

INCIDENCE OF PLAGUE ASSOCIATED WITH INCREASED WINTER-SPRING PRECIPITATION IN NEW MEXICO

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Abstract. Plague occurs episodically in many parts of the world, and some outbreaks appear to be related to increased abundance of rodents and other mammals that serve as hosts for vector fleas. Climate dynamics may influence the abundance of both fleas and mammals, thereby having an indirect effect on human plague incidence. An understanding of the relationship between climate and plague could be useful in predicting periods of increased risk of plague transmission. In this study, we used correlation analyses of 215 human cases of plague in relation to precipitation records from 1948 to 1996 in areas of New Mexico with history of human plague cases (38 cities, towns, and villages). We conducted analyses using 3 spatial scales: global (El Niño–Southern Oscillation Indices [SOI]); regional (pooled state-wide precipitation averages); and local (precipitation data from weather stations near plague case sites). We found that human plague cases in New Mexico occurred more frequently following winter-spring periods (October to May) with above-average precipitation (mean plague years = 113% of normal rain/snowfall), resulting in 60% more cases of plague in humans following wet versus dry winter-spring periods. However, we obtained significant results at local level only; regional state-wide precipitation averages and SOI values exhibited no significant correlations to incidence of human plague cases. These results are consistent with our hypothesis of a trophic cascade in which increased winter-spring precipitation enhances small mammal food resource productivity (plants and insects), leading to an increase in the abundance of plague hosts. In addition, moister climate conditions may act to promote flea survival and reproduction, also enhancing plague transmission. Finally, the result that the number of human plague cases in New Mexico was positively associated with higher than normal winter-spring precipitation at a local scale can be used by physicians and public health personnel to identify and predict periods of increased risk of plague transmission to humans.

Global climate dynamics are proposed by some to be responsible for recent outbreaks of infectious diseases, and others warn that long-term global warming could increase the risks of acquiring such diseases.^{1–6} Data on the relationships between global warming and disease outbreaks are scarce,⁷ however, and our understanding of this topic would be improved by additional insights into the effects of short-term climatic phenomena, such as El Niño, on the occurrence of disease outbreaks. For example, recent epidemics of hantavirus pulmonary syndrome (HPS) in the American southwest^{8,9} and malaria epidemics in Asia and Venezuela^{10,11} were reported to be associated with the El Niño events of 1992–1993 and 1997–1998, presumably because favorable weather led to population increases and temporary range extensions of rodent hosts and mosquito vectors, respectively. These well-publicized examples raise the question as to what extent climate plays a role in outbreaks of other diseases, particularly those associated with reservoirs or vectors that respond rapidly to periodic increases or decreases in rainfall and/or temperatures.

The role of climate dynamics, especially precipitation variability, in influencing small mammal population fluctuations is well established. The recent El Niño events of the 1990s (with attendant increases in rainfall) have been associated with large increases in rodent populations in both North and South America,^{8,12} and precipitation increases in the American southwest have been shown to result in rodent density increases following 3–6-month lag periods.¹³ Rodent population increases, in turn, have been correlated with numerous diseases, including HPS, Lyme disease, nephropathia epidemica, myocarditis, Guillain-Barré syndrome, and insulin-dependent diabetes mellitus^{8,9,14–16} (although cause-effect

mechanisms have only been identified in some of these diseases). Therefore, it stands to reason that there should be a statistical linkage between climate and zoonotic diseases, as mediated at least in part by the abundance of the hosts of these diseases. If true, climate measures may provide a forecasting tool for identifying periods of increased risk of disease transmission.

Plague was introduced into North America via San Francisco, California in 1899–1900 by shipboard transport of plague-infected rats from Asia.¹⁷ Having quickly infected the native mammal populations (particularly ground squirrels), plague spread throughout western North America. Field surveys for plague in small mammals during the 1930s and 1940s showed plague to be present in many western states, including 20 counties in New Mexico (a total of 19 species of mammals in New Mexico were found to be plague-infected at that time).¹⁷ Plague is now most commonly found in the southwestern United States, principally in New Mexico, Colorado, Arizona, and California.¹⁸ Plague is caused by the bacterium *Yersinia pestis* and is commonly transmitted to humans by fleas from wild and commensal rodents.¹⁸ Major risk factors for humans contracting plague include contact with diseased wild mammals and/or their infected fleas, and exposure to infected fleas carried by mammalian pets (principally dogs and cats).^{19,20} If climatic conditions become favorable for reproduction and survival of either the wild mammal populations or their flea populations, then these animal populations will naturally increase, thereby enhancing the probability of human infection via animal-flea-human contacts.

In this report, we examine the role of precipitation patterns as they relate to the occurrence of human cases of

plague in New Mexico. We have chosen plague for our analyses due to the relatively large number of human plague cases in New Mexico (55% of all cases in the United States), the exceptionally complete and detailed records of these cases, and the extensive network of long-term weather stations throughout New Mexico. We have addressed the overall hypothesis that there is a positive relationship between precipitation and incidence of human plague cases in New Mexico, and have examined this relationship using 3 spatial scales of precipitation indices: 1) local, site-specific precipitation amounts where actual human plague cases have been recorded; 2) regional state-wide precipitation averages for New Mexico; and 3) the El Niño–Southern Oscillation Index [SOI], which is an indicator of the strength of El Niño events. El Niño conditions result in increased precipitation over much of the American southwest during the winter-spring period (October to May) of the El Niño year; conversely, La Niña conditions (the opposite of El Niño) result in drier than normal winter-spring periods in the Southwest.

MATERIALS AND METHODS

Plague data sets. Data on all human cases of bubonic, pneumonic, and septicemic plague in New Mexico were obtained from the New Mexico State Department of Health and the Federal Center for Disease Control and Prevention. The data record represented the entire history of plague in New Mexico, including every known human case from its first occurrence in 1949 through 1996. These data, including those from the early years of plague in New Mexico, were considered accurate for 3 reasons: first, when plague initially occurred in New Mexico in 1949, a flurry of press reports followed, and physicians and medical investigators began to specifically look for additional cases; second, since plague is 1 of only 3 internationally reportable diseases, all cases are investigated as delineated under international health regulations; and third, for plague fatalities, the state of New Mexico has a centralized Office of the Medical Investigator in Albuquerque, and all corpses of persons who have unexplained deaths are sent to Albuquerque for autopsy in a central facility; thus, data quality on cause of death is, and has been, consistently high. Data for each plague case included the date of diagnosis and the estimated location of disease acquisition; published accounts from local newspapers on the circumstances of the cases provided additional details regarding infection locations. Total numbers of human plague cases were tallied for each year for the entire state. Population data for 1949–1996 in the State of New Mexico were obtained from the U.S. Bureau of the Census,²¹ and the annual per capita infection rate for plague was calculated by dividing the number of plague cases by the population size for each year.

Precipitation data sets. From the list of plague infection locations, the nearest National Oceanic and Atmospheric Administration (NOAA) weather station was determined (usually a city, town, village, airport, or ranger station; Figure 1). These stations were generally within ~20 km of the residences of the infected patients. Monthly precipitation totals were obtained from the NOAA for each station for the period of 1948–1996.²² From these data (48-year records), the site-specific, long-term, monthly precipitation averages

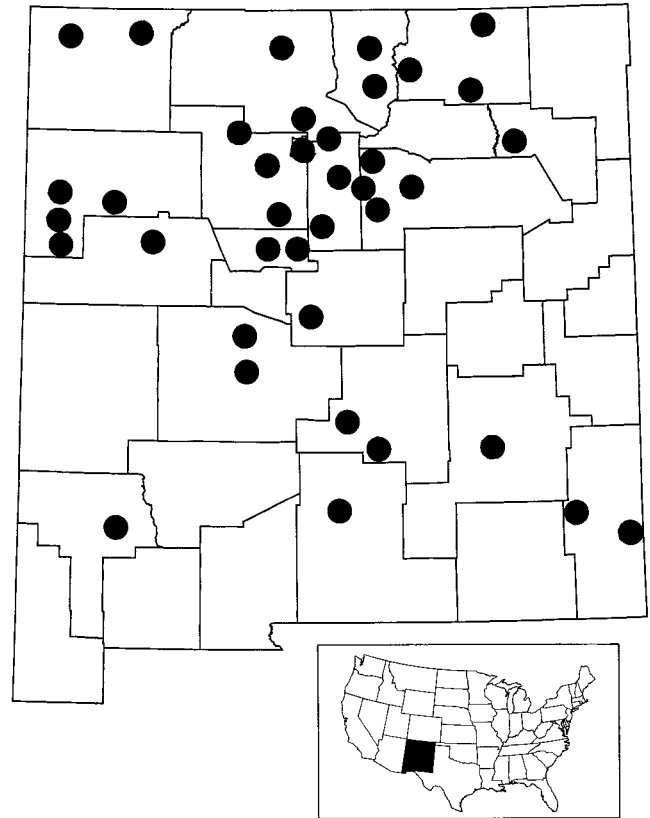


FIGURE 1. Map of New Mexico showing locations of National Oceanic and Atmospheric Administration weather stations in the 38 cities, towns, and villages associated with human cases of plague, 1949–1996. Lines indicate county boundaries.

were computed. In addition, state-wide means of monthly precipitation were calculated by averaging the data from all stations associated with 1 or more cases of human plague. Annual mean precipitation totals were computed by summing monthly means. (Note: NOAA data sets occasionally contain missing [unreported] precipitation values. When missing data were encountered, the long-term mean for that month and site was substituted for the missing value. If more than 1 month of data were missing for a particular site in a single year, then the next closest site (<20 km) was substituted for the site with missing data; this latter substitution was done only twice in 215 cases.) Finally, data for the SOI were obtained from NOAA for the period 1948–1996;²³ the annual SOI index used in this study was based on the mean of the monthly indices from October of the previous year through May of the current year (i.e., the winter months that are associated with El Niño-influenced changes in precipitation in New Mexico).

Hypothesis testing. The first hypothesis addressed the role of local, site-specific precipitation amounts as an associated variable with human plague cases. For the time period preceding each plague case, the site-specific precipitation totals for both prior summer (June–September in previous year) and winter (October–May of current year) were computed for the nearest NOAA weather station to case locale. These totals were then divided by the long-term means of the station for the same months; this produced a value that

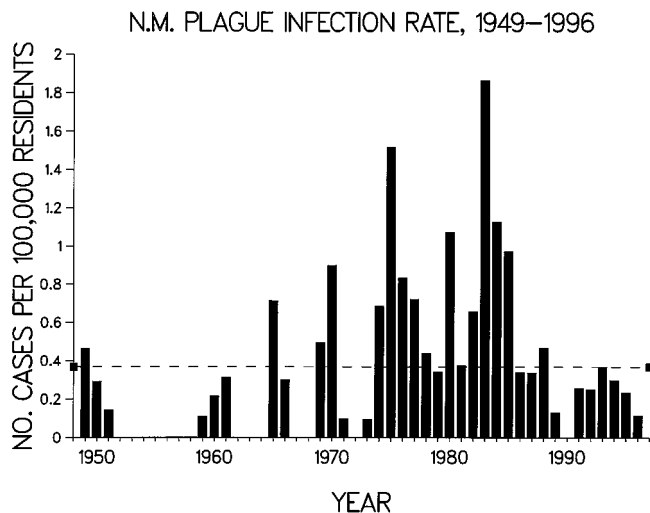


FIGURE 2. Annual infection rate of human plague in New Mexico (N.M.), 1949–1996. The dashed horizontal line indicates the long-term mean annual plague case rate.

indicated the percentage of local normal precipitation that had occurred in the 2 periods prior to the plague case (i.e., whether the preceding time period experienced greater than normal or less than normal precipitation). These percentage values were then averaged over all cases, and the resulting means were compared to the long-term mean (= 100% of normal precipitation). Comparison tests were conducted using both a parametric means test (Student's *t*-test) and non-parametric tests (sign test and Wilcoxon sign rank test). If increased local precipitation was associated with plague incidence, then the observed mean percentage of precipitation values for years with plague cases would be higher than the predicted normal values of 100%. For the prior summer (June–September) comparison, we used all available plague cases that occurred in the following calendar year; for the winter-spring (October–May) comparison, we used only those cases that occurred after May of that year (following the end of the spring precipitation record).

The second hypothesis dealt with the influence of regional precipitation totals on human plague case rates. For this, the state-wide mean monthly precipitation amounts comprised the independent variable and was used in a linear regression with plague case rates (number of human plague cases/100,000 residents in each year). Three combinations of monthly mean precipitation values were tested: 1) total mean state-wide annual precipitation during the calendar year prior to the cases; 2) total mean state-wide summer precipitation (June through September) of the year prior to the cases; and 3) total mean state-wide winter precipitation (October through May) of the winter prior to the cases. If precipitation amounts at a regional scale were associated with the human plague case rate, then the predicted regression lines would have positive slopes, with more cases occurring in years following periods of greater precipitation.

The third hypothesis concerned the relationship between the global scale SOI values and the incidence of human plague cases. This also was tested using a linear regression analysis, with the independent variable being the SOI value (range from -2.65 to $+1.8$, with negative values represent-

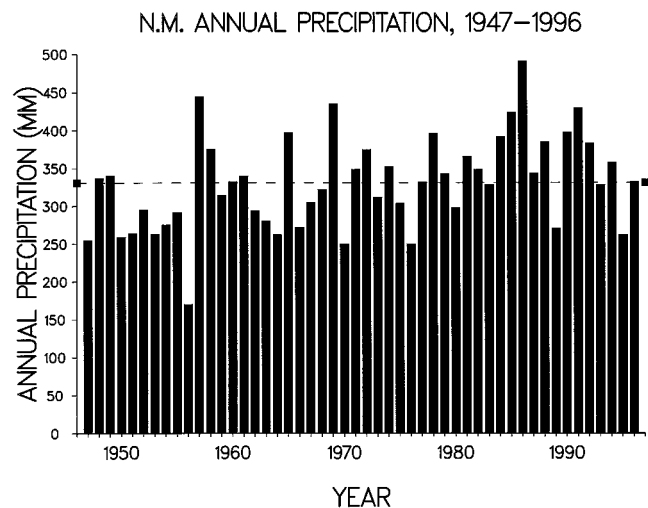


FIGURE 3. Total annual precipitation (mm) in New Mexico (N.M.) averaged across 38 sites with recorded human cases of plague. The dashed horizontal line indicates long-term mean annual total precipitation.

ing El Niño conditions and positive values representing La Niña conditions) and the dependent variable being the corresponding human plague case rate for that year. If the SOI was associated with the plague case rate via mediation of winter-spring precipitation amounts, then the predicted regression line would exhibit a negative slope, with more cases following the wetter winter-springs of the El Niño years and fewer cases after the drier La Niña winter-spring periods. All statistical tests were conducted using the SAS computer package.²⁴

RESULTS

Plague and precipitation. From 1949 through 1996, there were 215 human cases of plague, geographically representing 38 cities, towns, and villages in New Mexico (Figure 1). The analyses used 211 cases for which adequate site data were available. All of these cases were attributed to individual primary infection events from flea bites or direct contact with wild or domesticated mammals; none was due to human-to-human transmission. During this same period, the human population of New Mexico more than doubled, from 644,000 in 1949 to 1,713,000 in 1996. Annual plague infection rates averaged 0.37 cases/100,000 residents over the entire period (Figure 2), but varied widely from year to year (range = 0–1.87 cases/100,000 residents). Average annual state-wide precipitation from 1948 to 1996 was 336 mm, but this also varied greatly; the period included an extended drought in the 1950s (with a minimum of 173 mm in 1956) and an exceptionally wet period in the mid-1980s (with a maximum of 499 mm in 1986) (Figure 3).

In overview, the patterns shown in Figures 2 and 3 display some elements suggesting a general linkage between precipitation and rates of human plague. The mid-1950s were characterized by an extended drought, and produced no human plague cases from 1952 through 1958. A similar, shorter drought in 1962–1964 was mirrored by no plague cases. In contrast, the period of 1981–1986 was exceptionally moist,

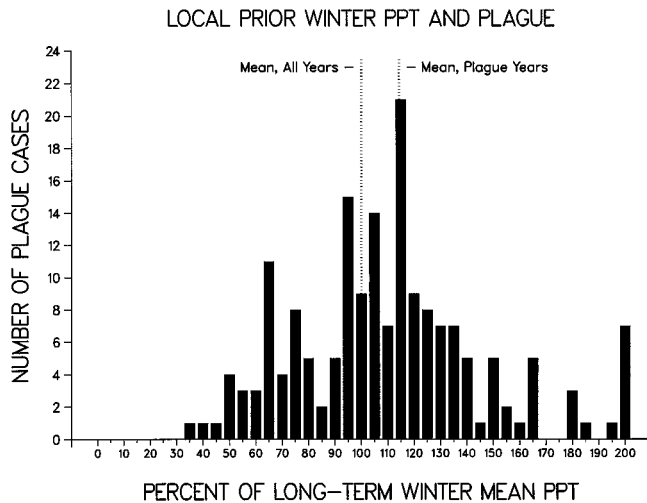


FIGURE 4. Distribution of human plague cases based on local (site-specific) winter precipitation (PPT) (October–May) in New Mexico, 1949–1996. Histograms represent the number of plague cases that occurred following different levels of precipitation; 100% represents long-term normal precipitation. The mean winter precipitation prior to a case of human plague was 113% of normal.

and displayed a concomitantly high rate of plague cases; in fact, the highest plague case rate ever recorded in New Mexico occurred in 1983 (following the intense El Niño of 1982–1983), with an annual case rate that was 5 times the normal rate (1.87 cases/100,000 residents; Figure 2). Finally, the recent La Niñas of 1988–1989 and 1995–1996, each characterized by dry winter-spring periods, exhibited precipitous decreases in plague cases.

Local precipitation and plague. In comparing the local, site-specific, winter-spring (October–May) precipitation values of plague incidences with their respective long-term mean precipitation values, the typical New Mexico plague case ($n = 177$ cases that occurred after May in each year following the winter-spring period) occurred in a year that had been preceded by a winter-spring precipitation amount that averaged 113% of normal (Figure 4); this difference was significantly greater than normal precipitation ($= 100\%$) in all statistical tests ($T = 3.5870$, degrees of freedom [df] = 176, $P = 0.0004$, by Student's t -test; $M = 21.5$, $P = 0.001$, by sign test; $S = 2074$, $P = 0.0001$, by Wilcoxon signed rank test). A total of 107 of the 177 cases (60.5%) occurred during above-normal precipitation years, while only 68 (38.4%) occurred during below-normal years (2 cases occurred during exactly normal years), which indicates that 60% more cases (107/68) were acquired during wet years than during dry years.

The relationship of plague case numbers ($n = 211$ cases) with the previous summer's precipitation was less pronounced; mean plague incidences occurred following summers that averaged only 106% of normal precipitation (Figure 5). Statistical tests of this difference yielded mixed results; the Student's t -test indicated a significant difference ($T = 2.7346$, $df = 210$, $P = 0.0068$), but non-parametric tests showed no significant difference ($M = -2.5$, $P = 0.7811$, by sign test; $S = 1676$, $P = 0.0519$, by Wilcoxon signed rank test).

Regional precipitation and plague. At the regional scale,

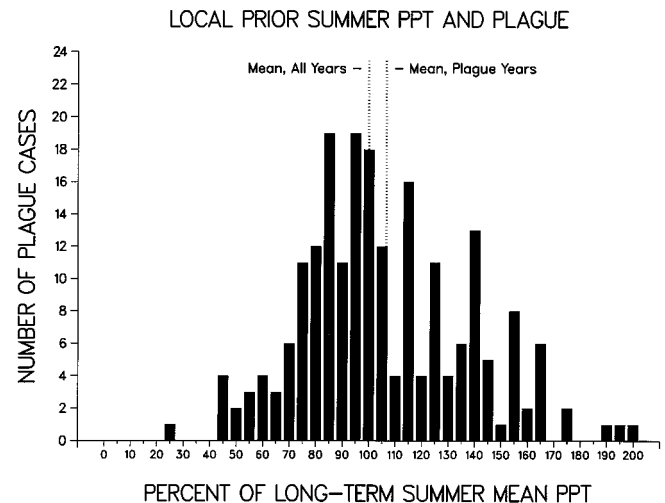


FIGURE 5. Distribution of human plague cases based on local (site-specific) previous summer precipitation (PPT) (June–September) in New Mexico, 1949–1996. Histograms are defined as in Figure 4. The mean summer precipitation prior to a case of human plague was 106% of normal.

the correlation analysis between average state-wide precipitation and the number of human plague cases in the following year produced the predicted positive relationship (Figure 6), although the high variability rendered the relationship non-significant ($P = 0.14$). Additional correlation analyses using average state-wide summer and winter precipitation amounts also produced non-significant relationships.

The SOI and plague. Similarly, the correlation analysis of the plague case rate in New Mexico to the SOI of the previous winter produced the predicted negative relationship (Figure 7), but this relationship was not statistically significant ($P = 0.12$). Much of this relationship was driven by a single outlier point, representing the 1983 plague outbreak (1.87 cases/100,000 residents) following the 1982–1983 El Niño ($SOI = -2.65$); excluding this point decreased the cor-

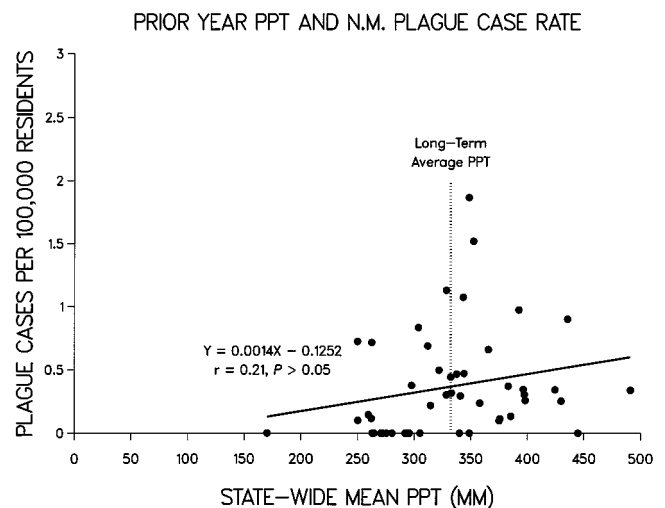


FIGURE 6. Linear regression analysis of mean total annual precipitation (PPT) and case rates of plague in New Mexico (N.M.), 1949–1996.

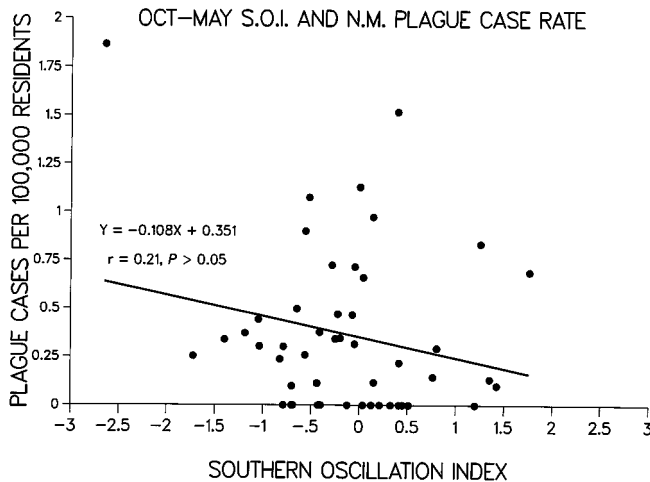


FIGURE 7. Linear regression analysis of the Southern Oscillation Index (S.O.I.) and case rates of plague in New Mexico (N.M.), 1949–1996.

relation coefficient from 0.21 to 0.03, and changed the P value from 0.12 to 0.85.

DISCUSSION

The results of these analyses indicate that winter-spring precipitation amounts can function as a predictor for increased risk of human plague infections, but only at a local, site-specific spatial scale. State-wide precipitation averages and SOI values are not well-correlated with plague incidence in New Mexico. These results are consistent with the ecology of mammal and flea populations in that local animal populations will respond to increased moisture only if it actually occurs in their immediate vicinity. Larger-scale indices of precipitation that integrate areas receiving both lower- and higher-than-average amounts of precipitation fail to capture the precipitation variability to which the local animal populations respond; thus, these large-scale indices are poor indicators of occurrences of human plague.

Given these insights, we hypothesize that the ecology of plague in the environment follows the trophic cascade pathways shown in Figure 8. First, increased precipitation during the winter-spring period in arid and semiarid regions (such as New Mexico) permits moisture recharge of soils, and results in an increase in ecosystem productivity (growth of leaves, flowers, seeds, fruits, nuts/acorns, and subsequently, many species of insects). These organisms comprise the food resources for many species of mammals, especially rodents.²⁵ Abundant food resources allow greater reproductive success during breeding seasons (usually spring and summer), leading to greater population sizes of potential plague hosts following a lag period of reproduction and growth. In New Mexico, recent studies on rodent populations have shown significant density increases within 2–6 months of site-specific above-average seasonal precipitation,¹³ which is entirely consistent with the trophic cascade hypothesis. Concomitantly, moist conditions in the soil (from increased winter and spring precipitation) may enhance the conditions for flea reproduction and survivorship,²⁶ thereby simultaneously increasing the number of available fleas. This dual enhance-

ment of mammal and flea host densities would lead to a greater frequency of plague in the wild animal populations if the fraction of plague infectious animals remains constant or increases.

Following a period of mammal population increases fueled by the increased precipitation and food resources, individuals within the populations will begin to disperse (during summer and autumn in many species) in search of mates and/or new home ranges; such events were observed prior to the 1993 hantavirus epidemic in the southwest.⁸ The reasons for this are not entirely understood, but presumably include 1) environmental changes (e.g., drought periods), resulting in decreased food resources, that can spur sudden dispersal or migration events, or 2) over-crowding of conspecifics during population explosions that may lead to increased pressures to disperse. Such movements of large numbers of plague-infected mammals would subsequently translate to an increased risk of human exposure to plague via direct contact with wild mammals or indirect contact through domesticated dogs and cats.

Accounts of human plague cases from other parts of the world are consistent with this hypothesis. In Africa²⁷ and central Asia,²⁸ medical personnel have noted plague case increases following periods of moisture when drier conditions set in. The anecdotal explanation given in these accounts suggests that rodent densities increase during the rainy season, and when the dry season arrives and rodent food supplies decrease, the plague-infected rodents disperse from their normal habitats and eventually contact humans.^{27,28} Surprisingly, while these explanations seem plausible, there have been no rigorous scientific field studies on rodents and plague to determine the spatial extent and epidemiologic impact of such dispersal movements.

The phenomena of rodent population increases and dispersal from their normal habitats following wet periods also may contribute to New Mexico's dubious distinction of being the chronic epicenter for plague in North America. The weather during the winter-spring months in New Mexico is typified by large frontal systems that drop widespread rains and snows, while mid- to late-summer (July through mid-September) is characterized by monsoonal thunderstorms (on average, 60% of the total annual precipitation falls during this period). However, the early summer months of May and June are usually hot and dry; i.e., nearly every year has a warm, seasonal drought period that can promote rodent dispersal movements. Plague cases in New Mexico generally occur in summer, during and after the early-summer dry period. Thus, the climate of New Mexico, coupled with an unusually high diversity of small mammal species,²⁹ may be ideal for the dispersal and transmission of plague bacteria to humans.

There is a general lack of information regarding environmental influences on wild flea populations in arid and semiarid ecosystems, and it is not entirely clear if increased precipitation is a benefit or a detriment to reproductive success of fleas in rodent burrows. Some of the most detailed studies on flea ecology have been performed on the cat flea (*Ctenocephalides felis*), an occasional, though apparently poor, vector of plague. These studies have shown that flea egg and larval survival and development times increase with greater soil relative humidity (range = 33–92%), and that dry soils

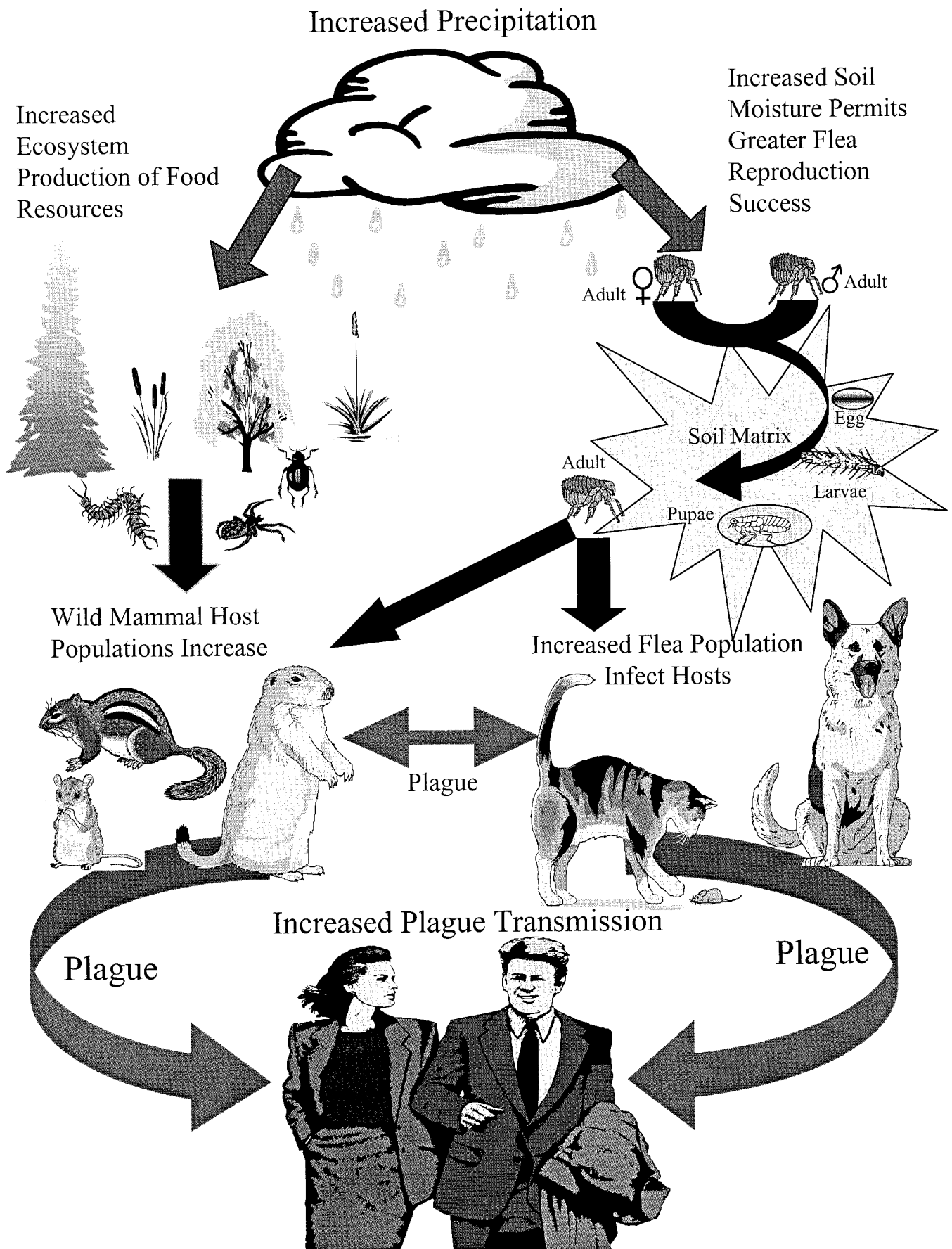


FIGURE 8. Schematic diagram of the effects of increased precipitation on ecosystem attributes, flea and mammal reproductive success, and potential transmission of plague.

(relative humidity <33%) are lethal to the larvae.³⁰ Flea reproductive success in the wild requires microsites with a relative humidity > 50%, and temperatures between 4°C and 35°C,³¹ conditions that are commonly achieved in soils given sufficient precipitation. The ecology of cat fleas, however, differs from that of other flea species that typically transmit plague; e.g., cat fleas lay eggs in more exposed sites instead of rodent burrows, and do not occur in most plague-enzootic areas. While some information exists on flea ecology with respect to mammal host specificity, habitat preferences, and seasonal abundances,^{32–35} we are unaware of any published studies on long-term dynamics of arid-land, plague-carrying flea populations and their relationships with climatic fluctuations; this is clearly an area in need of much additional research. However, if the cat flea model is correct, and fleas have a need for high soil relative humidity to maximize reproduction, we hypothesize that wet periods in arid environments would provide a greater number of microsites meeting the fleas' moisture requirements, and thus would increase flea population sizes during those periods.

It is interesting to note that too much rainfall in certain environments can actually suppress human plague occurrences, apparently by preventing successful flea reproduction. Soil relative humidity > 95% promotes growth of destructive fungi that kill flea eggs and larvae.^{30,31} In the rainforests of Vietnam, the numbers of fleas on rodents are significantly decreased during periods of high precipitation, and human cases of plague are practically non-existent.^{36,37} This pattern is similar to that of malaria in that vector mosquito populations in normally wet environments (rain forests) decrease during periods of above-average rainfall (due to flooding of rivers and streams, causing rapid flow rates and destruction of mosquito larvae), but thrive during drought (when river currents are slow and stagnant, and mosquito breeding pools are abundant).¹¹ In arid environments, the opposite is found in that the number of mosquitos decreases during droughts (few water sources), but increases during wet periods when temporary pools are common. It may be that plague-carrying flea populations follow similar patterns, being more abundant on rain-forest wild mammals during drought periods, but thriving on desert-dwelling mammals during and following wet periods.

The knowledge of the relationship between wet winter-spring periods and increases in human plague cases can be used as a forecasting tool by physicians and public health officials in the Southwest. Although there is considerable scatter in the data presented in Figure 4, when local winter-spring precipitation exceeds normal values, the number of human plague cases increased 60% compared with below-normal years. With known increased risk of plague transmission following unusually moist winter-spring seasons, localized public warnings and heightened medical surveillance can be arranged prior to the peak in human cases during the summer. Local physicians and health care professionals can determine if their cities and towns have received higher-than-normal precipitation, and increase their cognizance for plague patients. Finally, based on the relationships between precipitation and human plague cases, additional epidemiologic research can be directed at determining the details of the climate-rodent-flea-bacterium interactions, so as to de-

velop improved prevention strategies for plague in the American Southwest and other parts of the world.

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