



Informing surveillance for the lowland plague focus in Azerbaijan using a historic dataset



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A B S T R A C T

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Yersinia pestis is a gram-negative, zoonotic bacterium and the causative agent of plague. Plague is maintained in nature through a transmission cycle between partially resistant rodent hosts and fleas. There are natural reservoir populations on almost every continent, and the number of reported human plague cases has increased in recent years. Azerbaijan is a country at the crossroads of Eastern Europe and western Asia that has a history of environmental plague foci. Informing plague surveillance in this region is imperative due to the deteriorating public health system that resulted from the collapse of the Soviet Union. The aim of this study was to inform efforts to prioritize regions for plague surveillance in Azerbaijan. A 14-year historic data set was employed to analyze the spatio-temporal pattern of the primary plague host in the country, the Libyan gird, *Meriones libycus*, using the Space Time Analysis of Moving Polygons (STAMP) method. This method is useful for identifying areas of stable rodent abundance across the study period. The relationship between STAMP-defined stable *M. libycus* abundance and environmental variables including mean temperature, altitude, land cover type and annual precipitation was explored. We were particularly interested in identifying increasing human population trends in the area surrounding regions characterized by historically high *M. libycus* abundance, as the risk of human plague increases as humans come into close proximity with hosts and vectors. There was variation in *M. libycus* abundance over the historic period, but regions of stability were identified for each category of abundance evaluated. There were significantly different climatic conditions and land cover types associated with different categories of abundance. The human population in Azerbaijan has steadily increased over the past 30 years, including regions bordering plague foci. Surveillance should be prioritized for regions with historically stable high host abundance, regions with climatic conditions associated with high abundance, and regions with increasing human populations surrounding plague foci.

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Introduction

Plague is a flea borne zoonosis caused by the gram negative bacterium *Yersinia pestis* (Gage & Kosoy, 2005; Perry & Fetherston, 1997; Pollitzer, 1954), which has been associated with three pandemics throughout history (Gage & Kosoy, 2005). Since the onset of the most recent pandemic, which started in China during the mid-nineteenth century, the geographic range of plague has greatly expanded (Gage & Kosoy, 2005). The bacterium is maintained in

nature through a transmission cycle between partially resistant rodent hosts and adult hematophagous fleas (Gage & Kosoy, 2005; Meyer, 1942). *Y. pestis* foci can be maintained indefinitely in enzootic or maintenance cycles as long as sufficient numbers of rodent hosts and flea vectors are present (Beran, 1994; Gage & Kosoy, 2005; Gage, Ostfeld, & Olson, 1995).

Natural plague reservoirs are active in Asia, and parts of the Russian Federation (Gratz, 1999). Human plague cases have recently reemerged in this region (Pollitzer, 1954). During the past decade human plague cases have been reported in Saudi Arabia (Saeed, Al-Hamdan, & Fontaine, 2005), Jordan (Arbaji et al., 2005), Afghanistan (Leslie et al., 2011), Algeria (Bertherat et al., 2007) and a limited outbreak in Libya (Tarantola, Mollet, Gueguen, Barboza, & Bertherat, 2009). The reemergence of

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human plague in these areas suggests that there are still active environmental reservoirs, or foci.

Azerbaijan is a country at the crossroads of western Asia and Eastern Europe that has three well documented historical plague foci (Gurbanov & Akhmedova, 2010). Concern about plague has a long history in Azerbaijan. During the Soviet era, the Anti-plague system (APS) was created to respond to outbreaks of plague and other bacterial and viral diseases (Ouagrham-Gormley, 2006; Zilinskas, 2006). As part of routine surveillance and control in Azerbaijan, detailed yearbooks were published annually. The yearbooks outline many aspects of the APS efforts and provide a unique opportunity to better understand the dynamics of plague within the country. This is particularly relevant given the limited resources for surveillance following the collapse of the Soviet Union in 1991. With fewer resources available, detailed historic datasets can be used to help inform current plague surveillance efforts.

In order to successfully monitor and control plague on the landscape it is necessary to understand the distribution and abundance of hosts (Gage & Kosoy, 2005; Stenseth et al., 2008). The Libyan gerbil, *Meriones libycus*, is a major plague host in central and southwest Asia (Bakanidze et al., 2010; Gage & Kosoy, 2005; Gratz, 1999; Gurbanov & Akhmedova, 2010) with a natural range that spans from the Western Sahara to Western Xinjiang, China (Nowak & Paradiso, 1999). As early as 1953, *M. libycus* abundance was linked to a plague epizootic in the Absheron peninsula of Azerbaijan (Bakanidze et al., 2010). Home ranges vary between 50 and 120 m in diameter (Nowak & Paradiso, 1999). *M. libycus* is a ground dwelling gerbil that lives in complex, multi entranced burrows and many individuals may burrow in the same vicinity (Naumov, Lobachev, Dmitriev, Kanatov lu, & Smirin, 1973). Their preferred burrow location is under bush cover (Dcly & Daly, 2009), which puts them at close proximity to flea vectors (Gage & Kosoy, 2005).

Identifying regions of historically stable plague host presence on the landscape could provide important insight to current host distribution across Azerbaijan. The Space Time Analysis of Moving

Polygons (STAMP) approach is one method for addressing these objectives with data such as those available in the APS yearbooks. STAMP uses polygons representing a phenomenon from two consecutive time periods and describes the type of change that is taking place. The analysis includes the identification of regions that do not change, or that remain stable (Robertson, Nelson, Boots, & Wulder, 2007).

Exploring historical changes in *M. libycus* spatial patterns and abundance across the landscape can provide important insight into the distribution and ecology of this important plague host. It is also important to consider the relationship between these spatial patterns and environmental variables, as links have been made between climatic conditions and the presence of plague hosts throughout history (Ben Ari et al., 2011; Davis, 1953; Neerinckx, Bertherat, & Leirs, 2010; Perry & Fetherston, 1997; Stenseth et al., 2006). The distribution of plague hosts may be partially limited by variables such as rainfall, temperature and elevation (Ben Ari et al., 2011). One study presented a trophic cascade hypothesis where precipitation resulted in increased plant production and rodent food sources (Parmenter, Yadav, Parmenter, Ettestad, & Gage, 1999). Locally, there may also be negative associations with increased rainfall. Cavanaugh and Marshall (1972) suggested that high intensity rainfall is detrimental to rodent survival, as burrows may become flooded. There is a less apparent direct relationship between hosts and temperature although in temperate regions, low winter temperatures can impact food availability subsequently influencing rodent density and distribution (Korslund & Steen, 2005). An analysis of the relationship between environmental variables and the persistence of plague hosts in Azerbaijan is included in this analysis.

Research has also suggested that large rodent host populations increases the likelihood of epizootics and human cases (Parmenter et al., 1999). Therefore, understanding the distribution of plague hosts may also allow for better assessments of human risk. In the southwest United States distance to host habitat was a significant

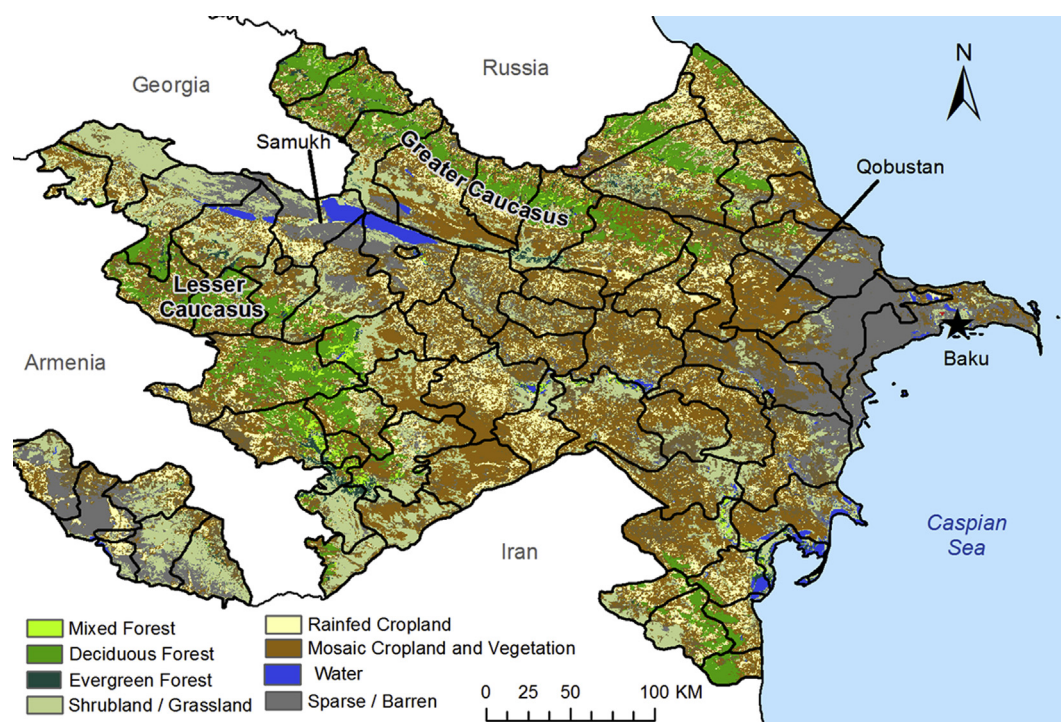


Fig. 1. Azerbaijan with land cover, bordering countries and important rayons identified. The land cover categories were derived from GlobCover v 2.2, and reflect the final eight categories resulting from collapsing the 16 categories identified in Azerbaijan by the GlobCover surface.

predictor of high human plague risk (Eisen, Enscoe, et al., 2007). Regions where human populations come into contact with disease host or vectors, such as national parks, have also been documented as high risk regions, and should be considered when evaluating human risk (Anisimov, 2002; Briggs et al., 2011; Nelson, 1980).

Objectives

The primary objective of this study was to explore the distribution *M. libycus* abundance over space and time, and identify regions of historically stable host abundance. A second objective was to identify specific climatic factors and land cover types associated with stable regions of mammal abundance by category. Our ultimate goal was to identify priority areas for plague surveillance and inform control in Azerbaijan, which is critically important due to the limited resources available for public health efforts after the collapse of the Soviet Union.

Methods

Study area

Azerbaijan is a small country located in the Caucasus region at the intersection of Western Asia and Eastern Europe (Fig. 1). This study focused on one of the three plague foci in Azerbaijan: The Transcaucasian Plain-sub Mountain Natural focus, which is commonly referred to as the Lowland focus. The outer boundaries of the plague focus were derived from expert opinion by APS personnel on the natural habitats of *M. libycus* because it is the primary carrier of plague in the region (Fig. 2).

M. libycus data

Annual APS yearbooks, housed at the APS in Baku, summarized regional plague station activities for the year. Host and vector data were displayed in hand drawn maps to represent different species, or abundance levels for the each year. Data from yearbooks were

digitized and georeferenced to convert them to an electronic database for spatial analyses in a geographic information system (GIS). For this study, we used a subset of APS yearbook data from 1972 to 1985 focusing on data describing *M. libycus* because of its history as an important plague host in the country. The historic Azerbaijan dataset included *M. libycus* data collected during the fall season across the country.

M. libycus themed maps defined abundance by classifying polygons using 5 categories from 1972 to 1980 in the historic yearbooks: very low, low, average, high, and very high (Fig. 3). Very low was defined as 0–1 specimen per hectare. Low was 2–5 specimens per hectare. Average was defined as 6–10 specimens per hectare. 11–20 specimens per hectare was high abundance. Greater than 20 specimens per hectare defined very high abundance. Each definition was based on APS zoological sampling surveys conducted each fall. After 1980, very low and low were collapsed into one category defined as less than or equal to 5 specimens per hectare. Very low was no longer used due to the inexpediency in identifying areas with close to absent rodent populations.

STAMP

A STAMP analysis was used to explore the spatial and temporal variability of *M. libycus* abundance across the landscape from 1972 to 1985. A separate STAMP analysis was conducted for each of the five abundance categories. The very low abundance analysis included 1972 to 1978, as very low and low abundance were collapsed after this time period. If a year was unavailable the next available year was used in its place. For example, 1979 was unavailable for all abundance categories, so polygons from 1978 were compared to 1980. STAMP is a freely available toolbar extension for ArcGIS v 9.3 (<http://www.geog.ubic.ca/spar/stamp/help/index.html>).

STAMP works by overlaying polygons from two consecutive time periods and evaluating changes in spatial position and overlap between time intervals (Fig. 4). If polygons from two consecutive time periods are overlapping that area is classified as stable.

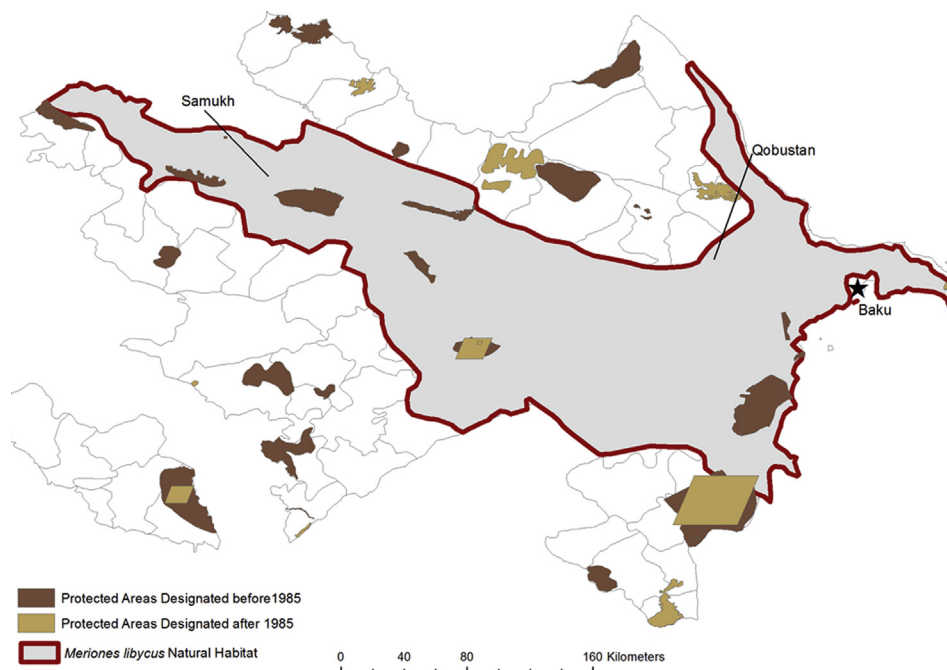


Fig. 2. Plague focus and protected areas in Azerbaijan. The focus is defined by *M. libycus* natural habitat in the area. The protected areas are depicted based on the year of their designation.

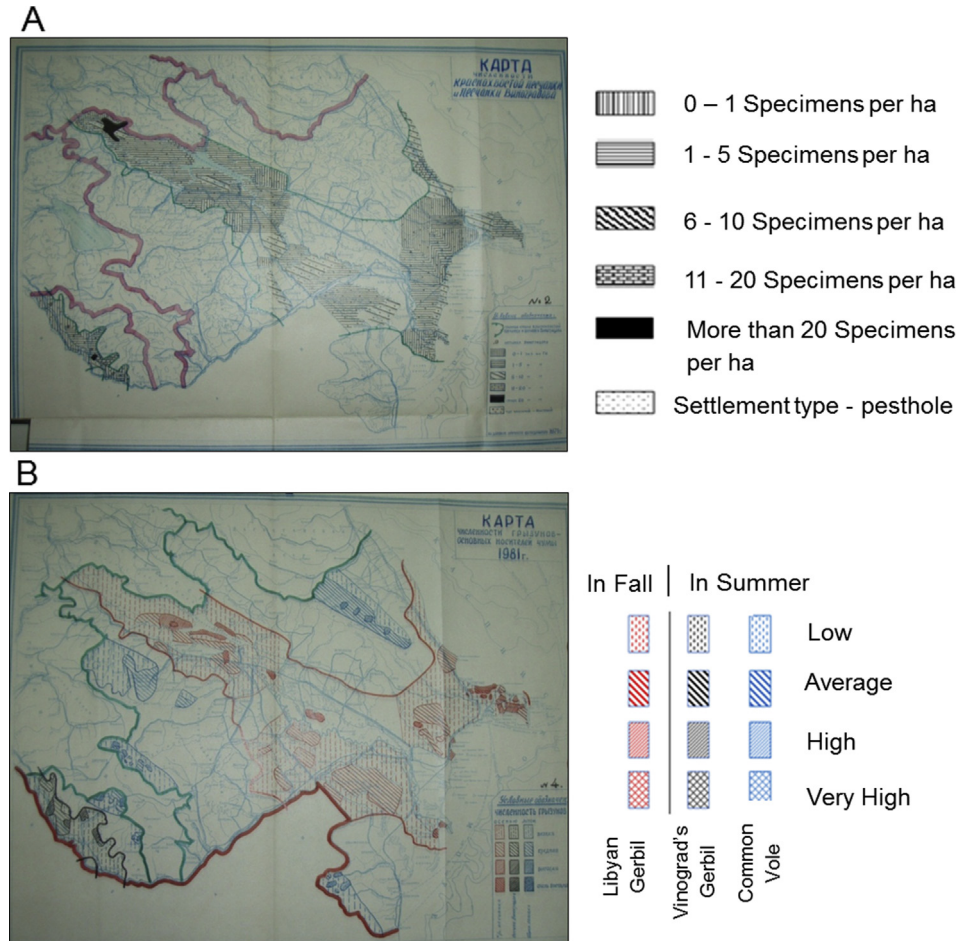


Fig. 3. Hand drawn maps delineating *Meriones libycus* (Libyan Gerbil) abundance with translated legends from annual yearbooks. A) 1972 *Meriones libycus* (Libyan Gerbil) abundance. B) 1980 *Meriones libycus* abundance.

Polygons from two consecutive time periods that are connected are classified as contraction or expansion. Contraction defines the area that was only present in the first time interval, while expansion is defined as any new area identified only in the second time interval.

Disappearance and generation events are spatially isolated, meaning that they are not connected to any region delineated in the opposing time period. Disappearance defines polygons present in the first time period and absent in the second, while generation defines polygons found only in the second time period.

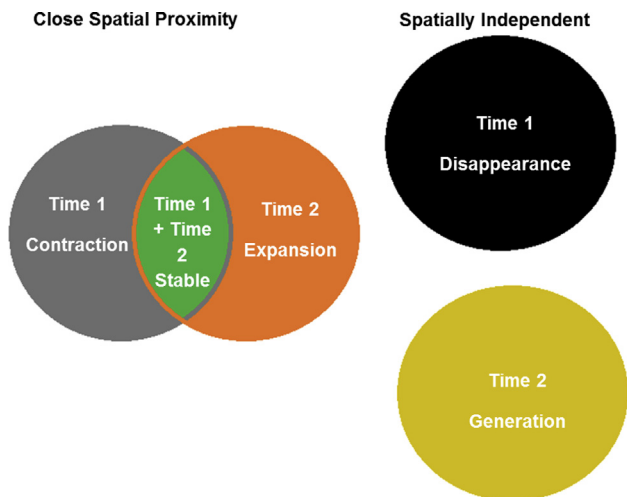


Fig. 4. Event definitions for Space Time Analysis of Moving Polygons (STAMP) outputs. Each circle represents an area in one of two consecutive time periods. Concentration, stable, and expansion are defined by overlapping areas, but contraction is only in time period one while expansion is only in time period two. Disappearance and generation are events that are spatially isolated from other areas.

Stable regions

We were also interested in identifying areas characterized by long-term persistence or stable areas. For this study we defined stable regions as any polygon spanning more than two years. Overlapping stable layers from consecutive years within each abundance category were identified using the intersect tool in ArcGIS v10. These stable regions were then used to evaluate environmental conditions associated with each abundance category.

Environmental analysis

STAMP allowed us to identify regions where a particular abundance category persisted for an extended time interval. Climatic variables were used to test whether climatic conditions were associated with each level of stable *M. libycus* abundance. Freely available gridded climatic data were downloaded from the WorldClim website (www.WorldClim.org) (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). For this study we used data at 30 Arc Second (~1 km²) spatial resolution. WorldClim data were derived from a network of ground based weather stations, and reflect data

Table 1

GlobCover classifications for land cover types found throughout Azerbaijan and definitions of land cover classifications. The definitions report the combined definitions of categories that were collapsed.

Name	Definition
Mixed forest	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5 m)
Deciduous forest	Closed or open broadleaved deciduous forest (>5 m)
Evergreen forest	Closed or open needleleaved deciduous or evergreen forest (>5 m)
Shrubland/grassland	Mosaic grassland, shrubland (broadleaved or needleleaved, evergreen or deciduous, <5 m), herbaceous vegetation (grassland, savannas or lichens/mosses)
Rainfed cropland	Rainfed croplands
Mosaic cropland and vegetation	20–70% Cropland, 20–70% vegetation (grassland/shrubland/forest)
Sparse/barren	Sparse (<15%) vegetation or bare areas
Water	Water bodies

collected between 1950 and 2000 (Hijmans et al., 2005). Polygons of all stable regions for each abundance category were combined using the merge and dissolve tools in ArcGIS v 10. Average annual temperature (bio1; C°), mean annual precipitation (bio12; mm), and altitude (alt; m) values were extracted from polygons representing the stable area for each abundance level using the raster clip tool in ArcGIS v 10. The resulting attribute tables were imported to the R statistical package for analyses (<http://www.r-project.org/>). The maximum value, minimum value, mean, median and range were calculated for each variable at each abundance level. The Mann–Whitney U test was used to determine if climatic conditions were significantly different for each abundance level. Raster surfaces, representing climatic conditions, were converted to points and a random sample of 75% of the data points of each variable for the three abundance levels were selected. An $\alpha = 0.05$ was used with a correction for multiple comparisons using the bonferri correction α/k where k is the number of multiple test being performed ($k = 9$ in this case) following Kracalik et al. (2012).

Similarly to our climate analysis, we attempted to identify unique land cover types associated with different levels of stable rodent abundance. We obtained land cover data from GlobCover v

Table 2

Changes in the area representing each abundance category over time. The total area associated with each abundance category for each year is reported.

Year	Very low abundance area (sq km)	Low abundance area (sq km)	Average abundance area (sq km)	High abundance area (sq km)	Very high abundance area (sq km)
1972	4859.67	15333.38	5419.4	717.91	305.05
1973	8738.92	13904.51	8478.61	6354.78	0
1974	4050.69	25070.44	5659.06	2639.57	290.63
1975	22564.16	9440.97	4178.55	1128.08	235.61
1976	10604.22	6824.64	2370.56	580.41	0
1977	15417.32	4303.45	2072.98	501.02	77.37
1978	7025.66	7687.52	2205.41	1026.39	165.53
1980	ND	27657.74	2853.18	626.12	241.45
1981	ND	21291.7	5033.66	544.52	948.64
1982	ND	28038.79	6114.36	56.77	0
1983	ND	30504.17	3815.76	6.64	160.36
1985	ND	29033.75	2108.9	305.42	172.22

Note: ND = No Data.

2.2 (ESA GlobCover project). GlobCover is a gridded land cover dataset at 300 m spatial resolution with a thematic resolution of 22 classes (<http://www.ionia1.esrin.esa.int>). The dataset was derived from satellite images obtained from 2005 to 2006. We collapsed land cover categories that comprised a small proportion of the Azerbaijani landscape, resulting in 8 categories used for analyses: rain-fed cropland, mosaic cropland, deciduous forest, evergreen forest, mixed forest, shrubland/grassland, sparse/barren, and water (Fig. 1, Table 1). The total number of raster cells of each land cover type within each polygon was calculated.

Human population analysis

The risk of human infection should be considered when prioritizing regions on the landscape for control and preventative measures, as human plague risk is inherently linked to the proximity of human populations to the pathogen. History Database of the Global Environment v 3.1 (HYDE) gridded time series population data were downloaded (<http://themasites.pbl.nl/tridion/en/themasites/hyde/>) in an effort to explore the relationship between *M. libycus* abundance and human population levels (Klein

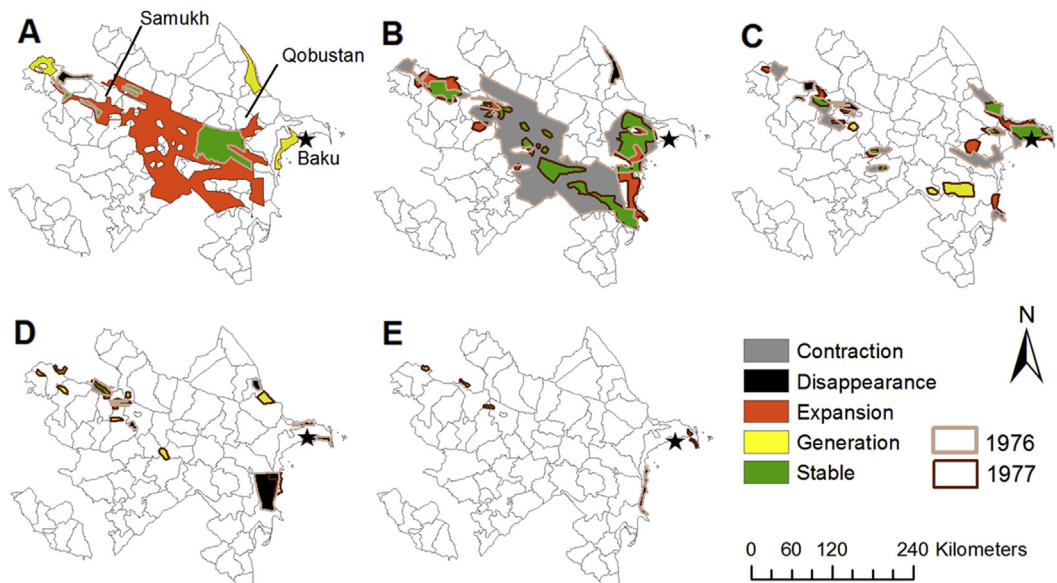


Fig. 5. STAMP outputs from 1976 to 1977. A) is the change in very low abundance from 1976 to 1977; B) is low abundance from 1976 to 1977; C) is average abundance from 1976 to 1977; D) is high abundance from 1976 to 1977; E) is very high abundance from 1976 to 1977.

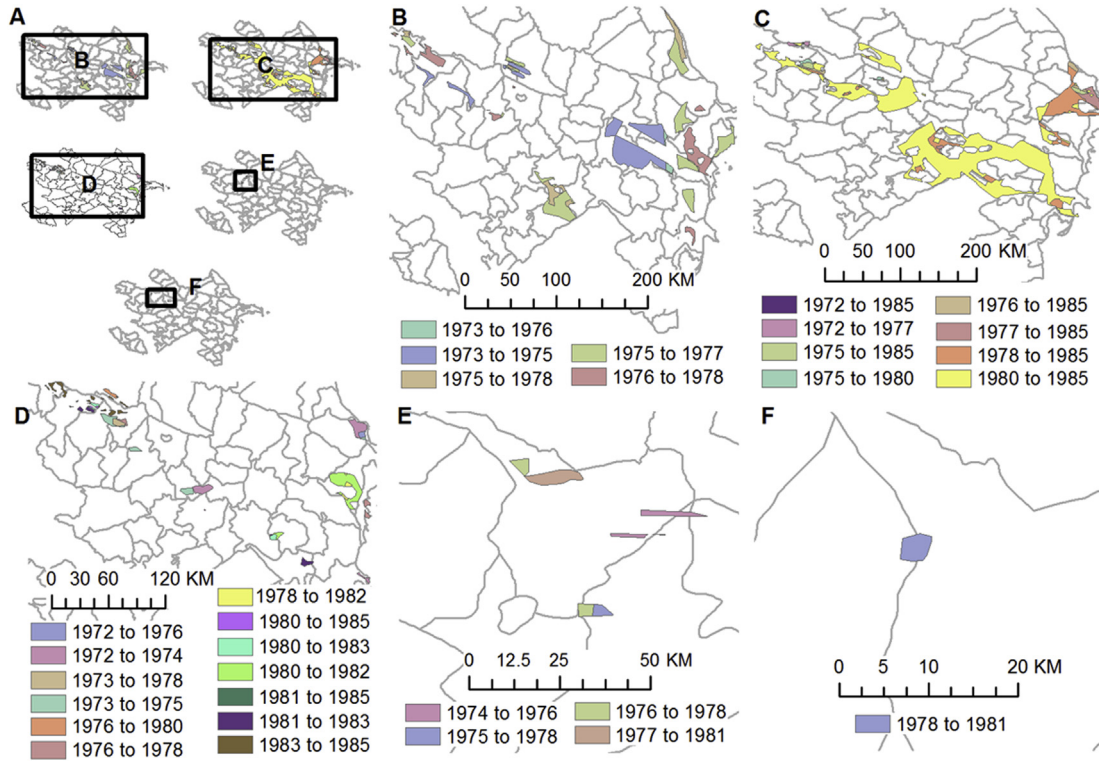


Fig. 6. Stable regions for each abundance category representing regions that remained stable for at least 2 consecutive years. A) shows the region of Azerbaijan that each of the subsequent maps focuses on; B) is very low abundance; C) is low regions of stability that persisted for at least 5 years; D) is average abundance stable regions; E) is high abundance stable regions; F) is very high abundance stable regions.

Goldewijk, Beusen, Van Drecht, & De Vos, 2011). HYDE includes georeferenced historical gridded population data for the past 12,000 years at 5 Arc Minute (9.56 km²) spatial resolution (Goldewijk, 2005). The population grids for 1970 and 2005 (the most recent available surface) were downloaded. The 2005 surface was projected to 2010 using the United Nations, medium variant, inter-censal growth rate by country (UNPD world population prospects), following Hay et al. (2009). The 2010 population surface was derived using

$$P_{2010} = P_x e^{rt}$$

Where P_{2010} is the population within each pixel, P_x represents the population at year x in the same pixel, r is average growth rate, and t is the number of years between 2010 and x (Hay et al., 2009). The resulting 2010 population grid was used to create a

surface representing the percentage change in population from 1970 to 2010.

There are currently 44 protected areas in Azerbaijan, which encompasses National parks, strict nature reserves, wildlife refuges and wildlife sanctuaries (Zazanashvili et al., 2009) (Fig. 2). We evaluated park locations relative to stable regions of *M. libycus* abundance and human population. Spatial data on protected lands was downloaded from the World Database on Protected Lands (<http://www.wdpa.org/>).

Results

STAMP

The spatial boundaries for each abundance category changed every year (Fig. 5). Low rodent abundance had the largest average

Table 3
Mann-Whitney U test results for temperature, precipitation, and altitude comparing five abundance categories. The null hypothesis being tested is that there is no significant difference in environmental variables between abundance categories. The adjusted level of significance was $P = 0.005$.

	High v. very high	High v. average	High v. low	High v. very low	Very high v. average	Very high v. low	Very high v. very low	Average v. low	Average v. very low	Low v. very low
<i>Temperature</i>										
Statistic	389.5	223,504.5	2,452,037.0	479,318.5	25,223.5	287,616.5	57,194.5	86,708,423.0	21,695,879.0	184,833,545.0
P. value	0.521	0.102	<0.001 ^b	<0.001 ^b	0.562	0.082	<0.001 ^b	<0.001 ^b	<0.001 ^b	<0.001 ^b
<i>Precipitation</i>										
Statistic	525.0	294,016.0	1,635,578.0	406,508.5	39,261.0	226,029.0	54,829.0	72,633,250.0	13,574,874.0	96,901,535.0
P. value	0.356	<0.001 ^b	<0.001 ^b	<0.001 ^b	<0.001 ^b	<0.001 ^b	0.002 ^a	<0.001 ^b	<0.001 ^b	0.014
<i>Altitude</i>										
Statistic	515.0	260,743.0	1,833,097.0	402,833.5	28,611.5	206,582.0	44,989.0	49,040,114.0	16,743,700.0	83,243,566.0
P. value	0.420	<0.001 ^b	<0.001 ^b	<0.001 ^b	0.164	0.005 ^a	0.116	<0.001 ^b	<0.001 ^b	<0.001 ^b

^a Reject the null hypothesis with 95% confidence.

^b Reject the null hypothesis with 99% confidence.

area over the study interval. Very high abundance had the smallest area and was located near Samukh. Low abundance spanned the entire central portion of the focus. The area calculations for all years and all abundance categories are shown in Table 2. All inter-annual STAMP outputs are shown in Appendix A.

Stable regions

Stable regions spanning more than two years were identified for every abundance category (Fig. 6). Regions of low stable abundance were the most widespread across Azerbaijan, and tended to persist longer than other abundance categories. Stable areas associated with average and high abundance did not consistently persist for more than five years. Areas of average abundance were more widespread, and tended to be smaller than low and very low abundance stable regions. All stable regions defining high and very high abundance were near Samukh.

Environmental analysis

Each environmental variable was analyzed for each of the five abundance categories. The adjusted level of significance was $\alpha = 0.005$. There was no significant difference between very high and high categories for any of the environmental variables based on the Mann–Whitney U test (Table 3). Data on very low abundance was not available after 1978. As a result, we were compelled to collapse very low and low into one category and high and very high into an additional category for environmental analyses. This resulted in three categories: low, average, and high abundance (Fig. 7). These three abundance categories were used for all subsequent analyses.

Each of the three abundance categories was characterized by significantly different climatic conditions and combinations of land cover type. Stable areas of high abundance had the highest mean annual temperature, altitude, and annual precipitation (Table 4). Stable low regions had the lowest mean annual temperature and altitude. Stable average abundance had the highest average precipitation, as a result of its overlap with the Lesser Caucasus mountain range along the western border of the country. All abundance levels were significantly different for each environmental variable except temperature in high abundance regions compared to temperature in average abundance regions (Table 5).

The regions associated with each abundance category had a different land cover composition. The landscape delineating low rodent abundance was dominated by mosaic cropland based on GlobCover characterizations (Fig. 8, Table 6). High abundance regions were dominated by shrubland/grassland and sparse/barren land cover. The landscape associated with average abundance was ~30% mosaic cropland and ~22% grassland / shrubland. Mixed forest, evergreen, and deciduous all comprised less than ~1% of total land cover for each abundance category, but were the most prominent in stable areas of low abundance.

Human population analysis

The greatest percent increase in human population was along the southern border of the plague focus in the lesser Caucas region (Fig. 9, Appendix B). The area surrounding Samukh, which included the stable region of high abundance, was characterized by ~50% increase in population since 1970. The central portion of Azerbaijan also experienced a ~50% increase in population levels over the 40 year period. The Greater Caucas region, which borders stable low abundance, was another region that experienced up to a 100% increase in human population between 1970 and 2010.

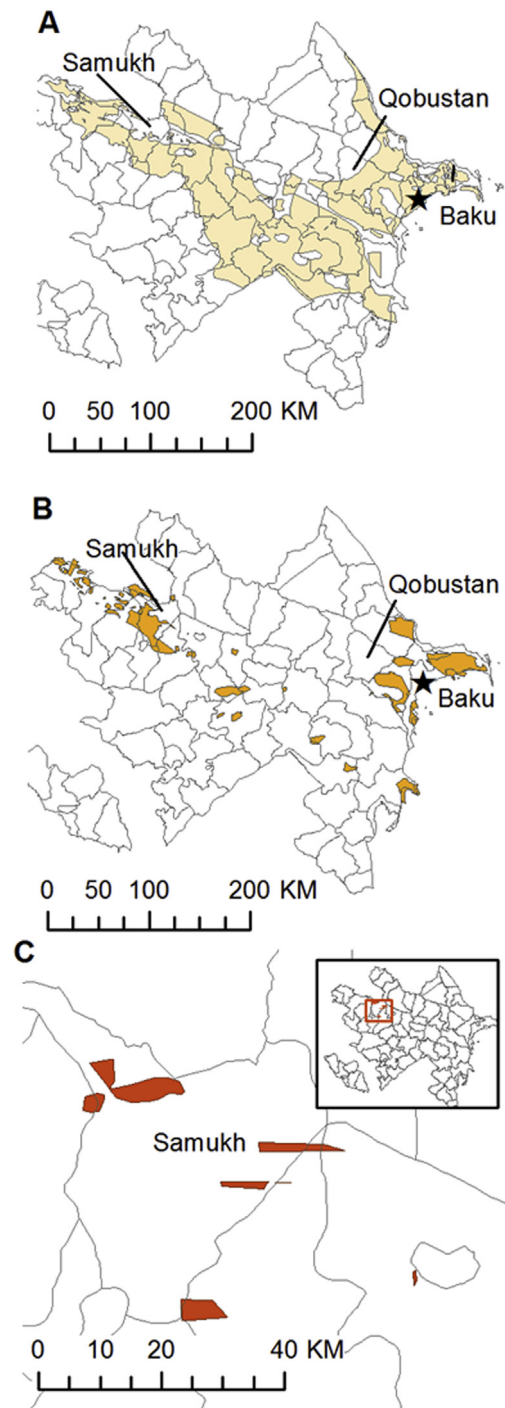


Fig. 7. Regions of stability for each abundance level. Each polygon represents the area that was stable for at least 2 consecutive years anytime between 1972 and 1985. A) is low abundance; B) is average abundance; C) is high abundance.

Discussion

Plague presents a pressing public health concern in the developing world, as there has been an increase in human cases in recent years. This threat is particularly relevant in the former Soviet Union, and its bordering countries. The collapse of the Soviet Union was accompanied by a deteriorating public health system that was left with limited resources for disease control and surveillance efforts. There is also evidence of active historical plague foci in countries

Table 4

Descriptive statistics for the distribution of temperature, precipitation, and altitude associated with each of the three abundance levels.

	Low	Average	High
<i>Temperature (Degrees Celsius)</i>			
Min.	10.1	10.1	13.7
1st Qu.	13.5	14	14.3
Median	14.2	14.6	14.5
Mean	14.03	14.31	14.55
3rd Qu.	14.7	14.8	14.8
Max.	15.4	15.3	15.2
<i>Precipitation (Millimeters)</i>			
Min.	243	243	337
1st Qu.	348	343	396
Median	373	371	416
Mean	377.9	369.7	406.9
3rd Qu.	398	395	429.5
Max.	672	601	473
<i>Altitude (Meters)</i>			
Min.	−42	−32	70
1st Qu.	−7	15	154
Median	41	122	209
Mean	126.2	161.8	202.8
3rd Qu.	204	259	257.5
Max.	1023	993	402

surrounding Azerbaijan. In Iran, a recent study found high numbers of host and vectors in a historically active focus that has not been sampled in decades. *Y. pestis* antibodies were detected in rodent hosts, suggesting continued enzootic maintenance (Esmaeili et al., in press). The study also confirmed sero-positive dogs in the community suggesting recent spillover from the enzootic host to the dog population. Such evidence supports the need to study historical foci and to continue surveillance.

The goal of this study was to evaluate historical patterns of plague host abundance in an important plague focus in Azerbaijan. Such patterns can be used to identify priority areas for modern surveillance and inform public health initiatives. We identified regions of historically stable *M. libycus* abundance. We also established a relationship between environmental conditions and each level of abundance. In general, warmer and wetter conditions were associated with higher levels of *M. libycus* abundance. Finally, we explored changes in human population densities. There has been an increase in human populations in and around the plague focus in recent years, and an expansion of the protected lands system.

While the goal of this current study was to evaluate regions of persistent *M. libycus* abundance levels, it is important to consider the variability in abundance identified in the STAMP analysis. There were no abundance levels that were spatially or temporally stable over the entire study period. Abundance levels fluctuated within

Table 5

Mann-Whitney U test results for temperature, precipitation, and altitude comparing three abundance categories. The null hypothesis being tested is that there is no significant difference in environmental variables between abundance categories. The adjusted level of significance was $P = 0.005$.

	High v. average	High v. low	Average v. low
<i>Temperature (Degrees Celsius)</i>			
Statistic	223,504.5	2,452,037.0	86,708,423.0
P. value	0.102	>0.001 ^a	>0.001 ^a
<i>Precipitation (Millimeters)</i>			
Statistic	294,016.0	1,635,578.0	72,633,250.0
P. value	>0.001 ^a	>0.001 ^a	>0.001 ^a
<i>Altitude (Meters)</i>			
Statistic	260,743.0	1,833,097.0	49,040,114.0
P. value	>0.001 ^a	>0.001 ^a	>0.001 ^a

^a Reject the null hypothesis with 99% confidence.

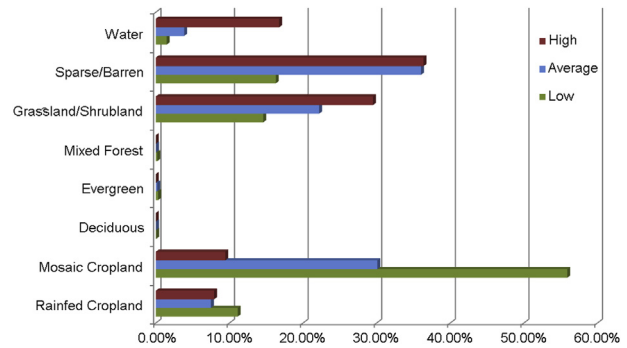


Fig. 8. The percentage of each land cover type associated with regions of high, average, and low rodent abundance.

the boundaries representing each category; however, those boundaries represent regions that were characterized by the persistence of one abundance level for multiple years at some point between 1972 and 1985. From a surveillance perspective, these historically stable regions can help inform surveillance by prioritizing regions with a history of higher abundance levels. If a region was historically characterized by high abundance, modern surveillance should prioritize that region for zoological surveys.

The relationship between environmental variables and host abundance can also be employed to predict regions that are predisposed to higher levels of *M. libycus* abundance. Land cover characteristics associated with different levels of abundance may be used to identify previously unsampled areas for surveillance priorities. If climate and land cover characteristics remains stable, the levels of rodent abundance will likely reflect historical distributions of *M. libycus* abundance. Under the scenario where climatic conditions become warmer and wetter then we might hypothesize *M. libycus* abundance is more likely to increase. Recent studies have suggested that the Caucasus region has experienced a warming trend (Evans, 2009; Githeko, Lindsay, Confalonieri, & Patz, 2000). In Europe, there is a concern that warmer winters induced by climate change could enhance the spread of vector borne diseases. by reducing the mortality of small vertebrate hosts and lengthen the activity of vectors, such as ticks (Githeko et al., 2000). It is possible that warming could have similar impacts on the natural plague cycle. Changes in rainfall are harder to predict; however, Githeko et al. (2000) hypothesize winters becoming wetter and summers becoming drier.

It is also important to think about the relationship between plague prevalence and host abundance. Ideally, control efforts would be prioritized for *M. libycus* populations with evidence of active *Y. pestis*. Here we have shown a relationship between relatively warm, wet climatic conditions and *M. libycus* host abundance in Azerbaijan. An association between warm, moist climate and higher levels of flea vectors has also been discussed in the literature

Table 6

The percentages of each land cover type that comprises the landscape for high, medium, and low *M. libycus* abundance.

Land cover type	Low	Average	High
Rainfed cropland	11.13%	7.49%	7.92%
Mosaic cropland	55.90%	30.10%	9.43%
Deciduous	0.06%	0.03%	0.00%
Evergreen	0.33%	0.20%	0.00%
Mixed forest	0.20%	0.03%	0.00%
Grassland/shrubland	14.60%	22.19%	29.51%
Sparse/barren	16.30%	36.04%	36.38%
Water	1.48%	3.85%	16.75%

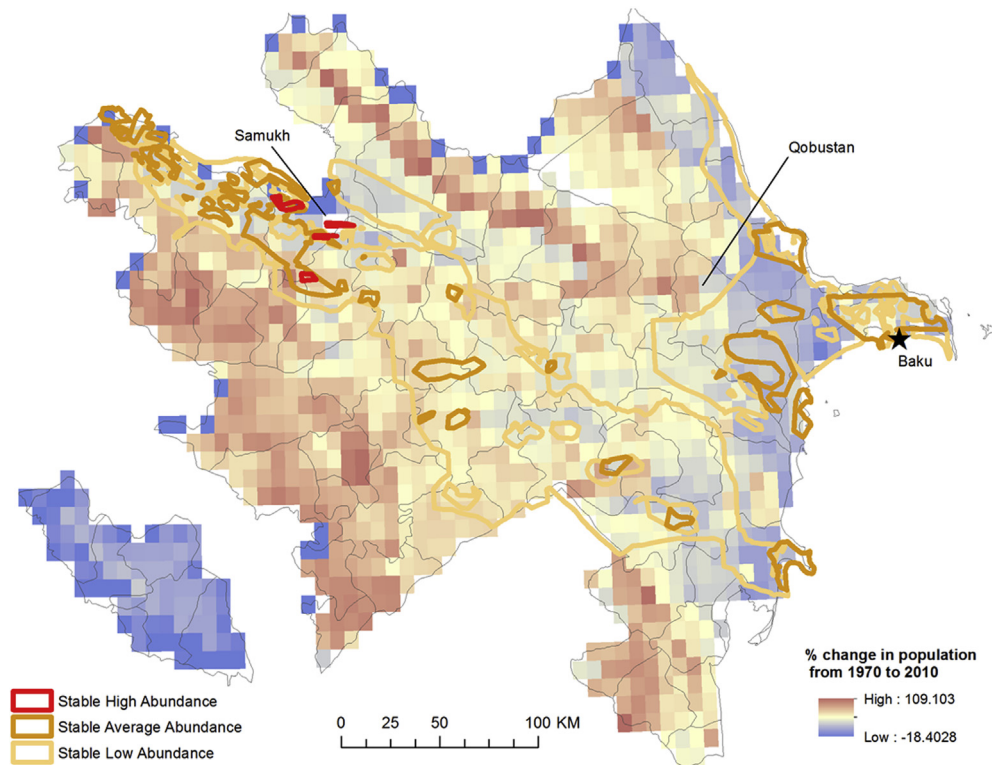


Fig. 9. The percentage population change between 1970 and 2010. Dark red indicates an increase in population. Stable regions for high, average, and low abundance area are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Cavanaugh & Marshall, 1972; Davis, 1953). Plague is a complex system with numerous factors affecting prevalence and spread; however, in general terms, high host abundance, high vector abundance and pathogen presence have been related to similar, broad scale environmental conditions. It is also important to consider that plague is more likely to persist in the environment with a higher abundance of rodent hosts (Gage & Kosoy, 2005; Stenseth et al., 2008). These findings suggest that regions associated with stable high rodent abundance are likely at greater risk of plague prevalence. Areas historically categorized as high abundance should be prioritized for surveillance efforts because they are the most likely to support plague prevalence.

Several studies have suggested that human proximity to plague hosts is a risk factor for human infection (Eisen, Reynolds, et al., 2007; Kartman, 1970; Schotthoefer et al., 2012). Schotthoefer et al. (2012) found that living close to environmental plague reservoirs in New Mexico was a significant risk factor for human plague. In Azerbaijan, human populations have increased in and around the plague focus. This is particularly concerning in the area surrounding regions of historically high *M. libycus* abundance. Increasing human populations, high levels of host abundance, and stable climate could create an intensified human plague risk in this region. Locations with growing human populations in close proximity to natural plague foci should be prioritized for surveillance and control efforts.

The increasing number of protected lands, coupled with growing populations also has potential implications for plague risk in Azerbaijan. In other parts of the world, national parks have been correlated with increased human disease risk. In Kyrgyzstan, the highest risk region of tick borne encephalitis is in Ala-Archa National Park, which is close to the capital city (Briggs et al., 2011). The park is a popular attraction for hikers, climbers, and tourists who come into close proximity with the rodent hosts and tick vectors

that inhabit the park (Briggs et al., 2011). In California, human plague cases have also been linked to host and vector populations in national parks. One model predicting plague host distribution identified national parks in California as a probable location for vector distribution (Adjemian, Girvetz, Beckett, & Foley, 2006). These predicted distributions also reflected sites of previous human cases (Adjemian et al., 2006). In the 1970's, California experienced an increase in human plague cases, and many of those cases were attributed to host populations in national parks (Nelson, 1980). Wilderness areas and national monuments were also locations marked as high risk for plague maintenance in the state (Nelson, 1980). The increase in national parks in Azerbaijan has the potential to provide an opportunity for plague hosts, such as *M. libycus*, and flea vectors to come into contact with people visiting the park. National parks, particularly those in close proximity to large population centers, should be prioritized for surveillance.

Working with historical data is inherently associated with challenges. Our original data were in the form of hand drawn maps that were georeferenced and digitized. This process, while crucial for utilizing historical documents, was likely associated with some degree of error. This error may have skewed the calculation of polygon area for *M. libycus* abundance. The historic field data collection may have also been prone to sampling bias. Sampling efforts were largely driven by expert opinion of known rodent habitat, which created a biased sampling design. It is possible that some of the spatial variation identified in *M. libycus* abundance is due to this sampling bias. The historic *M. libycus* dataset was created using polygons and pre-defined abundance categories, which limited opportunities to analyze differences in level of abundance within polygons. In reality, the host likely experiences heterogeneity in population size within categories and within polygons that cannot be accounted for with this dataset. Additionally, the GlobCover dataset was derived from satellite images

taken in 2005 and 2006, which might not reflect conditions at the time these *M. libycus* data were collected. While it is important to consider the challenges related to historic datasets, analyzing such data can provide crucial insight. Similarly to the challenges we encountered with our data, the literature has established sampling bias, or non-uniform reporting as the primary hurdle associated with employing historic data sets (Cliff, Haggett, Smallman-Raynor, Stroup, & Williamson, 1997). Despite these complications, historic data still have the potential to provide context for current outbreaks (Cliff, Haggett, & Smallman-Raynor, 2008). Cliff et al. (1997) liken the use of historic public health records to the use of long term climate data. In order to effectively improve short term forecasts, it is necessary to understand the long term patterns (Cliff et al., 1997). The reemergence of infectious disease is another reason studying past patterns is important (Cliff et al., 1997; Cliff et al., 2008). Using GIS is an effective method for analyzing historic data because of its capacity to integrate data from different sources and dates (Gregory & Healey, 2007). Cunfer (2005) used annual agricultural data and environmental data sets to explore the cause of the great plains dust storm. In another example, Skinner, Henderson, and Yuan (2000) also used GIS to analyze trends in fertility rates in China from the 1960s to the 1990s.

Despite such limitations, valuable information was obtained from this analysis. Our findings are important and relevant for three primary reasons. First, plague still affects human populations worldwide and needs to be carefully monitored (Perry & Fetherston, 1997; Stenseth et al., 2008). Second, impending climate change has the potential to increase prevalence of gerbil hosts in the future, which can increase the frequency at which plague can occur (Stenseth et al., 2006). Finally, changes in the public health system that accompanied the collapse of the Soviet Union have limited resources available for plague surveillance.

Our results can be used to prioritize limited resources for the surveillance and control of environmental plague foci in Azerbaijan. Regions of historically high *M. libycus* abundance should be prioritized. Regions of the country with climatic conditions associated with high abundance should also be prioritized. Employing predictive climate change models is one way to identify regions likely to experience a climatic shift towards favorable plague conditions (Holt, Davis, & Leirs, 2006). Similarly, stable climate is likely to be associated with stable rodent abundance. Regions with increasing human populations bordering plague foci should be monitored, as these present a high risk of human infection. Finally, protected lands with public access should be monitored because of the close proximity of humans and vectors.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.apgeog.2013.09.014>.

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