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Using very high spatial resolution remote sensing to monitor and combat outbreaks of bubonic plague in Kazakhstan

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Abstract. Bubonic plague, caused by the bacteria *Yersinia pestis*, persists as a public health problem in many parts of the world, including central Kazakhstan. Bubonic plague occurs most often in humans through a flea bite, when a questing flea fails to find a rodent host. For many of the plague foci in Kazakhstan the great gerbil is the major host of plague, a social rodent well-adapted to desert environments. Intensive monitoring and prevention started in 1947, reducing the number of cases and mortalities enormously. However, the monitoring is labour-intensive and hence expensive and is now under threat due to financial restraints. Previous research showed that the occupancy rate of the burrow-systems of the great gerbil is a strong indicator for the probability of a plague outbreak. The burrow-systems are around 30m in diameter with a bare surface. This paper aims to demonstrate the automatic classification of burrow-systems in satellite images using object-oriented analysis. We performed a field campaign in September 2007 and acquired a QuickBird image in the same period. Overall accuracy of the classification reached 95%, providing proof of concept that automatic mapping of burrow-systems using high-resolution satellite images is possible. Such maps, by better defining great gerbil foci, locating new or expanding foci and measuring the density of great gerbil burrow-systems could play a major role in a renewed monitoring system by better directing surveillance and control efforts. Furthermore, if similar analyses can separate occupied burrow-systems from empty ones, then very-high-resolution images stand to play a crucial role in plague surveillance throughout central Asia.

Keywords: Plague, *Yersinia pestis, Rhombomys opimus*, QuickBird imagery, Object-based image analysis

1. Introduction

Bubonic plague is best known for its disastrous effects that it had in the mid 14^{th} century. This outbreak of bubonic plague, more commonly referred to as the black death or black plague, was one of the deadliest pandemics in human history. Death toll estimates greatly vary but it is believed that in southern Europe around 75% of the population fell victim and in central Europe around 50% of the population died from this disease. The plague disease, caused by the bacteria *Yersinia pestis*, is commonly present in populations of ground rodents in central Asia, but it is not entirely clear where the 14th century pandemic started.

Although plague is now absent from Europe and can be treated with antibiotics, it persists on all continents except for Australia. In North America, human cases occur but plague is mainly a conservation concern as it plays havoc with efforts such as re-introductions of the black-footed ferret. Most human cases reported to WHO now come from Africa, and in places like Madagascar and Tanzania it is a serious public health issue with frequent human cases and deaths (Davis et al., 2004; Laudisoit et al., 2007). In central Asia too, plague remains a public health concern. The PreBalkhash focus is the site of this study and is located in the vast steppes north of the city of Almaty and south-east of Lake Balkhash. Fleas carried by the great gerbil living on the steppes of Asia are the vector of the disease. At the conclusion of world war II, the then soviet government of Kazakhstan began an intensive monitoring and control programme to prevent outbreaks of human plague. Within this monitoring system samples (of fleas and rodents) were collected from 10 by 10 km areas (hereon called sectors) and tested for plague by the Anti Plague Institute of Kazakhstan. The PreBalkhash focus (one of at least 18 plague foci in Kazakhstan) alone has over 350 such sectors spread out over an area of a few thousand square kilometers. The monitoring programme is very labor intensive and expensive and in this study we investigate how high resolution earth observation may contribute to the monitoring program and in controlling the outbreaks of bubonic plague.

The objective of this paper is to provide proof of concept that it is possible to reliably extract burrow-systems locations from very-high-resolution imagery. A larger project, set to begin in 2009, will focus on the distinction of occupied burrow-systems from empty ones and the development of a monitoring system in which remote sensing plays a key role.

2. The Bubonic plague system

The great gerbil (*Rhombomys opimus*) is a desert rodent of approximately 20 cm in size (figure 1) and is the major host of the plague bacterium (*Yersinia pestis*) in the Asian deserts and steppes. Great gerbils are social animals and live in family groups in underground burrow-systems comprising a complex network of tunnels and chambers until a depth of several meters. The underground burrow-system protects the family from predators and the extreme temperatures. The various chambers serve as storage space for food, as well as being dormitories and nursing space. A typical family group comprises of one adult male, one or more adult females and their immature offspring (Davis et al., 2004).

The vectors of the plague are primarily fleas that inhabit the burrow-system of the great gerbil. The gerbil itself is fairly resistant against the plague. Many studies have linked outbreaks in abundance of the gerbil population with variability of the numbers of (new) human cases of plague. Infectious fleas have easy access to great gerbils living together in the same burrow-system but limited access to families living in neighboring burrow-systems. Adult gerbils are believed to visit neighbouring burrow-systems up to 400 meters away, though dispersal movements from sub-adult males seeking to establish a new family group can be much further, up to 5 km (Randall & Rogovin, 2002).

In this study we investigate the possibilities of using high resolution earth observation to map and monitor the burrow-systems of the great gerbils. The burrow-systems vary in size but are often large, more or less circular complex constructions with a diameter of 15 to 40 meters. The vegetation above and around the burrow-system disappears, most likely due to herbivory by great gerbils and reduced soil water availability above the burrow-system. The individual burrow-systems are often connected by small trails and tracks resulting in star-like spatial patterns. The discs of bare earth that form above the burrow-systems, especially for the circular burrow-systems, are clearly visible on very-high-resolution satellite images (figures 1 and 2).

Figure 1. Great gerbil (*Rhombomys opimus*) (left) and burrow-system in the field (right). Several entrances are visible in the front of the photo.

3. Study area

The area selected for this study covers approximately 1.6 by 1.6 kilometers and is located northeast of the village of Bakanas around 200 km north of Almaty between Lake Balkhash in the North and the Ili river in the South. Central co-ordinates of the area are N45º05' and E76°25'. This area was selected because it comprises one of the monitoring sectors of the Kazakh Anti Plague Institute with known occurrence of the *Yersinia pestis* bacteria. The area is part of the central Asian desert and steppe region and has a sharply expressed continental climate due to its far away position of the oceans. It has very hot summers, cold winters, sharp annual and daily fluctuations of the temperatures, little and irregular seasonal precipitation, dry air, little cloudiness and many hours of sunlight (Suslov, 1961). Average annual rainfall is less than 200 mm. The focus area is a flat plateau bordered by a flood plain in the West and sand dunes up to 15 meters high in the East. Vegetation cover is sparse and is dominated by black saxaul (*Haloxylon aphyllum*), white saxaul (*Haloxylon persicum*) and various grass species. Some of the higher parts of the area are covered by lichens and mosses. The presence of mosses and lichens enhance the contrast in the satellite image with the burrow-systems where lichens and mosses are removed due to digging activities.

4. Data

We acquired a QuickBird image of the area on 19 September 2007, i.e. during the dry period. The image came with two different spatial resolutions, 1) 0.6m with three bands showing blue, green and red reflection, and 2) 2.4m with four bands showing near-infrared reflection in addition to blue green and red. Preprocessing was applied by the provider; we used the data as we received them, i.e. with DN's rather than radiance values.

We had a field campaign in the same period as the image was taken, i.e. 5-7 September 2007. We followed a stratified random sampling design, such that we would spread field observations over the area but locally at random locations. We walked transects 1.5km long and 20m wide. Each encountered burrow-system was surveyed with the following variables: position (GPS), GPS estimated position error, burrow length and width, orientation, and

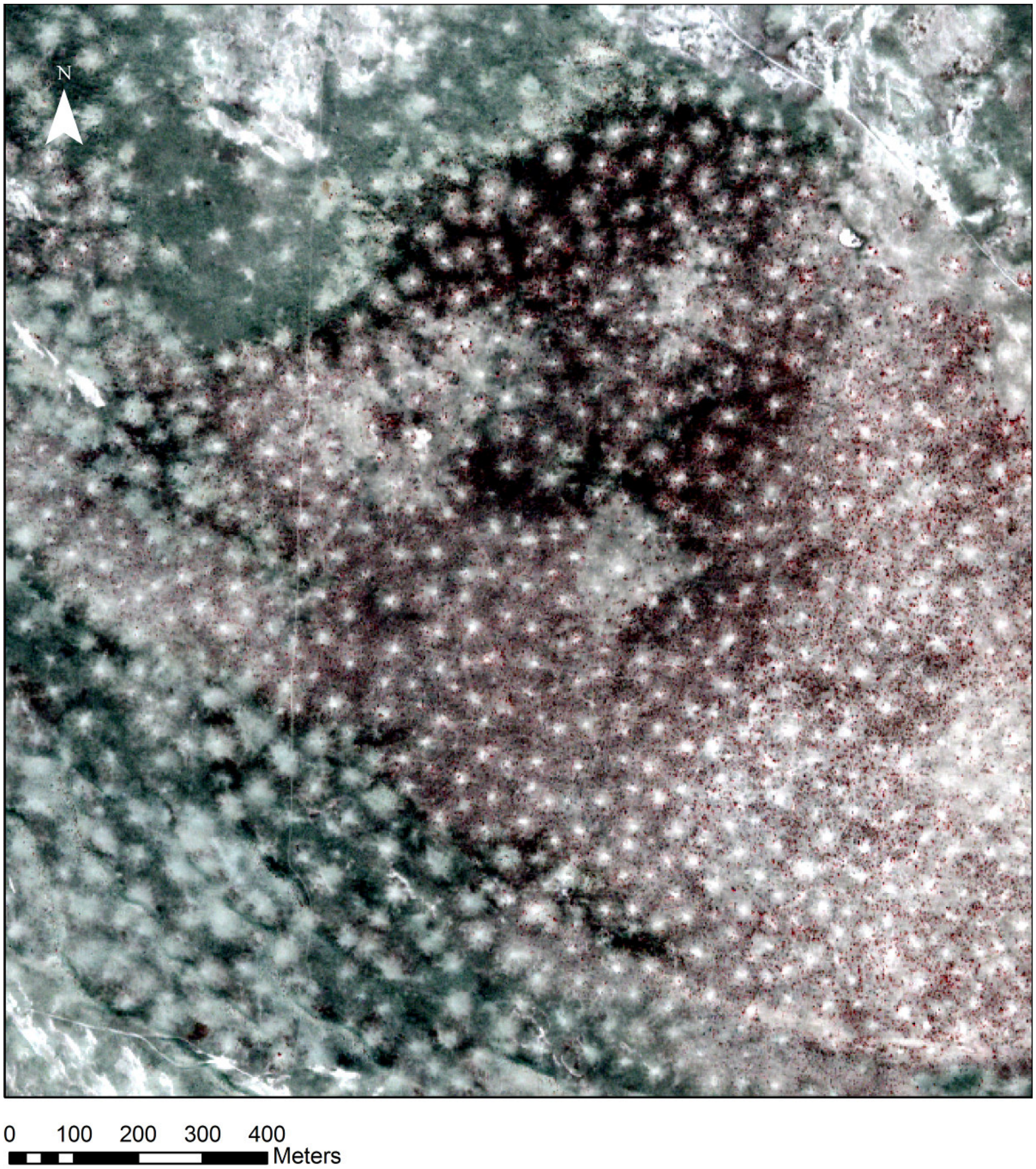

Figure 2: QuickBird satellite image of the study area 200 km North of Almaty, Kazakhstan. Acquired on 19 September 2007, pixel size = 2.4m, RGB= nIR, R, G

whether the burrow-system was occupied, empty or visited (indicating that it was infrequently used by a neighbouring family group). Starting points and directions of transects were determined randomly. We surveyed 71 burrow-systems and in addition we collected coordinates of 65 locations that represented non-burrow-systems.

5. Methods

5.1 Image preparation

As a first step in the interpretation of the images, the locations of burrow-systems as observed in the field were plotted on the images. These corresponded very well to the bright spots visible in the images (figure 3).

After comparing reflectance curves of the burrow-systems with different land cover types encountered in their surroundings, we concluded that pixel-based analysis would not provide an accurate classification. Instead we decided to work with an object-based approach. Two methods are available to create objects in an image (Addink et al., 2007), segmentation and stratification, where the first only uses information from the image itself, whereas the latter includes additional information. Since no external, spatially continuous data on the burrow-systems were available, segmentation was used to build the objects. When segmenting an image, neighboring pixels that are similar in spectral behavior are grouped into objects. The user sets a threshold regarding the heterogeneity allowed within an object; higher heterogeneity thresholds will result in larger objects. We used eCognition 3.1 (Definiens, 2003) to build the objects, which uses randomly located seeds to let new objects grow. To reduce the effect of the seed location, we subjected the images first to an edge-preserving-feature filter.

The images were segmented with a heterogeneity threshold such that the brightest spots in the centre of the larger burrow-systems would coincide with a single segment. The 0.6m images proved to contain too much spatial detail to derive meaningful objects, hence the analysis was performed with the 2.4m images. The four bands were equally weighed during the segmentation. For each object three types of variables were determined: 1) spectral attributes (mean, variance, brightness), 2) shape attributes (size, compactness, etc.), and 3) neighbor attributes (difference to neighboring objects in various aspects).

5.2 Combining field data with the image objects

The field data set consists of points representing burrow-systems and non-burrow-systems. Each observation point was buffered by a distance equal to its GPS estimated position error (EPE) and the resulting polygons were intersected with the image objects. For each field observation of a burrow-system, the intersecting object with the highest brightness was selected and labeled as a burrow-system. For each observation of a non-burrow-system, the intersecting object with the lowest brightness was labeled as a non-burrow-system.

The field data set was split into a training set and a validation set. We used the objects from the training set with their attributes to create classification trees (Breiman et al., 1984), which were then applied to the validation set. Although classification trees are not commonly used within the remote sensing community, they have some major advances over the widely spread maximum likelihood classifier, particularly for object-based image analysis. With OBIA, the number of variables is huge when compared to the number of spectral bands. Intercorrelation between some of those variables is very likely, which will put too much weight to the independent variance they represent. Furthermore, the number of observations for each class incorporated in the classification procedure must exceed the total number of variables when applying MLH. This is not an issue with classification trees. With MLH, all variables are assumed to show a normal distribution. Again, with classification trees this is no issue. A drawback of classification trees is that they consider single variables at a time in a step-wise manner. At each step the best variable is selected without taking further steps into account. This may lead to a sub-optimal performance when a multi-variate approach would lead to higher accuracy than a single variable.

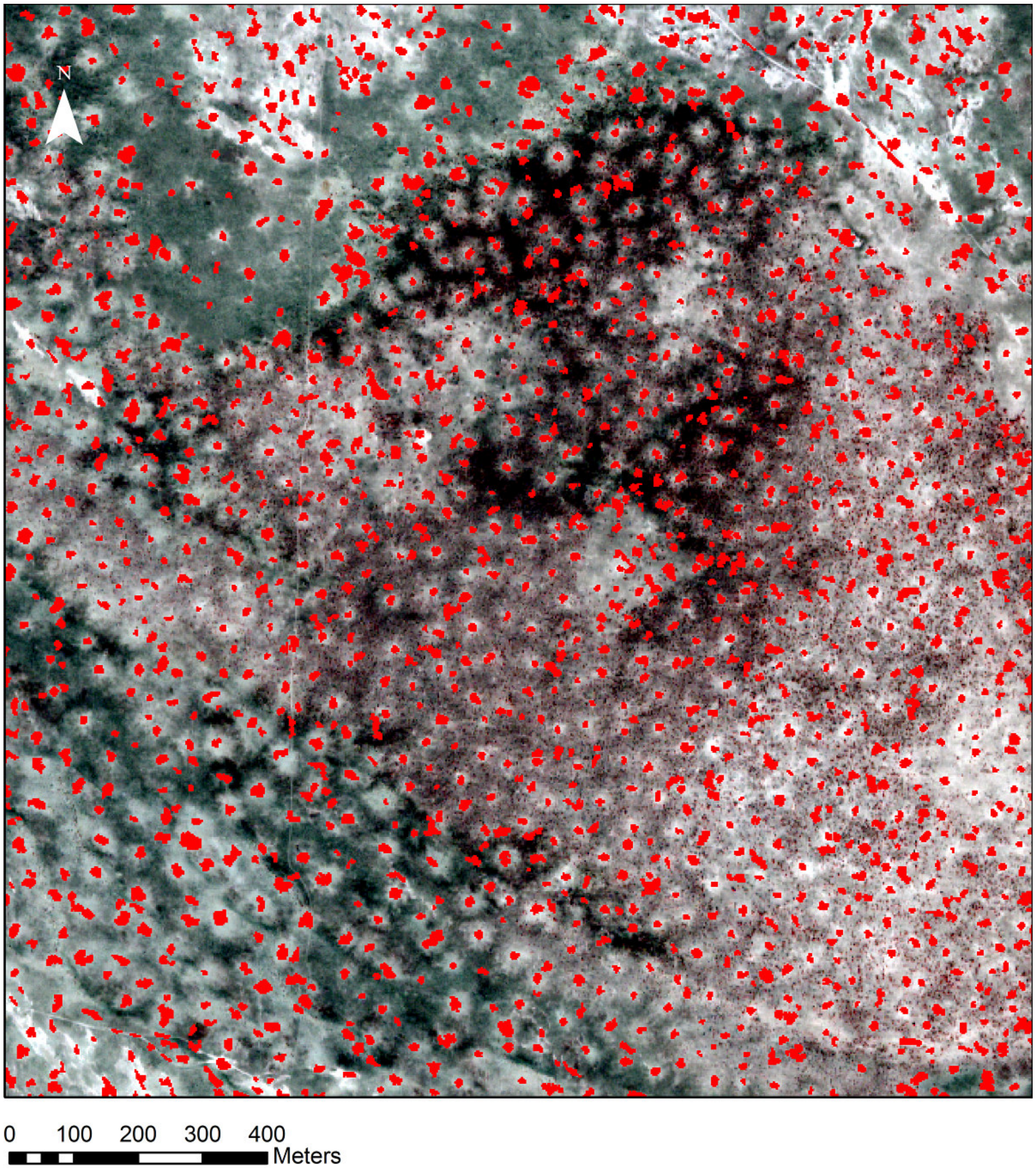

Figure 3. QuickBird image overlaid with segments classified as burrow-system in red. See figure 2 for image details.

Classification with the classification trees showed all objects that based on their attributes (spectral, shape and neighbor) were recognized as a potential burrow-system. This procedure would not take into account, however, that burrow-systems are separated from each other by a non-burrow-system object. Hence, a second classification step was performed to introduce the condition that only one of two neighboring objects can be a burrow-system. In case two or more adjacent objects were indicated as burrow-systems, the brightest object would be selected and classified as a burrow-system.

6. Results

Fieldwork in the Bakanas plain, southeastern Kazakhstan, yielded locations of 71 burrow-systems of which 98% were occupied. Besides, 65 locations were sampled for the class non-burrow-system. The corresponding segments from the QuickBird image together with their attributes were used as a training set in the classification of the entire image.

Overall classification accuracy was 96%. 98% of the observed burrow-systems were identified correctly, whereas 93% of the non-burrow-system segments were classified correctly.

The variables used in the classification tree were the relative border to neighboring segments with higher values in band 1, mean value for band 1, difference to brighter neighboring segments in band 4 and the area of the objects.

7. Discussion

We performed an object-based classification of burrow-systems in a desert area with sparse vegetation. Overall accuracy was 95%, while 98% of the burrow-systems and 93% of the non-burrow-systems was classified correctly. Although accuracy values for both classes are high, future focus for classification will be on improving the classification of the non-burrow-systems. The burrow-systems can be considered as one spectral class with land cover being bare soil, whereas the non-burrow-systems class contains a variety of spectral coverages: vegetation, bare patches, dried, crusted ponds. During the next field campaigns we will pay extra attention to include sufficient samples of the different cover types.

Identifying the occupancy state of the burrow-system is outside the scope of this paper but, in any case, could not have been studied with the collected field data due to the extremely high occupancy rate of 98%.

8. Conclusions

We performed classification of burrow-systems of the great gerbil in southeastern Kazakhstan to show that with limited field work a relatively large area can be surveyed. The burrow-systems stand out clearly from their surroundings because of their non-vegetated surface and their compact shape. With object-oriented image analysis we had an overall classification accuracy of 95%, whereas 98% of the observed burrow-systems were classified correctly.

The density of burrow-systems is an important determinant in the spread of *Yersinia pestis*, the bacteria responsible for bubonic plague. Intensive monitoring programmes have been performed since the late 1940's, but because of economic restrictions these programmes are under threat. The estimation of burrow-system density from high-resolution satellite images is an exciting first step towards improving the surveillance of plague as the programme comes under financial pressures. From a public health perspective, such mapping capabilities already indicate we can better define great gerbil habitat, identify expanding foci and detect new great gerbil populations. Such steps provide a basis for directing financially-constrained effort towards places where great gerbil populations are in close proximity to human settlements or activity. Our satisfying results indicate that we should definitely continue to explore the possibilities of very-high-resolution imagery for the monitoring and control of bubonic plague in Kazakhstan.

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