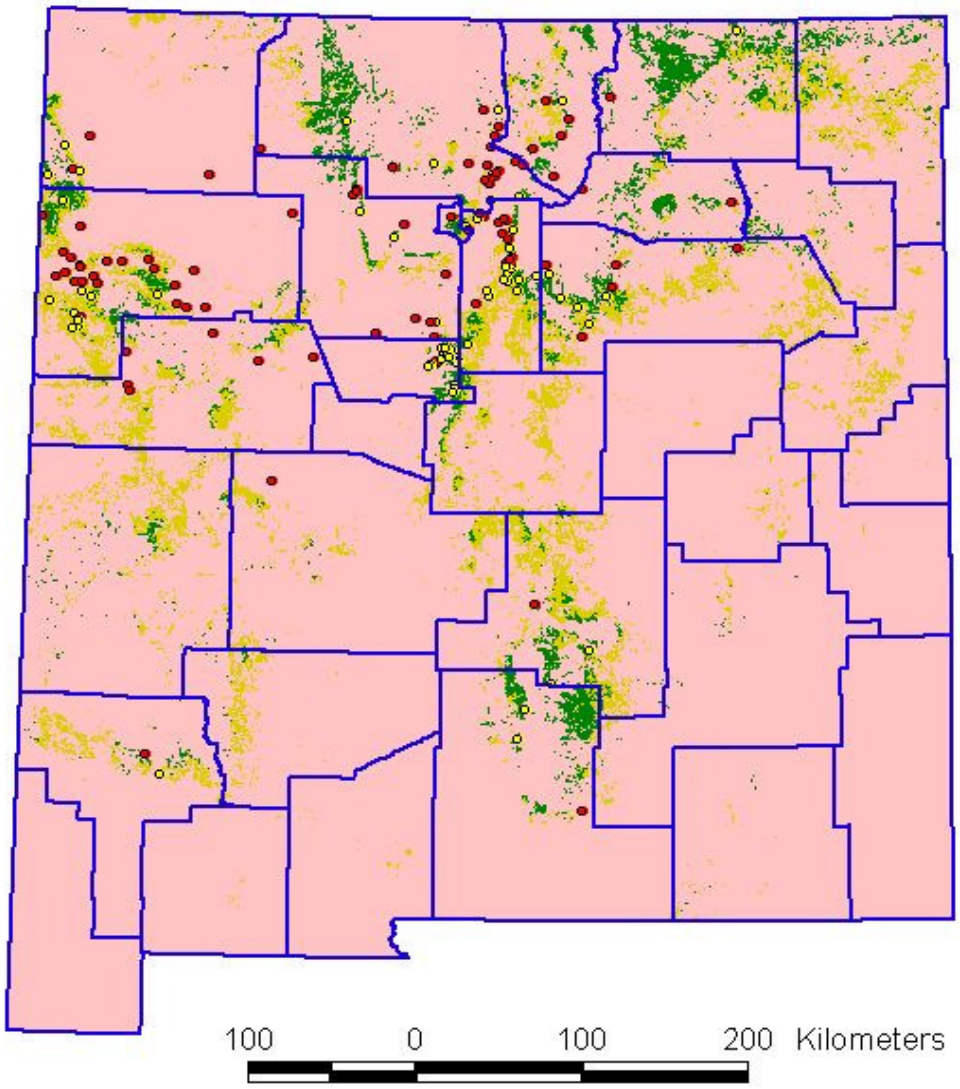
Human Cases and Rocky Mountain Great Basin Open and Closed Coniferous Woodlands (Private and Tribal Lands)



Human cases within habitats

Human cases outside habitats

County Boundaries

Private-Tribal Great Basin Open Coniferous Woodland

Private-Tribal Great Basin Closed Coniferous Woodlands

N

W E

S

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Logistic Regression Analyses of Human Plague in New Mexico (Eisen et al. – unpublished)

- Used logistic regression to develop a predictive model of areas at risk for human plague
- Compared the distribution of case points with random points generated using human population density data (Census)
- Used NM GAP Analysis data as habitat layers and USGS land stewardship information

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Random selection of control points, weighted by human population density in 1990

(R. Eisen et al. - unpublished)

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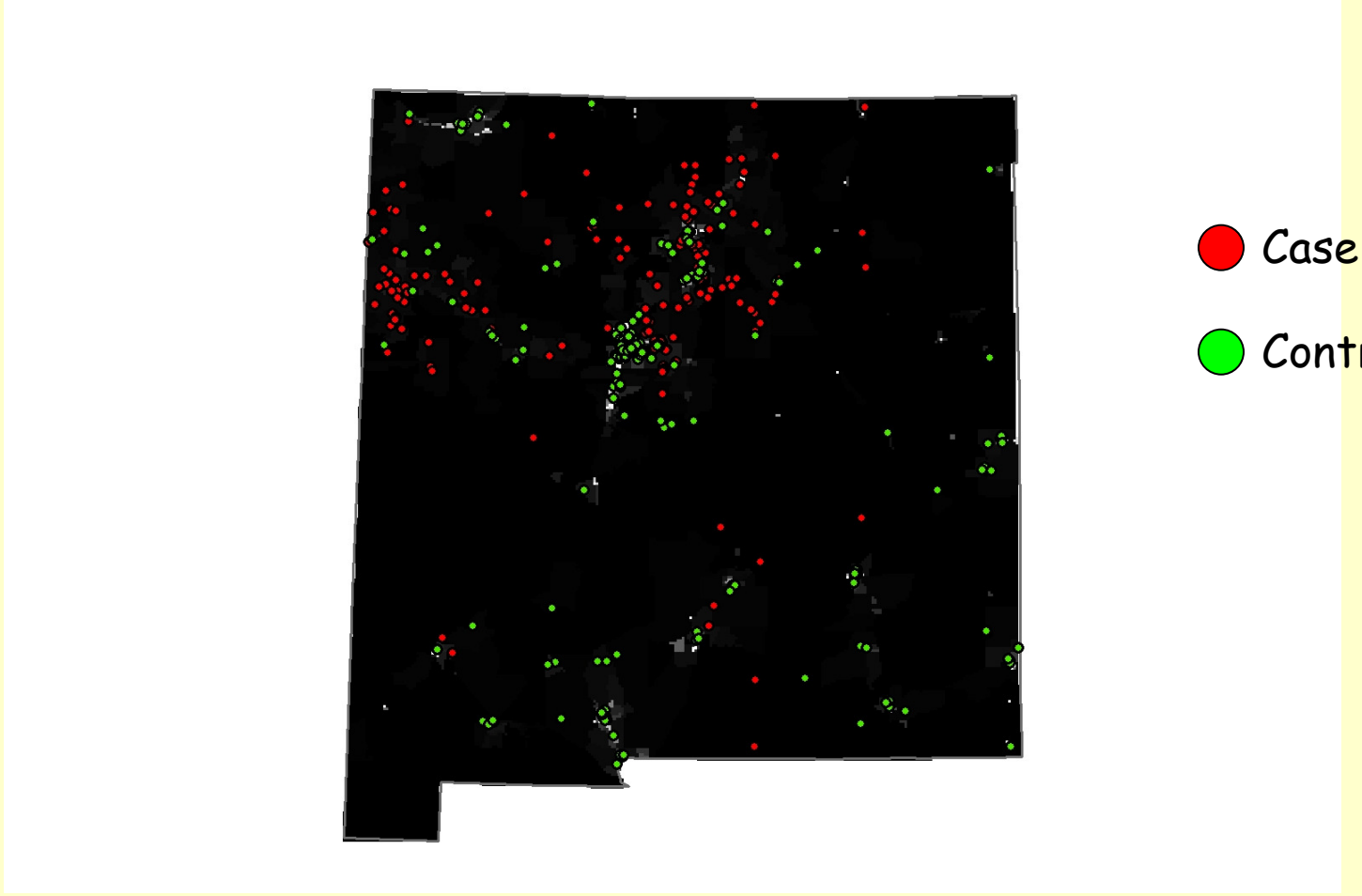
Random control point selection, weighted by human population density in 1990



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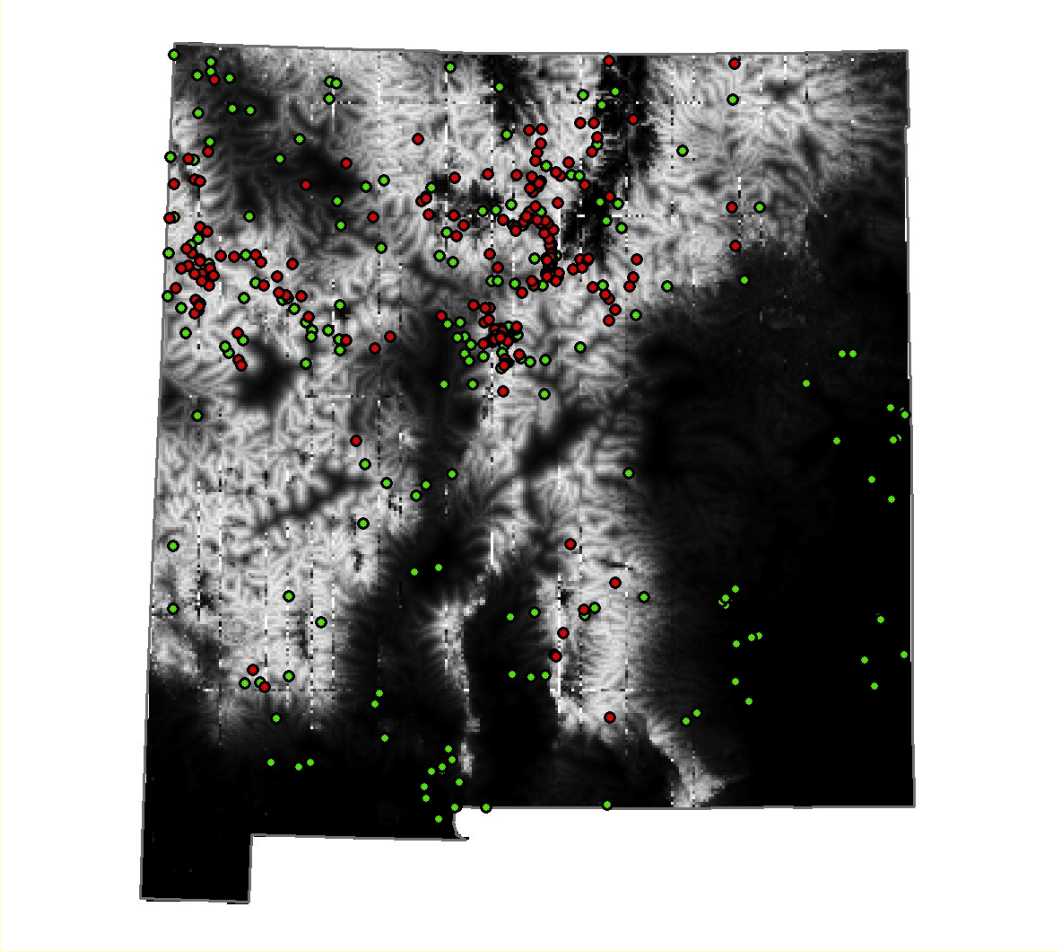
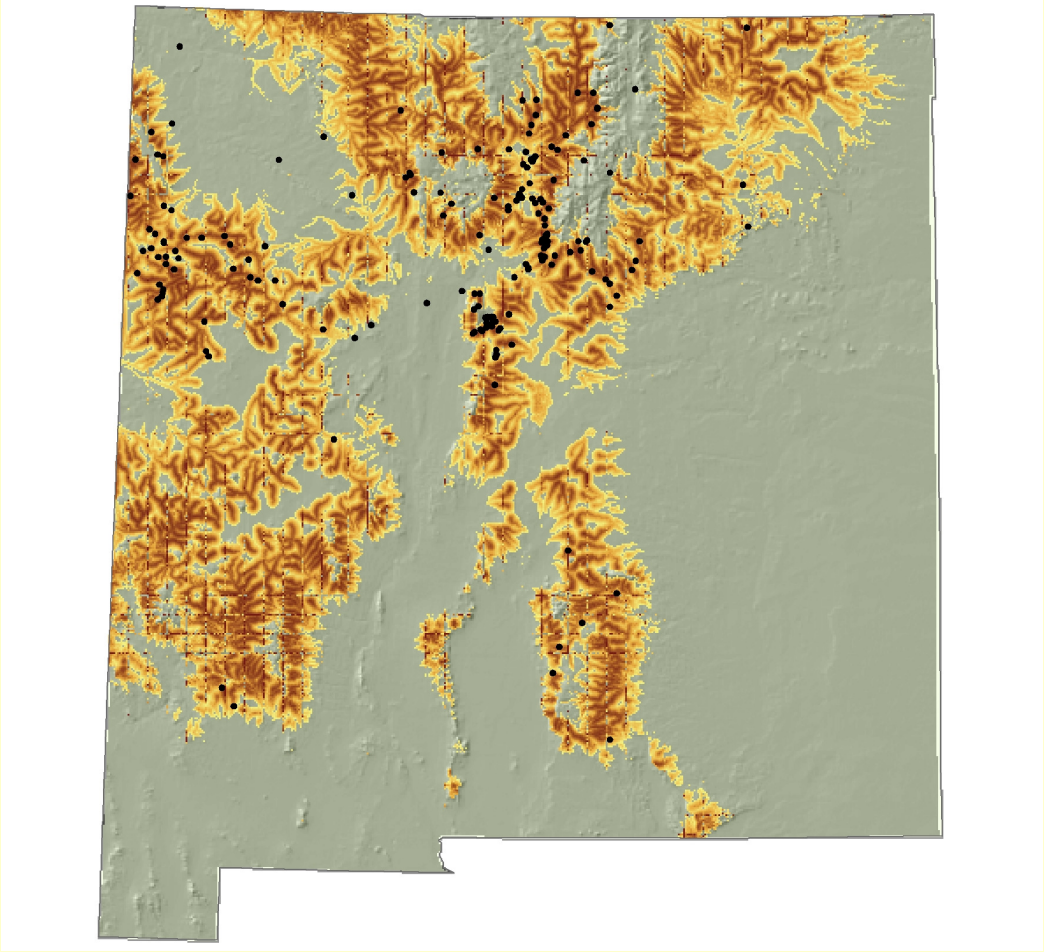
Peri-domestic plague risk increases with elevation (up to ~2,100 m), and is higher in close proximity to piñon-juniper ecotones and water

Covariates	k	neg_loglikelihood	AIC	delta AIC	AIC weight	lack of fit p-value	AUC
elevation + elevation^2 + dist to 3121_3122 ecotone + dist2 water	5	202.75	415.5	0	100	0.105	0.8
elevation + elevation^2 + dist to 3121_3122 ecotone	4	211.92	431.84	16.34	0	0.04	0.76
elevation + elevation^2	3	218.75	443.5	28	0	0.0035	0.73
elevation + dist to 3121 or 3122	3	225.79	457.58	42.08	0	0.005	0.73
elevation + distkeyhab	3	231.56	469.12	53.62	0	0.0007	0.7
elevation + distance to water	3	238.18	482.36	66.86	0	0.0002	0.73
elevation	2	247.7	499.4	83.9	0	<0.0001	0.68

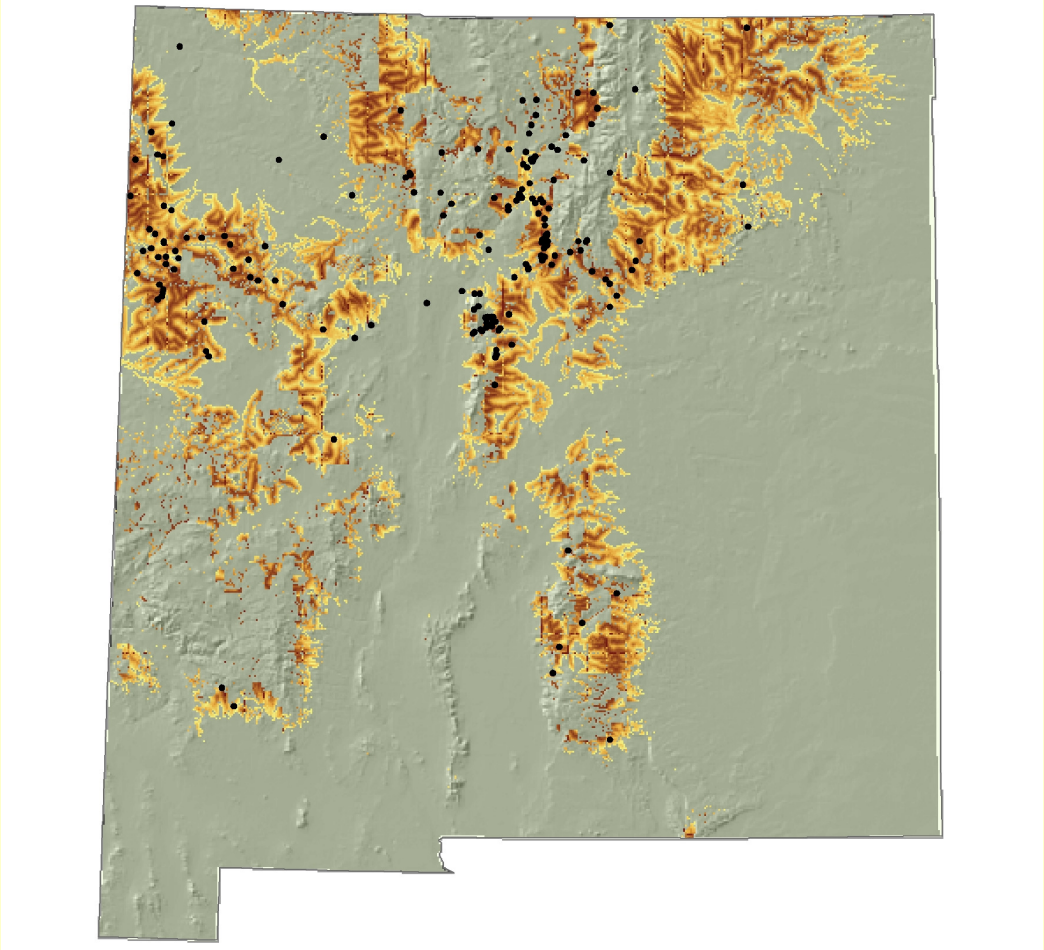
Probability of plague



35.1% of the state is classified as high risk plague habitat



19.4% of the state is classified as high risk plague habitat and is privately or tribally owned.



Model evaluation based on buildset and a probability cut-off value ≥ 0.4686

	Actual classification		
Model classification[a]	Human plague case	Control	% correct[b]
Human plague case	172	77	69.08
Control	23	118	83.69
% correct[c]	88.21	60.51	

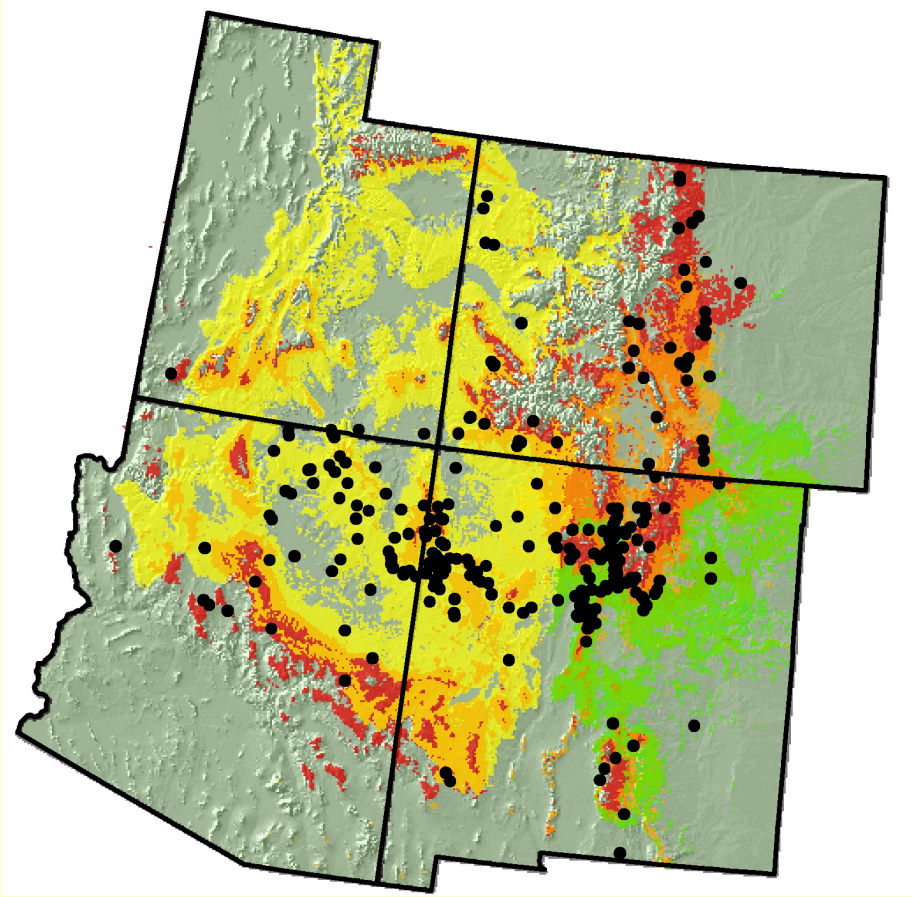
Logit (P) = -20.48 + (elevation * 0.020) – (elevation^2 * 0.0000047) - (distance to 3121_3122 ecotone * 0.000055) – (distance to water * 0.00029)

[a] Probability cut-off value used to classify a 30 m raster as suitable was based on the ROC optimal cut-off probability (P ≥ 0.4686).

[b] User accuracy (commission error).

[c] Producer accuracy (omission error).

Key habitat types



- Rocky Mtn. Ponderosa Pine
- So. Rocky Mtn. Pinyon-Juniper woodland
- Colorado Pinyon-Juniper woodland
- So. Rocky Mtn. Juniper woodland or savanna

Habitat categories derived from the Southwest Regional Gap Analysis (USGS)

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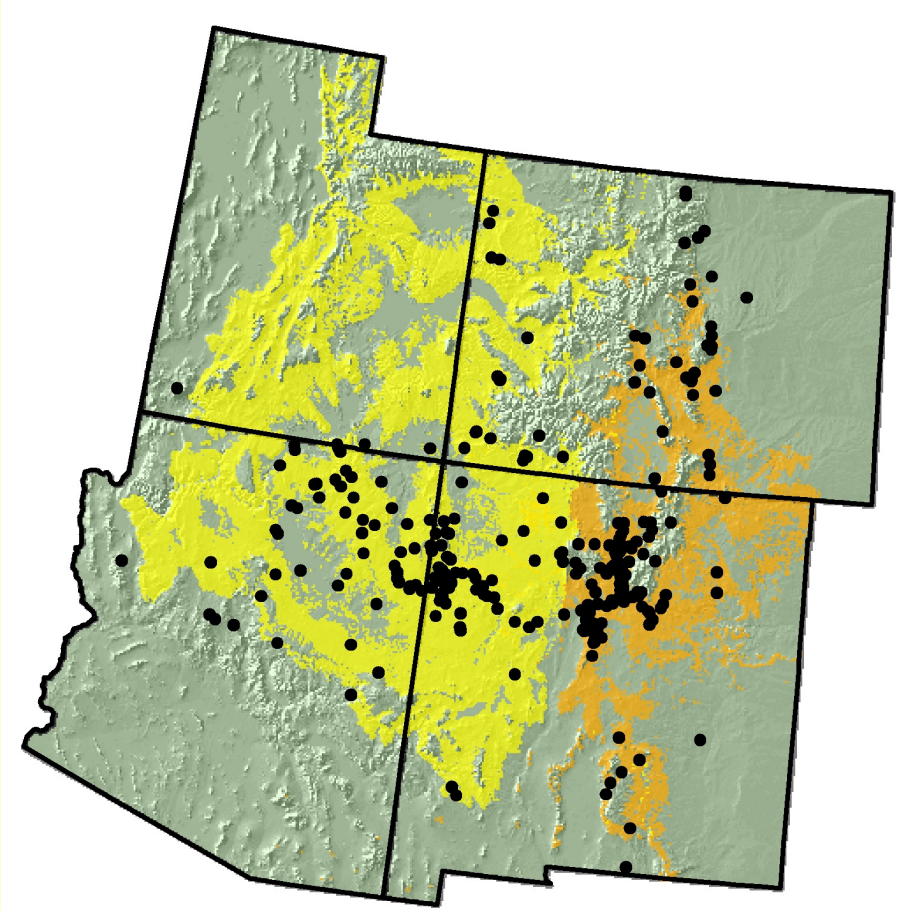
Pinyon-Juniper habitats



So. Rocky Mtn. Pinyon-Juniper woodland

Colorado Pinyon-Juniper woodland

Habitat categories derived from the Southwest Regional Gap Analysis (USGS)

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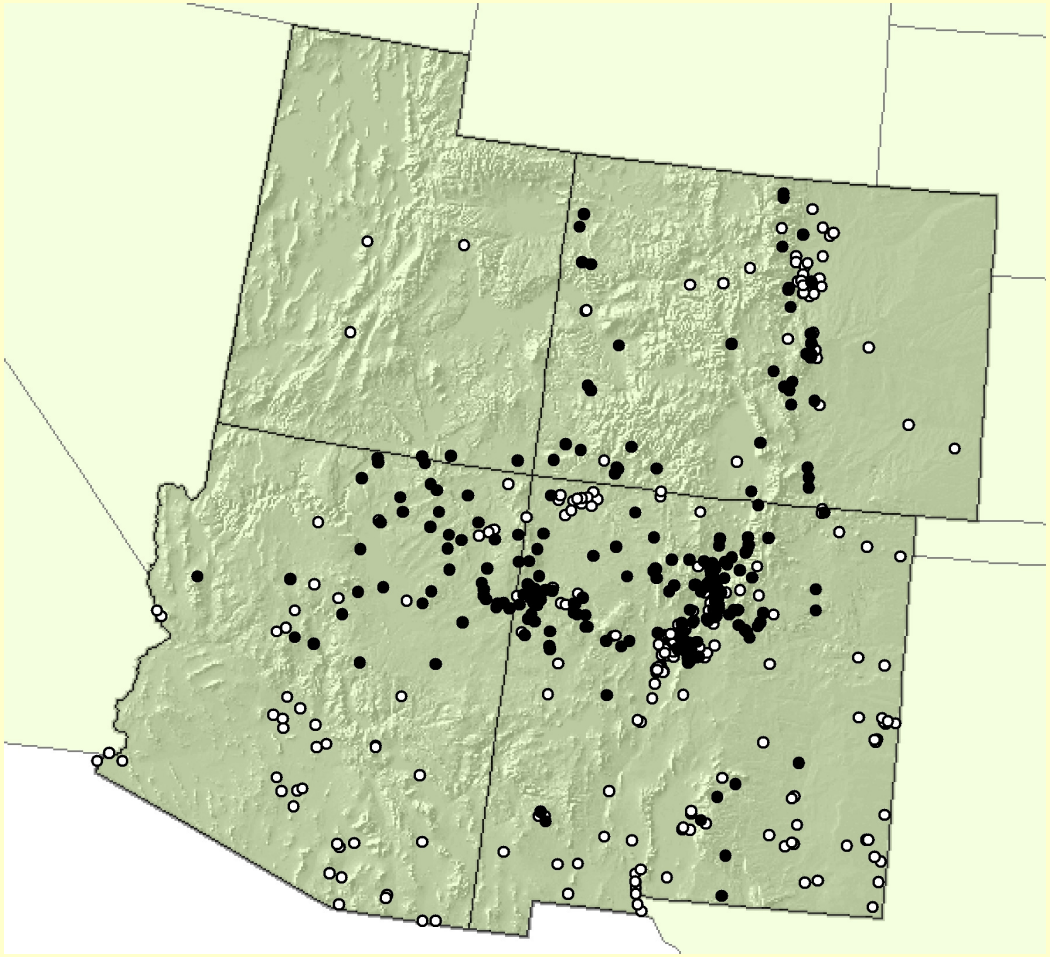
Cases and Controls, build set (recreational and peridomestic exposure)



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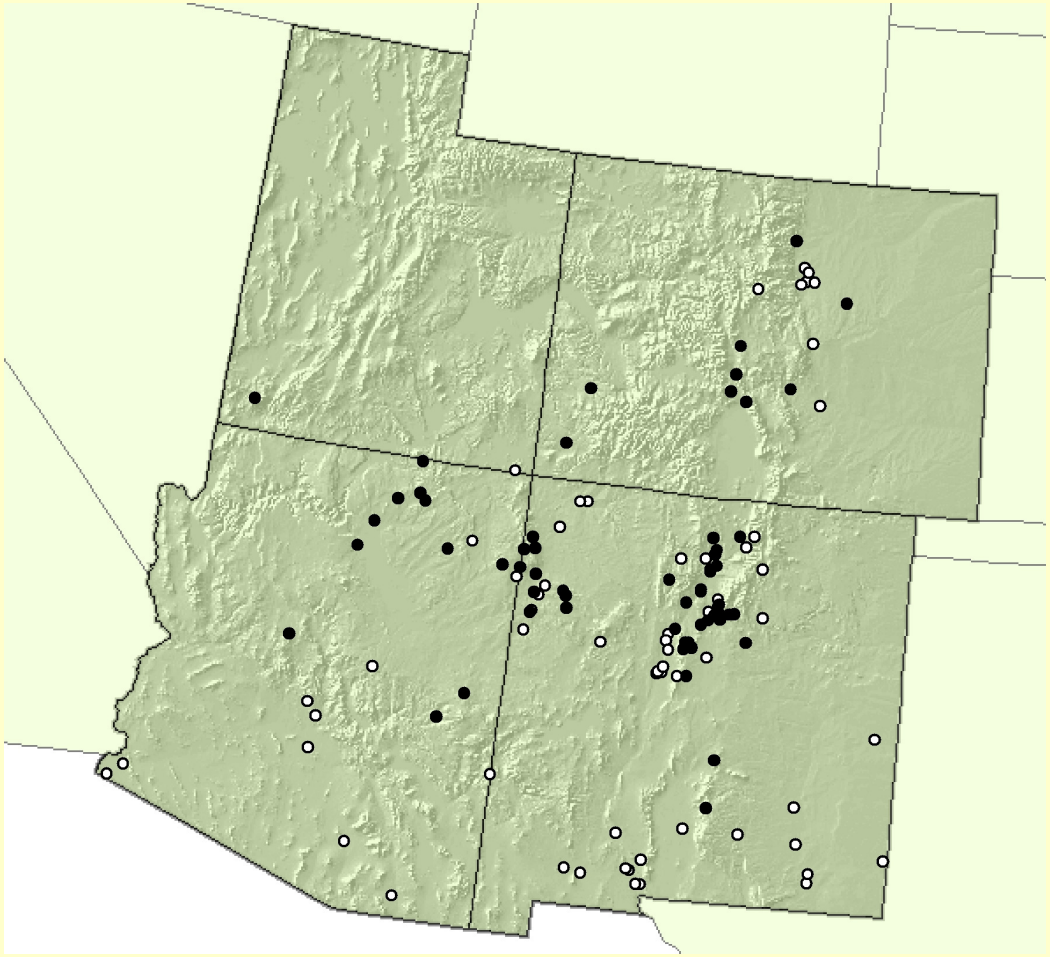
Cases and Controls, evaluation set (recreational and peridomestic exposure)



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Candidate Models

peridomestic and recreational exposure

Covariates	model #	k	neg_loglikelihood	AIC	delta AIC	AIC weight	lack of fit p-value	AUC
elevation + elevation^2 + dist to key habitat	1	4	252.15	512.3	0	0.9	0.3492	0.81
dist to key habitat	2	2	256.39	516.78	4.48	0.1	0.6657	0.81
elevation + elevation^2 + dist to pjwoodlands	3	4	261.98	531.96	19.66	0	0.1135	0.8
elevation + elevation^2	4	3	263.79	533.58	21.28	0	0.1132	0.8
dist to pjwoodlands	5	2	285.1	574.2	61.9	0	0.062	0.8

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Evaluation matrix, buildset

peridomestic and recreational exposure

	Actual classification		
Model classification[a]	Human plague case	Control	% correct[b]
High risk plague habitat	205	71	74.28
Not high risk	48	182	79.13
% correct[c]	81.03	71.94	

[a] Probability cut-off value used to classify a 30 m raster as suitable was based on the ROC optimal cut-off probability ($P \geq 0.6409$).
[b] User accuracy (commission error).
[c] Producer accuracy (omission error).

$$\text{Logit}(P) = -8.80 + (\text{elevation} * 0.008971) - (\text{elevation}^2 * 0.000002) - (\text{distance to key habitat} * 0.0003225)$$

Evaluation matrix, evaluation set

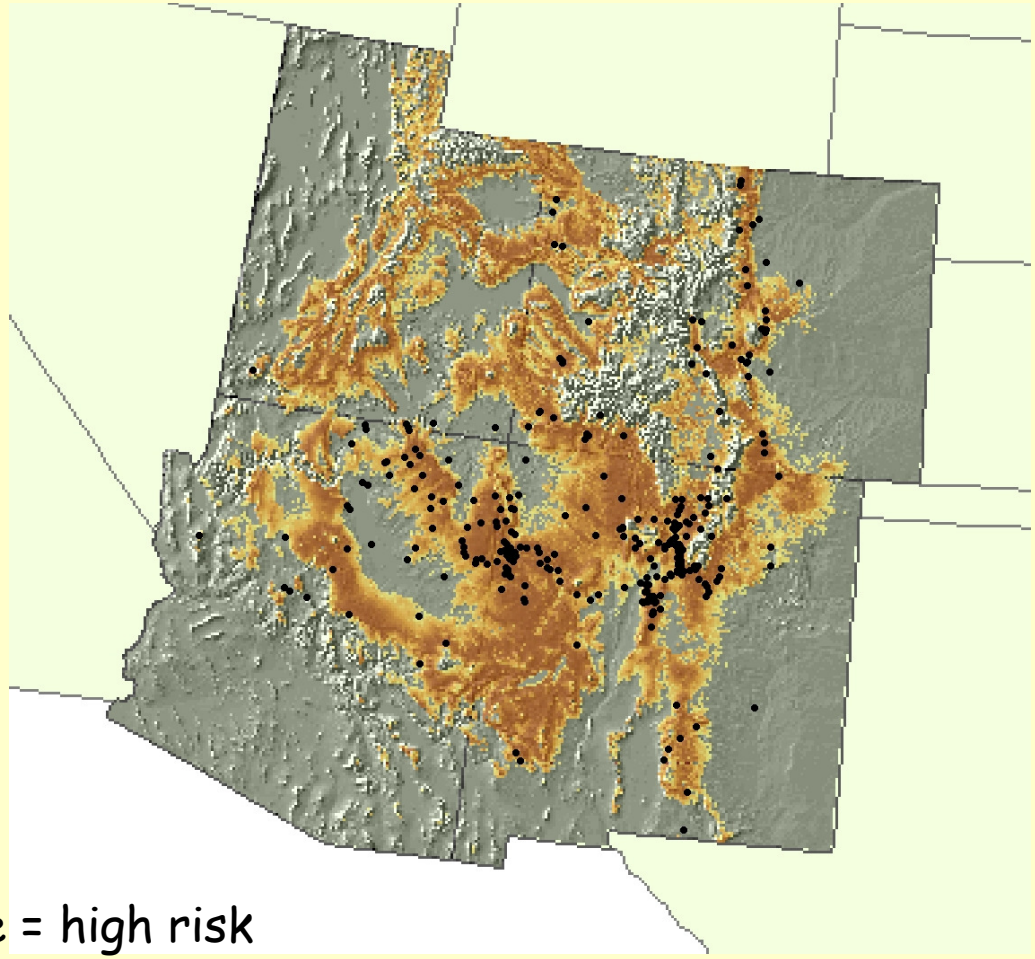
peridomestic and recreational exposure

	Actual classification		
Model classification[a]	Human plague case	Control	% correct[b]
High risk plague habitat	52	19	73.24
Not high risk	11	44	80.0
% correct[c]	82.54	69.84	

[a] Probability cut-off value used to classify a 30 m raster as suitable was based on the ROC optimal cut-off probability ($P \geq 0.6409$).
[b] User accuracy (commission error).
[c] Producer accuracy (omission error).

$$\text{Logit}(P) = -8.80 + (\text{elevation} * 0.008971) - (\text{elevation}^2 * 0.000002) - (\text{distance to key habitat} * 0.0003225)$$

Probability of plague (recreational and peridomestic exposure) within high risk plague habitat (P>0.6409)



35.14% of image = high risk

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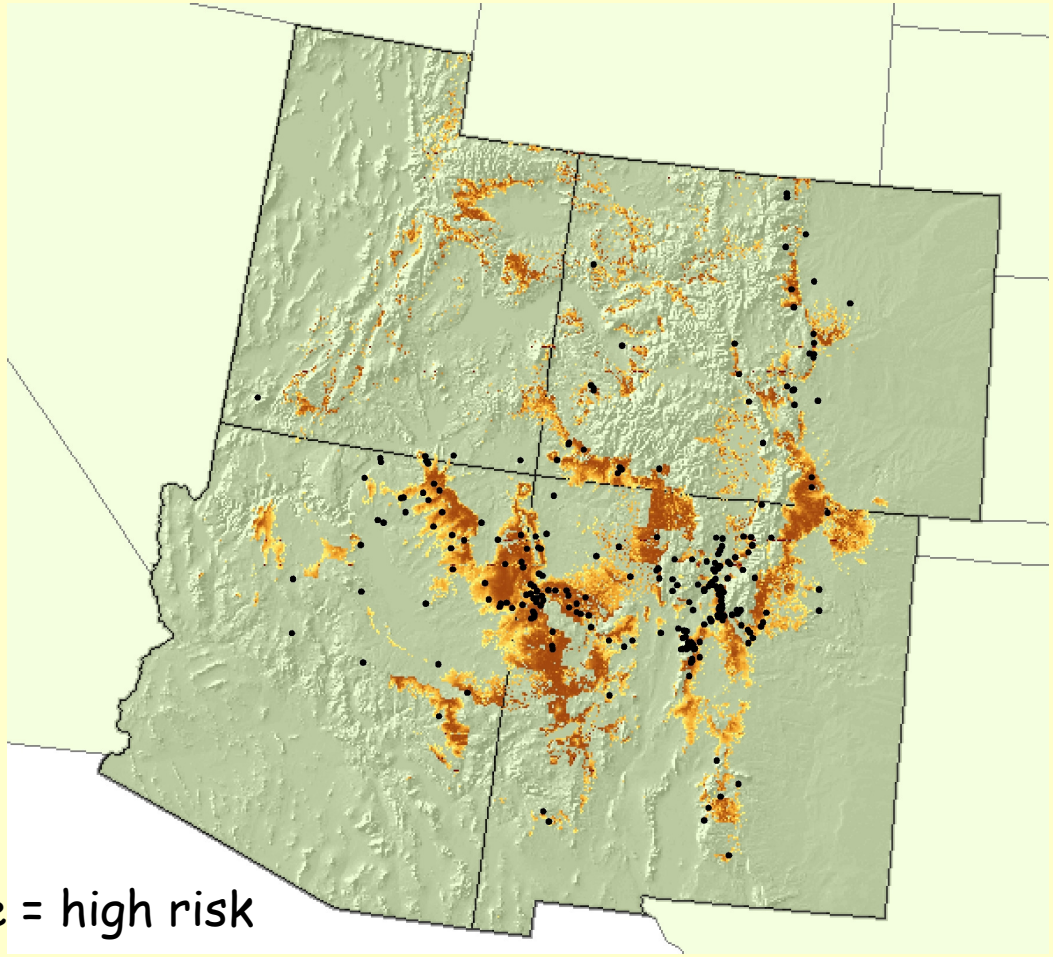
Probability of plague within high risk, non-federally owned plague habitat (P>0.6690)



11.65% of image = high risk

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Our model identified landscape features associated with human plague cases

- Plague risk increases up to an elevation of approximately 2,300 m and declines as elevation increase thereafter.

- Plague risk is highest in southern Rocky Mtn. PJ, Colorado PJ woodlands, Rocky Mtn. Ponderosa pine, or So. RM PJ woodlands or savanna habitats and decreases with distance away from these habitats.

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Ecological Niche Modeling

- Often referred to as GARP (Genetic Algorithm for Rule set Prediction)
- Uses an iterative, AI-based approach with four types of algorithms (Atomic, logistic regression, bioclimatic envelope and negated bioclimatic envelope) to produce component rules in a broader rule
- Inputs are data layers providing spatial information on various environmental parameters (vegetation types, greenness indices, climatic variables, elevation, slope, aspect, etc.)
- Identifies non-random correlations between the environmental parameters and the presence or absence of the species or phenomenon of interest
- Model outputs represent environmental conditions where species should be able to maintain populations
- Check fit of models using test points (20-50% of points withheld at random from original set or use points from new region)
- Used successful to identify sites of likely species invasions, organism distributions and risk areas for disease (Chagas' disease, filovirus infections, etc.)

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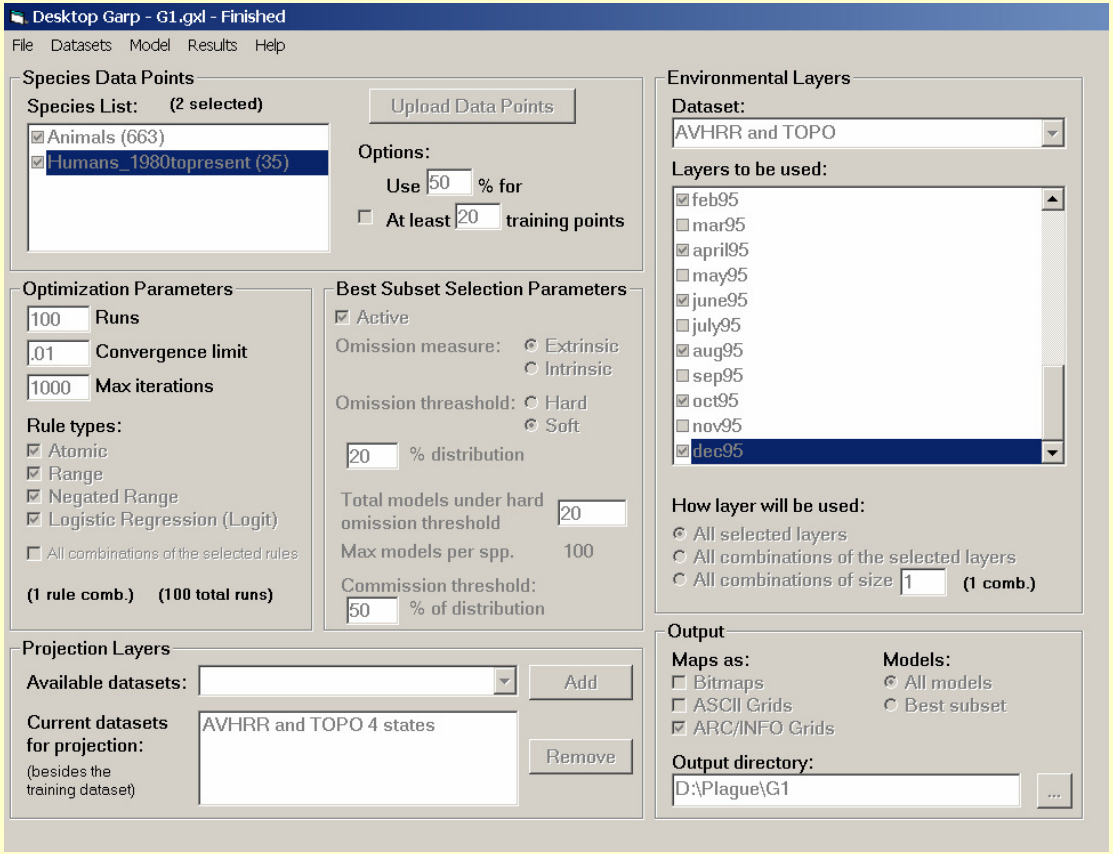
Ecological Niche Model for Human Plague in Colorado

Model Constructed Using

- Human case exposure site data (point occurrences in Colorado 1980-2004)
- Elevation, slope, aspect
- NDVI values from (AVHRR)
- Similar environmental parameters used for modeling entire Four Corners region (NM, CO, AZ, UT)
- 50% of cases used as training points



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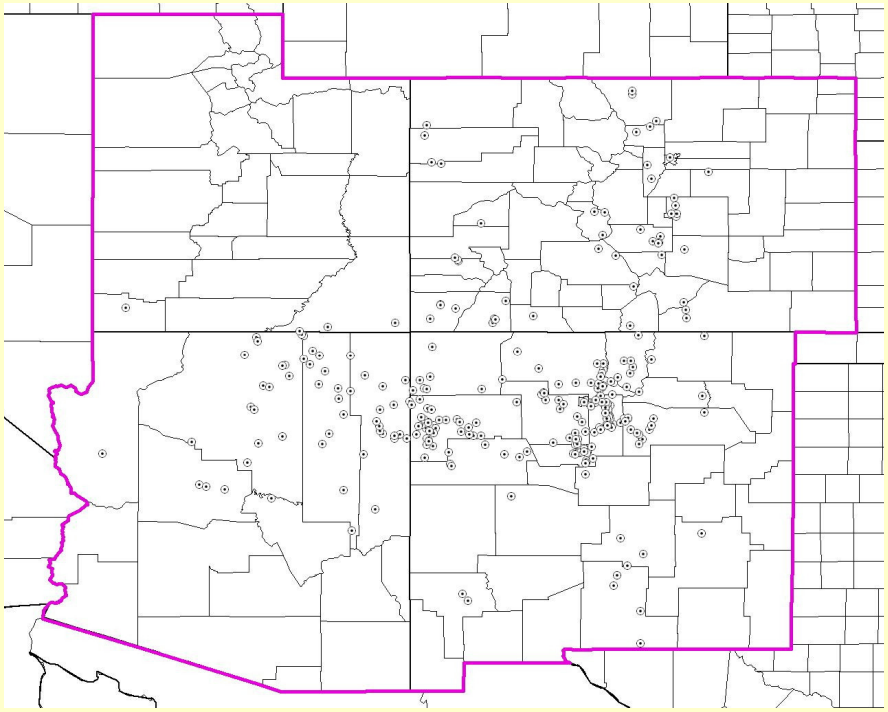
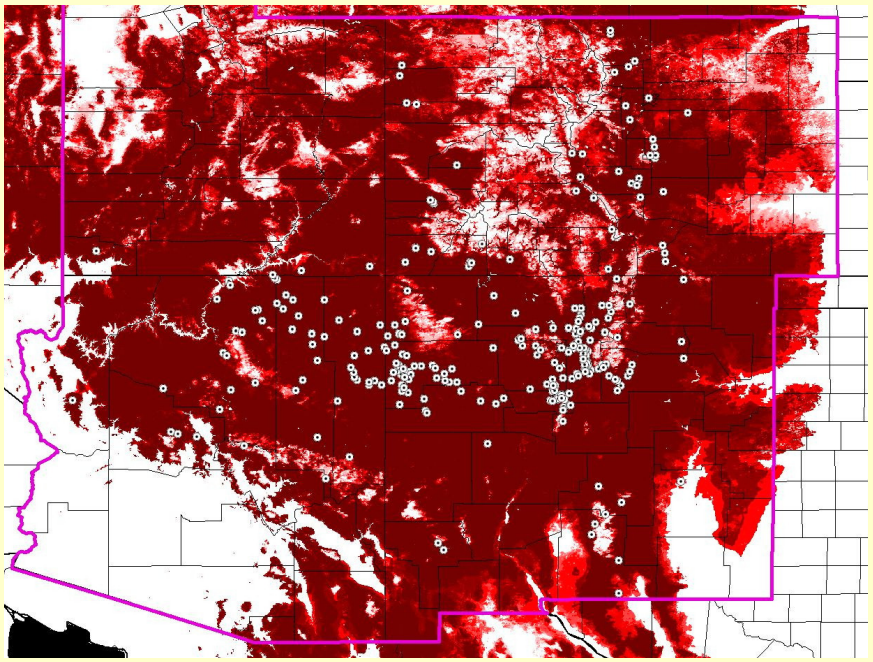
Four Corners model made with case exposure points from all 4 states (NM, UT, AZ, and CO)





- Highly significant results ($p << 0.00001$ or less for each of top 10 models)
- 97.5% of test points included in high risk area
- Approximately 68% of region in risk area

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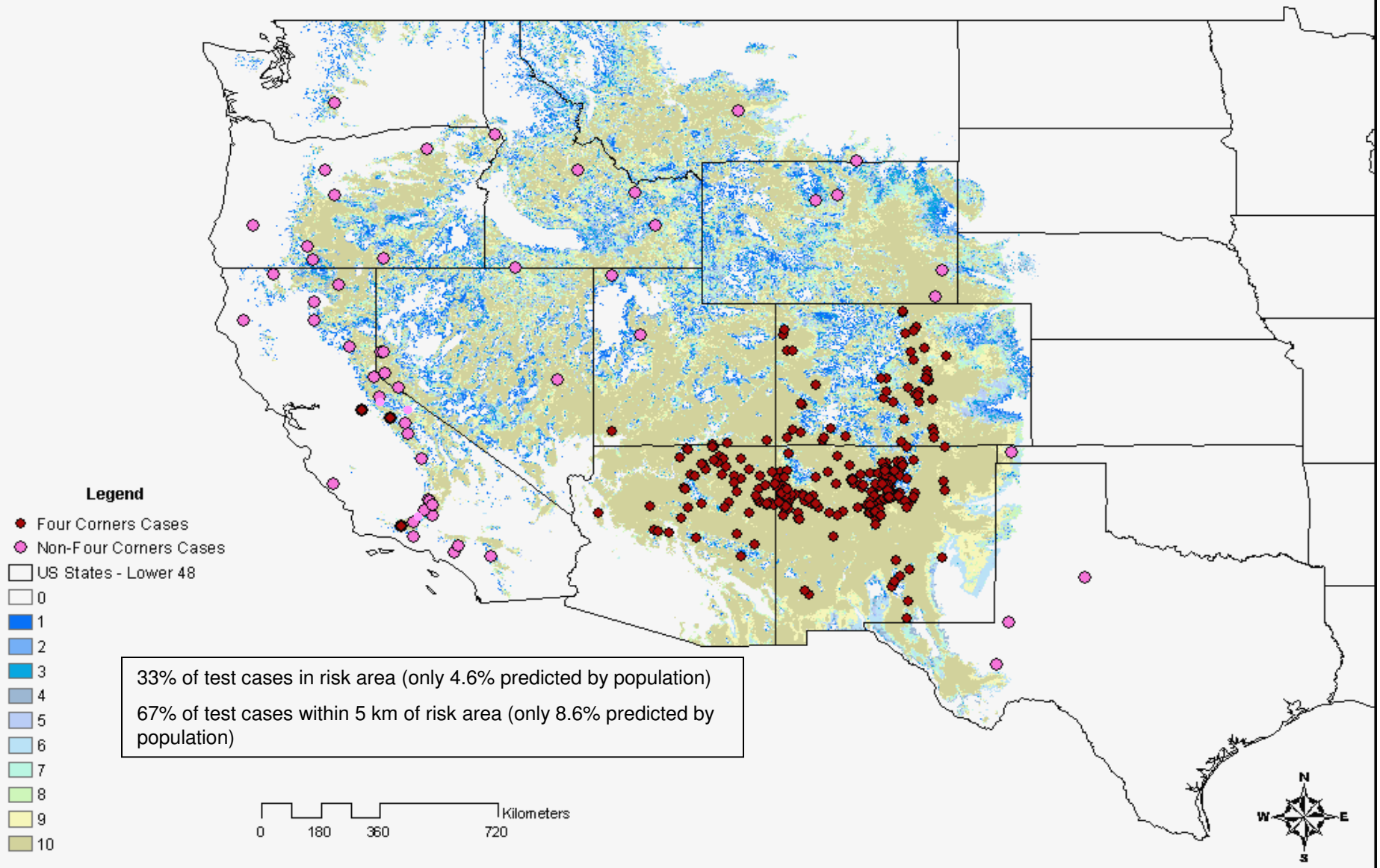
GARP Model Based on Four Corners States' Human Case Exposure Sites (Image shows composite of 10 best models)



Plague in North America

- U.S. - Commonly found in western states
- Mexico –
  - Single report of infected *Cynomys mexicanus*
  - Evidence of *Y. pestis* infection identified in U.S. border counties
- Canada –
  - Previous reports in ground squirrels in Alberta
  - Suspect human case in Alberta (1939)
  - Wood rat positives in British Columbia (Morshed pers comm)
  - Leighton et al. (2001) report of seropositive cats and dogs in southwestern Saskatchewan and Alberta
  - Evidence of *Y. pestis* infection near U.S. border counties

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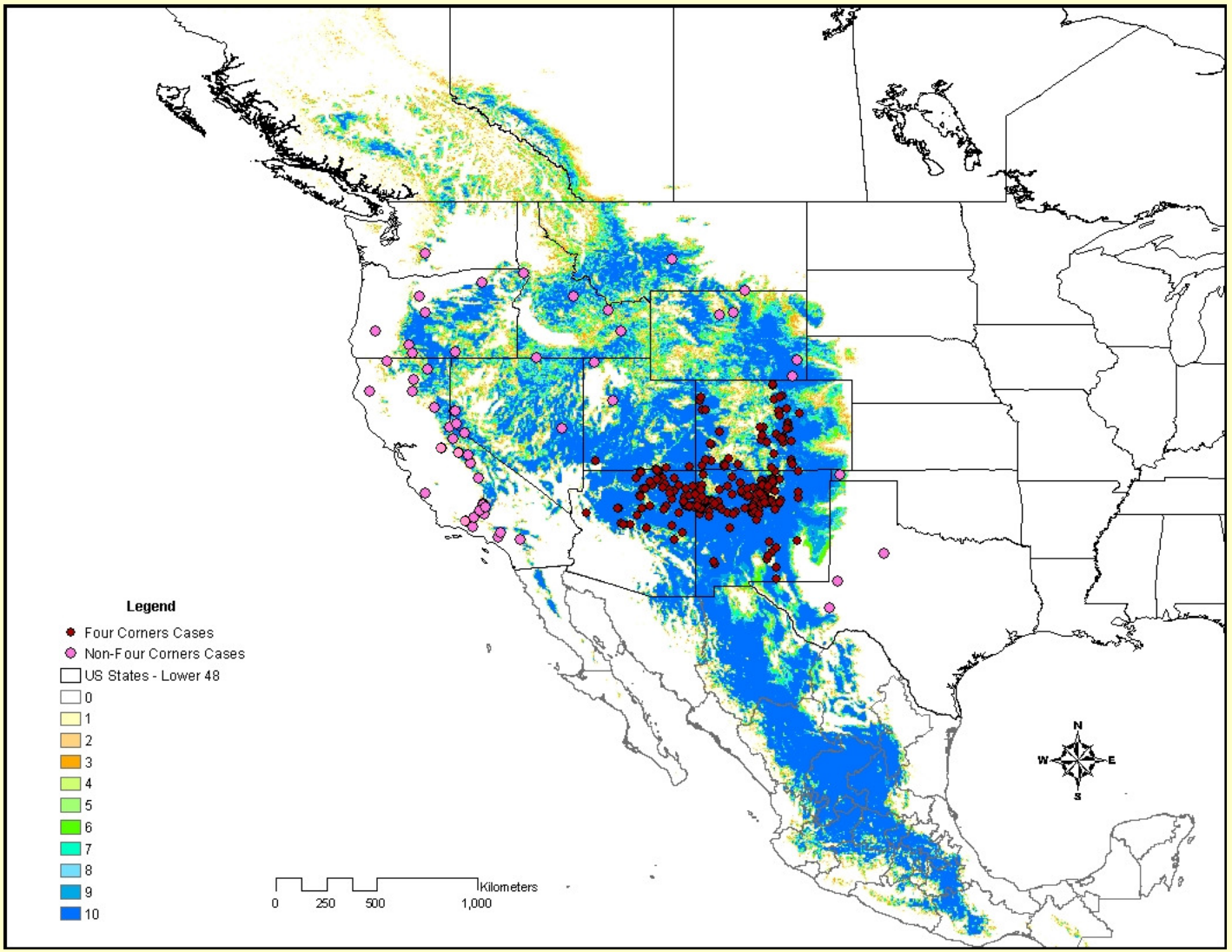

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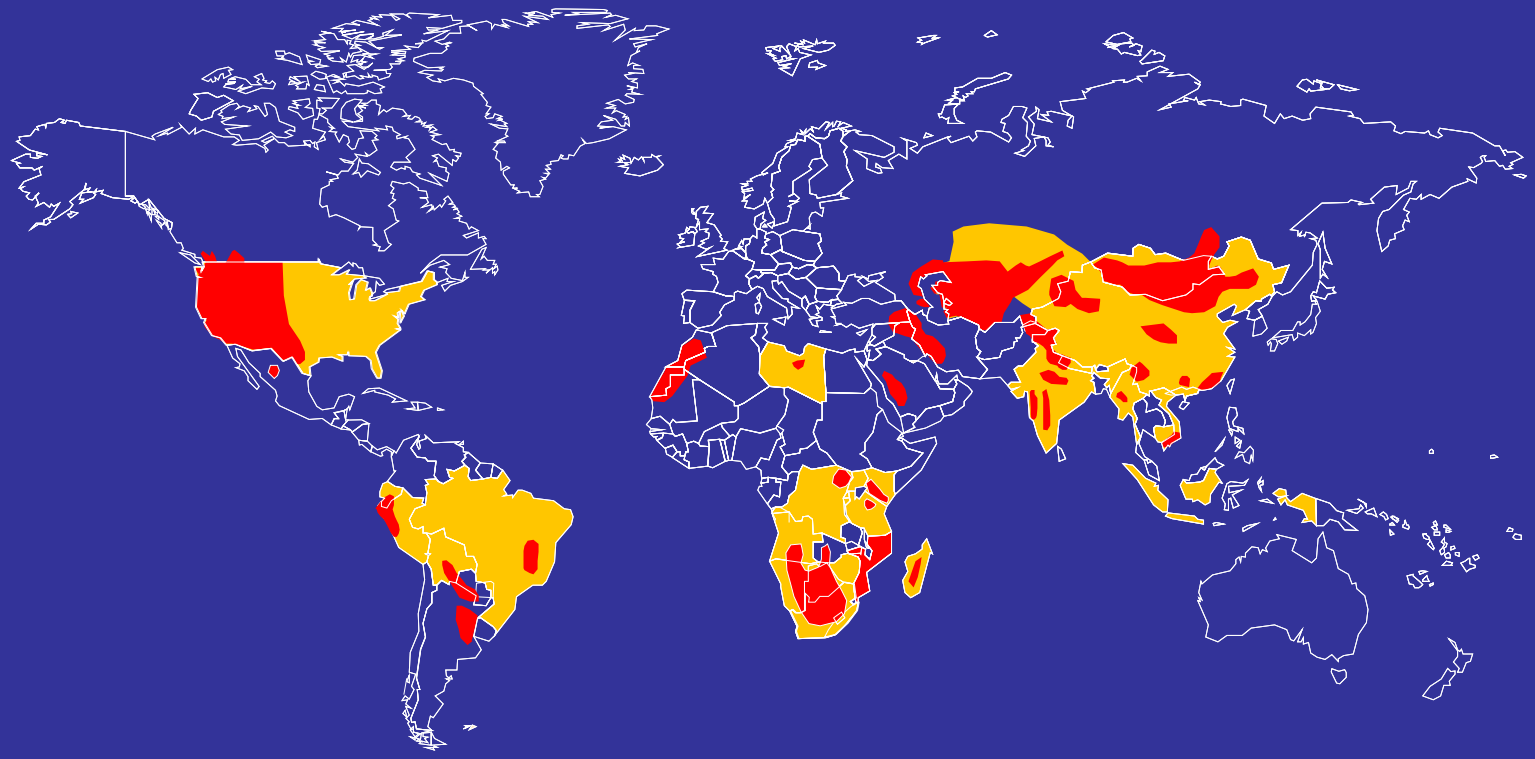

Countries reporting plague, 1970-2000

Probable Sylvatic foci

Compiled from WHO, CDC, and country sources

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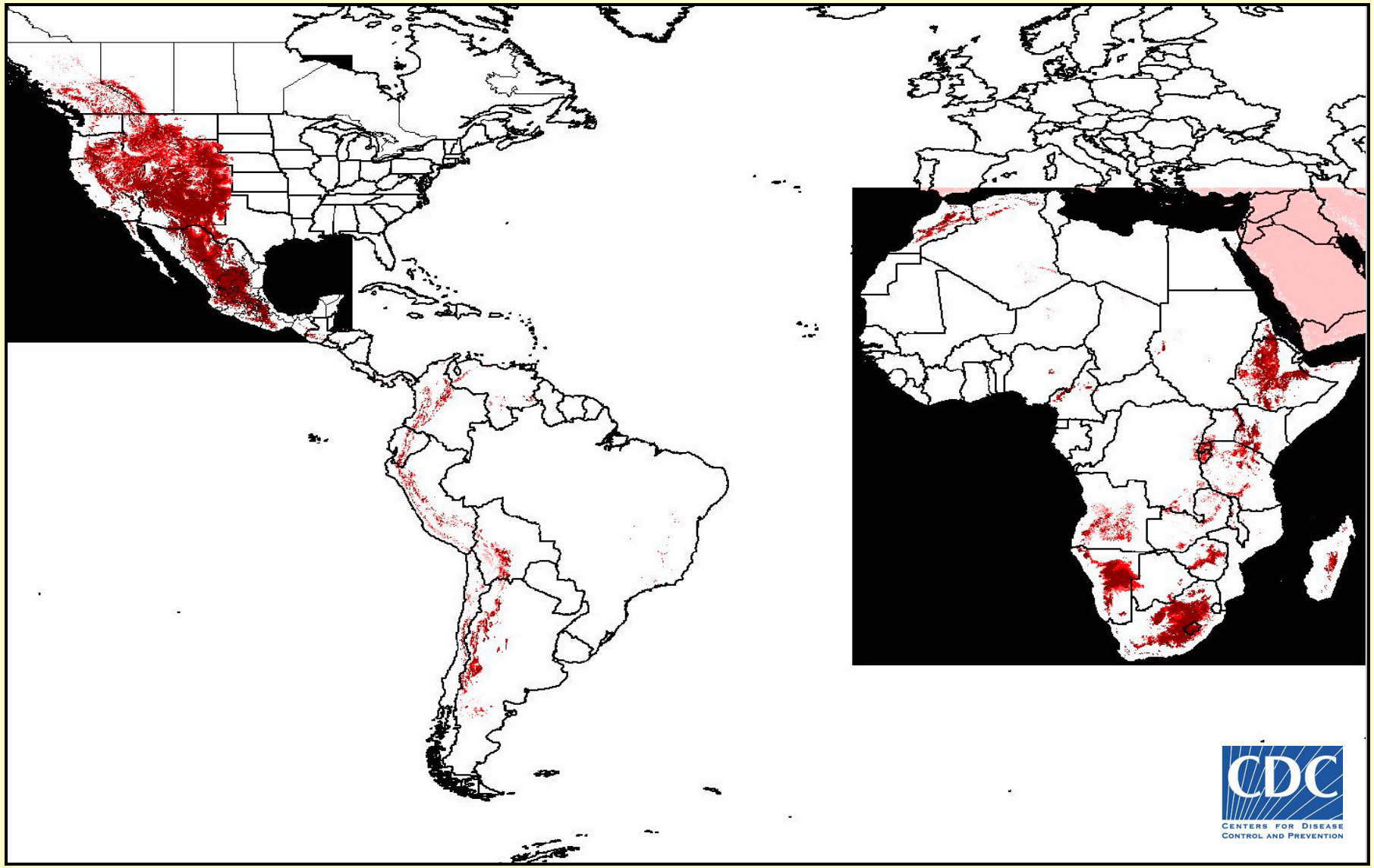
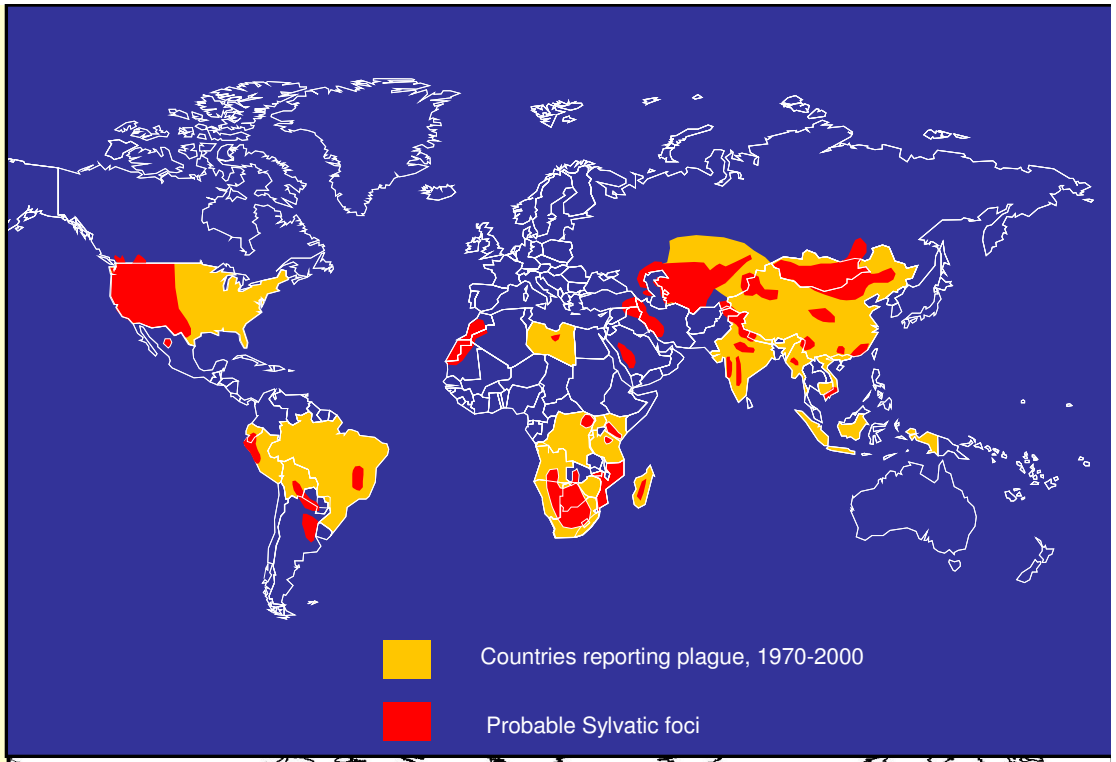
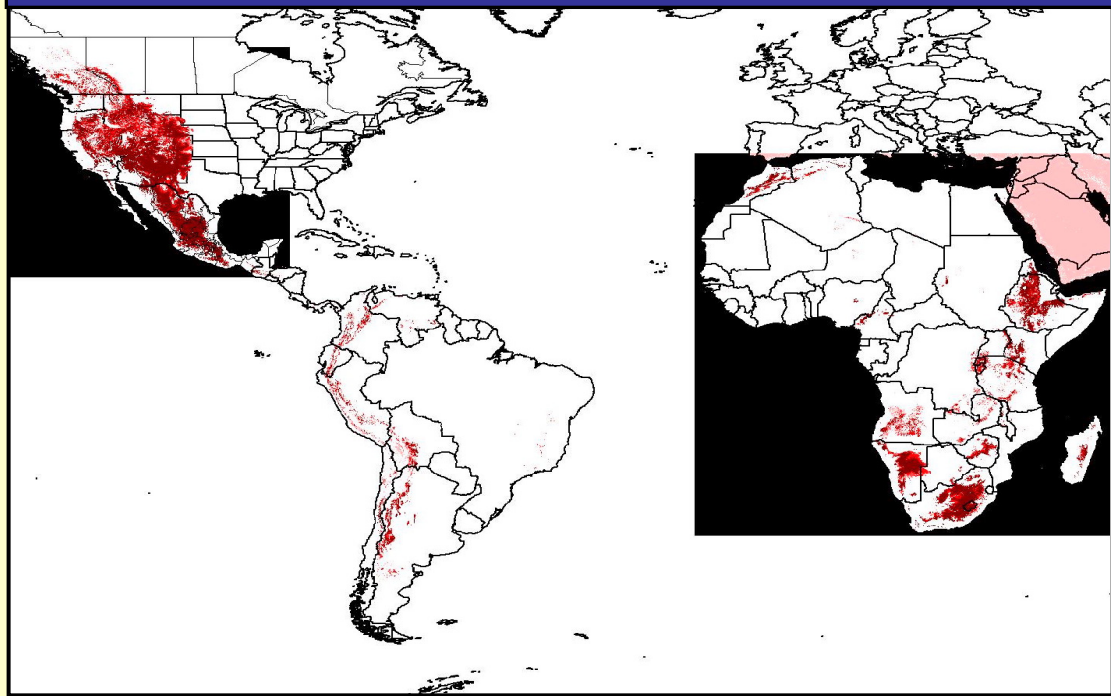
Four Corners GARP model projected to South America and Africa



Comparison of World Plague Map with 4-Corners Model Projected to Africa and South America

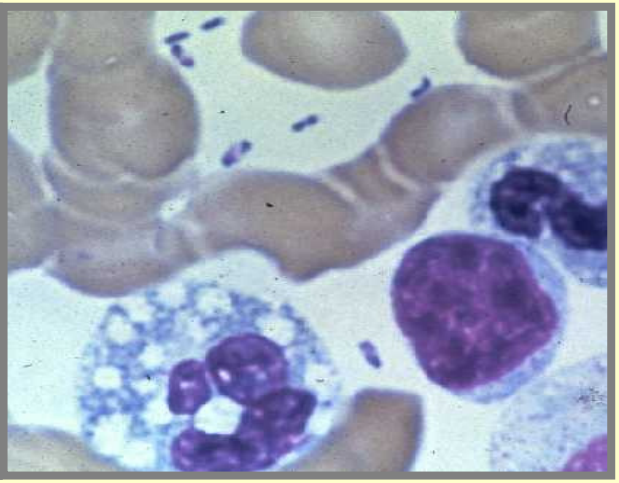




PLAGUE PREVENTION

Fuge cito, vade longe, rede tarde





Flee quickly, go far, return slowly

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