Remote sensing data enable scientists to study the earth’s biotic and abiotic components. These components and their changes have been mapped from space at several temporal and spatial scales since 1972. A small number of investigators in the health community have explored remotely sensed environmental factors that might be associated with disease-vector habitats and human transmission risk. However, most human health studies using remote sensing data have focused on data from Landsat’s Multispectral Scanner (MSS) and Thematic Mapper (TM), the National Oceanic and Atmospheric Administration’s Advanced Very High Resolution Radiometer (AVHRR), and France’s Système Pour l’Observation de la Terre (SPOT). In many of these studies (Table 1), remotely sensed data were used to derive three variables: vegetation cover, landscape structure, and water bodies.

International space agencies are planning an estimated 80 earth-observing missions in the next 15 years (29). During these missions >200 instruments will measure additional environmental features such as ocean color and other currently detectable variables, but at much higher spatial and spectral resolutions. The commercial sector is also planning to launch several systems in the next 5 years that could provide complementary data (30). These new capabilities will improve spectral, spatial, and temporal resolution, allowing exploration of risk factors previously beyond the capabilities of remote sensing. In addition, advances in pathogen, vector, and reservoir and host ecology have allowed assessment of a greater range of environmental factors that promote disease transmission, vector production, and the emergence and maintenance of disease foci, as well as risk for human-vector contact. Advances in computer processing and in geographic information system and global positioning system technologies facilitate integration of remotely sensed environmental parameters with health data so that models for disease surveillance and control can be developed.

In 1998, the National Aeronautics and Space Administration’s (NASA) Center for Health Applications of Aerospace Related Technologies (CHAART) evaluated current and planned
satellite sensor systems as a first step in enabling human health scientists to determine data relevant for the epidemiologic, entomologic, and ecologic aspects of their research, as well as developing remote sensing-based models of transmission risk. This article discusses the results of the evaluation and presents two examples of how remotely sensed data have been used in health-related studies. The first example, a terrestrial application, illustrates how a single Landsat TM image was used to characterize the spatial patterns of key components of the Lyme disease transmission cycle in New York. The second example, which focuses on the coastal environment, shows how remote sensing data from different satellite systems can be combined to characterize and map environmental variables in the Bay of Bengal that are associated with the temporal patterns of cholera cases in Bangladesh. These examples demonstrate how remote sensing data acquired at various scales and spectral resolutions can be used to study infectious disease patterns.

**Lyme Disease in the Northeastern United States**

During the past 10 years, NASA’s Ames Research Center has been collaborating with the New York Medical College and the Yale School of Medicine to develop remote sensing-based models for mapping Lyme disease transmission risk in the northeastern United States (31,32). The first study compared Landsat TM data with canine seroprevalence rate (CSR) data summarized at the municipality level (31). The canine data were used as a measure of human exposure risk, the assumption being that dogs were more likely to acquire tick bites on or near their owner’s property. The second study used TM data to map relative tick abundance on residential properties by using TM-derived indices of vegetation greenness and wetness (32). Figure 1 shows a subset of the TM data used in both studies, as well as some of the products (e.g., maps) derived from the data. Each product illustrated Lyme disease transmission variables, such as vector and reservoir habitats, as well as human risk for disease. Figure 1a shows raw Landsat-5 TM data, which are recorded in six spectral bands (excluding a seventh thermal band) at a spatial resolution of 30 m. These data were processed to derive the products shown in Figures 1b-d.

The image in Figure 1b was used to explore the relationship between forest patch size and deer distribution. Because white-tailed deer
Figure 1. Landsat Thematic Mapper (TM) satellite data for a 6x6-km area in Westchester County, New York. Shown are the raw data (a), as well as products (e.g., maps) derived from the data (b-d) that might be used for modeling Lyme disease transmission risk. a) Raw Landsat TM image composed of bands 5, 4, and 3 (mid-infrared, near-infrared, and red bands). Vegetation is shown in shades of green, with bare soil and urban areas shown in shades of pink and purple. The spatial resolution of these data is 30x30 m. b) Map showing contiguous forest patches, derived from a Landsat TM classification. Colors represent discrete patches, with white indicating the absence of contiguous forest. c) A 12-class land cover map derived from the Landsat TM data. d) Composite image of three spectral indices derived from the Landsat TM data, showing the contributions of scene brightness in red, greenness in green, and wetness in blue.
serve as a major host of the adult tick as well as its primary mode of transportation, deer distribution was a potentially important factor in a Lyme disease risk model.

Figure 1c shows 12 classes used in two separate analyses of risk at two different scales (31). These classes include water, evergreen trees/vegetation, sparse deciduous trees, dense deciduous trees, clearings, golf courses (managed grass), urban/commercial, miscellaneous urban, residential-lawn, residential-sparse vegetation, residential-medium vegetation, and residential high-vegetation. In the first scale, the amount of remotely sensed deciduous forest was positively correlated (r = 0.82) with canine exposure to Borrelia burgdorferi, as indicated by CSR data summarized by municipality. In the second analysis, a linear regression of the residential-high vegetation pixels (i.e., wood-edge) and CSR data resulted in a correlation coefficient of 0.84—indicating that human-host contact risk (e.g., deer leaving the forest to feed on residential ornamental vegetation) might be a good measure of human-vector contact risk.

The image in Figure 1d was derived from the Landsat TM data by a Tasseled Cap Transformation (33). Tasseled Cap greenness and wetness were positively correlated with tick abundance on residential properties in this study area (32).

Cholera in Bangladesh
The second example of the use of remotely sensed data to provide information for health research and applications concerns cholera in Bangladesh. In this study, described by Lobitz et al. (34), remotely sensed datasets, downloaded from the Internet at no cost, were used to search for temporal patterns in the Bay of Bengal associated with cholera outbreaks in Bangladesh.

Figure 2a shows a color-infrared image of the Ganges River, where it empties into the Bay of Bengal. These data, which were acquired by NOAA’s AVHRR sensor, have a spatial resolution of 1.1 km. The sediment load, transported to the Bay of Bengal by the Ganges and Brahmaputra rivers, includes nutrients that could support plankton blooms. Plankton is an important marine reservoir of Vibrio cholerae, which attaches primarily to zooplankton, which, in turn, is associated with phytoplankton (35).

In Figure 2b, the AVHRR data shown in Figure 2A were processed to show sea surface temperature (SST) (36). Because these data are for large-area studies, they have been processed at a spatial resolution of 18 km. Figure 2c represents sea surface height (SSH) anomaly data derived from the TOPEX/Poseidon satellite (37). These data have a spatial resolution of 1 degree. Increases in SST and SSH have preceded cholera outbreaks in Bangladesh (34).

In the next 15 years, new sensors will provide valuable data for studies of infectious diseases similar to the ones described here. For Lyme disease, new sensors could provide similar information about ecotones, human settlement patterns, or forests. These sensors include ARIES-1, scheduled for launch by Australia; CCD and IR/MSS sensors onboard CBERS, launched by China and Brazil in late 1999; IKONOS, a commercial satellite with 4-m spatial resolution; LISS III, onboard the orbiting Indian IRS-1C and -1D satellites; and ASTER, onboard the recently launched Terra satellite. Information from these sensors could also be used to address other vector-borne diseases, such as malaria, schistosomiasis, trypanosomiasis, and hantavirus, whose patterns are likewise influenced by environmental variables.

SeaWiFS, the Sea-Viewing Wide Field-of-View Sensor, with its increased spectral resolution of 1.1 km, is already providing imagery critical to understanding the temporal and spatial pattern of cholera risk (35). This sensor was specifically designed to gather information about ocean color (38) (Figure 2d).

Sensor Evaluation Project
CHAART evaluated data from current and planned satellite instruments for mapping, surveillance, prediction, and control of human disease transmission activities, including vector ecology, reservoir and host ecology, and human settlement patterns. From hundreds of potential sensors, 54 were identified that were current (or would be launched within the next 5 years), operational (not reserved for the scientific community), and digital (not photographic).

Beginning in 1985, NASA has held a series of workshops to elicit input from the health community on the use of remote sensing in the areas of entomology, ecology, epidemiology, vector control, and infectious diseases. In addition, NASA has participated in sessions on remote sensing and health at professional meetings sponsored by national and international health.
Perspectives

Figure 2. Datasets used to model the temporal patterns of cholera outbreaks in Bangladesh. 

Figure 2. a) Advanced Very High Resolution Radiometer (AVHRR) satellite image showing the mouth of the Ganges River and the Bay of Bengal. Vegetation is shown in shades of red and water in shades of blue. The spatial resolution of these data is 1.1 km. b) Sea surface temperature data, derived from AVHRR thermal bands. Temperatures range from low (purple) to high (red). c) Sea surface height data, derived from TOPEX/Poseidon satellite data. The spatial resolution of these data is 1 degree. d) Image derived from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) showing chlorophyll concentration, ranging from low (blue) to high (red). These satellite data have a nominal spatial resolution of 1.1 km.

organizations. On the basis of this experience as well as a review of the scientific literature (Table 1), there does not appear to be consensus in the health community regarding requirements for a remote sensing system. Some investigators use remotely sensed data to resolve questions regarding the relationship between an aspect of disease transmission and an environmental variable. Other researchers already have a model of disease transmission and have specific spatial, temporal, or spectral requirements for the remotely sensed variables.

No single spatial, temporal, or spectral resolution is universally appropriate for understanding the transmission risk for any disease, given the variety of vectors, reservoirs, hosts,
geographic locations, and environmental variables associated with that disease. Therefore, in evaluating the existing sensors, CHAART used an approach that allowed individual investigators to identify satellite data appropriate for their own needs. This approach defined 16 groups of physical factors that could be used for both research and applications. Each factor is essentially an environmental variable that might have a direct or indirect bearing on the survival of pathogens, vectors, reservoirs, and hosts. These factors may also affect many types of non-vector-borne diseases, such as waterborne diseases. The factors are vegetation or crop type, vegetation green-up, ecotones, deforestation, forest patches, flooded forests, general flooding, permanent water, wetlands, soil moisture, canals, human settlements, urban features, ocean color, SST, and SSH. Precipitation, humidity, and surface temperature were not included because deriving these measurements from raw data requires highly specialized processing and calibration, routinely performed by qualified groups who often make the information available on Internet websites (Appendix B).

The sensor evaluation project generated a series of tables that associated each of the 16 factors with the 54 sensors according to spatial, temporal, and spectral characteristics. For example, factors requiring frequent monitoring, such as vegetation green-up, are linked with sensors with shorter repeat overpasses. Similarly, factors requiring very high spatial resolution, such as mapping urban features, are linked with sensors having a spatial resolution of 10 m or less, regardless of their temporal or spectral resolutions.

Perhaps the broadest use of Landsat and SPOT data has been to identify and map vegetation or crop types. This factor is important because the distribution of vegetation types integrates the combined impact of rainfall, temperature, humidity, topographic effects, soil, water availability, and human activities. Nearly all vector-borne diseases are linked to the vegetated environment during some aspect of their transmission cycle; in many cases, this vegetation can be sensed remotely from space. The spatial and temporal distribution of vector or reservoir and host species may relate to the occurrence and distribution of specific vegetation or crop types, not simply to whether an area has forests or grasslands. For example, food and cover preferences of the white-tailed deer, the host for adult ticks that transmit Lyme disease in the northeastern United States, might well encourage deer to live near certain types of forest. Crop-type information may also be important for studying the effects of pesticides (e.g., vector resistance; illnesses caused by exposure to toxins).

The sensor evaluation procedure has identified many potentially useful sensors for mapping vegetation and crop type beyond the Landsat and SPOT systems (Table 2). A ground resolution threshold of 30 m was used as the upper limit for exploring the relationship between vegetation (or crop) type and disease vectors, reservoirs, and hosts; above 30 m, vegetation and crop type are more difficult to ascertain. Many of the sensors could also be used for mapping the boundary

| Temporal resolution (d) | Spatial resolution (m) |
|-------------------------|------------------------|
|                         | 1-5                    |
|                         | 6-10                   |
|                         | 11-30                  |
| Daily 2-7               | (QuickBird)\(^c\)      |
|                         | (Orbview-3,4)          |
|                         | (QuickBird)            |
|                         | (Almaz-1b MSU-E2)      |
|                         | (ALOS AVNIR-2)         |
|                         | (Orbview-4)            |
|                         | (SPOT-5a,b 3xHRG)      |
| 8-14                    | Ikonos                 |
| 15-30                   | Priroda/Mir MOMS-2P    |
| >30                     | (ALOS AVNIR-2)         |

\(^a\)This matrix is the output from an interactive search with the search engine located at http://geo.arc.nasa.gov/sge/health/sensor/senchar.html.

\(^b\)See Appendix A for explanations of sensor acronyms.

\(^c\)Sensors in parentheses have not yet been launched.
between vegetation types, or ecotones, which provide habitat for insects and animals critical to the maintenance and transmission of vector-borne diseases. These edges may be areas for increased risk for vector-human contact, as indicated by the relationship between Lyme disease transmission and suburban encroachment into forested areas in the northeastern United States. The movement of humans into forested edges where potential vectors are established could also be important for predicting malaria or yellow fever transmission.

The list of 16 factors used in the CHAART evaluation includes some that have not yet been quantified because available sensors do not provide adequate spatial, spectral, or temporal resolutions. Two of these factors are briefly described below to illustrate how remotely sensed data might be used to explore their potential links to human health. More links between the factors and various diseases are listed in Table 3.

Table 3. Potential links between remotely sensed factors and disease

| Factor                  | Disease                          | Mapping opportunity                                                                 |
|-------------------------|----------------------------------|-------------------------------------------------------------------------------------|
| Vegetation/crop type    | Chagas disease                   | Palm forest, dry & degraded woodland habitat for triatomines                         |
|                         | Hantavirus                       | Preferred food sources for host/reservoirs                                          |
|                         | Leishmaniasis                    | Thick forests as vector/reservoir habitat in Americas                                |
|                         | Lyme disease                     | Preferred food sources and habitat for host/reservoirs                                |
|                         | Malaria                          | Breeding/resting/feeding habitats; crop pesticides → vector resistance               |
|                         | Plague                           | Prairie dog and other reservoir habitat                                            |
|                         | Schistosomiasis                  | Agricultural association with snails, use of human fertilizer                        |
|                         | Trypanosomiasis                  | Glossina habitat (forests, around villages, depending on species)                   |
|                         | Yellow fever                     | Reservoir (monkey) habitat                                                          |
| Vegetation green-up     | Hantavirus                       | Timing of food sources for rodent reservoirs                                        |
|                         | Lyme disease                     | Habitat formation and movement of reservoirs, hosts, vectors                        |
|                         | Malaria                          | Timing of habitat creation                                                          |
|                         | Plague                           | Locating prairie dog towns                                                          |
|                         | Rift Valley fever                | Rainfall                                                                            |
|                         | Trypanosomiasis                  | Glossina survival                                                                   |
| Ecotones                | Leishmaniasis                    | Habitats in and around cities that support reservoir (e.g., foxes)                  |
| Deforestation           | Chagas disease                   | New settlements in endemic-disease areas                                             |
|                         | Malaria                          | Habitat creation (for vectors requiring sunlit pools)                                |
|                         | Yellow fever                     | Habitat destruction (for vectors requiring shaded pools)                            |
|                         |                                   | Migration of infected workers into forests where vectors exist                       |
|                         |                                   | Migration of disease reservoirs (monkeys) in search of new habitat                  |
| Forest patches          | Lyme disease                     | Habitat requirements of deer and other hosts/reservoirs; human/vector contact risk  |
|                         | Yellow fever                     | Reservoir (monkey) habitat, migration routes                                        |
| Flooded forests         | Malaria                          | Mosquito habitat                                                                    |
| Flooding                | Malaria                          | Mosquito habitat                                                                    |
|                         | Rift Valley fever                | Flooding of dambos, breeding habitat for mosquito vector                            |
|                         | Schistosomiasis                  | Habitat creation for snails                                                         |
|                         | St. Louis encephalitis           | Habitat creation for mosquitoes                                                     |
| Permanent water         | Filariasis                       | Breeding habitat for Mansonia mosquitoes                                            |
|                         | Malaria                          | Breeding habitat for mosquitoes                                                     |
|                         | Onchocerciasis                   | Simulium larval habitat                                                             |
|                         | Schistosomiasis                  | Snail habitat                                                                       |
| Wetlands                | Cholera                          | Vibrio cholera associated with inland water                                         |
|                         | Encephalitis                     | Mosquito habitat                                                                    |
|                         | Malaria                          | Mosquito habitat                                                                    |
|                         | Schistosomiasis                  | Snail habitat                                                                       |
| Soil moisture           | Helminthiases                    | Worm habitat                                                                        |
|                         | Lyme disease                     | Tick habitat                                                                        |
|                         | Malaria                          | Vector breeding habitat                                                             |
|                         | Schistosomiasis                  | Snail habitat                                                                       |
| Canals                  | Malaria                          | Dry season mosquito-breeding habitat; ponding; leaking water                         |
|                         | Onchocerciasis                   | Simulium larval habitat                                                             |
|                         | Schistosomiasis                  | Snail habitat                                                                       |
| Human settlements       | Diseases                         | Source of infected humans; populations at risk for transmission in general          |
| Urban features          | Chagas disease                   | Dwellings that provide habitat for triatomines                                      |
|                         | Dengue fever                     | Urban mosquito habitats                                                             |
|                         | Filariasis                       | Urban mosquito habitats                                                             |
|                         | Leishmaniasis                    | Housing quality                                                                     |
|                         |                                  |                                                                                     |
| Ocean color (Red tides) | Cholera                          | Phytoplankton blooms; nutrients, sediments                                          |
| Sea surface temp.       | Cholera                          | Plankton blooms (cold water upwelling in marine environment)                        |
| Sea surface height      | Cholera                          | Inland movement of Vibrio-contaminated tidal water                                  |
Urban Features

The detection of urban features requires higher spatial resolution systems than needed for detecting the presence of human settlements. Some disease vectors are associated with specific urban features such as housing type, which can only be detected by sensors with very high spatial resolution. In the future, new sensors may be able to provide information on the urban environment (Table 4).

Table 4. Current and proposed sensor systems for identifying and mapping urban features

| Temporal resolution | Spatial resolution a (m) |
|---------------------|-------------------------|
| (d)                 | 1-5                     | 6-10                   |
| Daily 2-7           | (QuickBird)             | (ALOS AVNIR-2)         |
|                    | (Orbview-3,4)           | (ALOS AVNIR-2)         |
|                    | (QuickBird)             | (ARIES-1)              |
|                    | (SPOT-5a,b 3xHRVIR)     | (ALOS AVNIR-2)         |
| 8-15                | Ikonos                  | IRS-1C,D PAN           |
| 15-30               |                         | Priroda/Mir MOMS-2P    |
| >30                 | (ALOS AVNIR-2)          | (ALOS AVNIR-2)         |

aThis matrix is the output from an interactive search with the search engine located at http://geo.arc.nasa.gov/sge/health/sensor/senchar.html.

Soil Moisture

Wet soils indicate a suitable habitat for species of snails, mosquito larvae, ticks, and worms. Several types of sensors can detect soil moisture, including synthetic aperture radars (SARs), shortwave-infrared, and thermal-infrared sensors (Table 5). SARs are particularly important for sensing ground conditions in areas of cloud cover or vegetation canopy cover, two factors commonly found in the tropics.

Conclusions

The extent to which remotely sensed data are used for studying the spatial and temporal patterns of disease depends on a number of obstacles and opportunities. Many of the obstacles—including cost, inadequate spatial, spectral, or temporal resolutions, and long turnaround times for products—have restricted the use of remote sensing within the user community as a whole. Many of these barriers will be addressed by new sensor systems in the next 5 years. The recently launched Landsat-7 ETM+ sensor, for example, is now providing 30-m multispectral data, a 15-m panchromatic band, and an improved 60-m thermal infrared band, all at a cost that is an order of magnitude less than current Landsat-5 TM data.

With the higher spatial and spectral resolutions, more frequent coverage, lower price,
and increased availability offered by the range of new sensors, human health investigators should be able to extract many more environmental variables than previously realized. These improvements will provide new opportunities to extend the uses of remote sensing technology beyond a few vector-borne diseases to studies of water- and soil-borne diseases (for example, cholera and schistosomiasis [waterborne] and the helminthiasis) and the mapping of human settlements at risk. The next generation of earth-observing remote sensing systems will also allow investigators in the human health community to characterize an increasing range of variables that are key to understanding the spatial and temporal patterns of disease transmission risk. These improved capabilities, when combined with the increased computing power and spatial modeling capabilities of geographic information systems, should extend remote sensing into operational disease surveillance and control.

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Appendix B. Partial list of Internet locations that contain (or will contain) products derived from remotely sensed precipitation, moisture, relative humidity, and surface temperature data

| Parameter          | Mission/sensor | Spatial   | Temporal | Web site                                                      |
|--------------------|----------------|-----------|----------|---------------------------------------------------------------|
| Precipitation      | TRMM/TMI       | 10 km     | D        | daac.gsfc.nasa.gov/CAMPAIGN_DOCS/hydrology/                 |
|                    | TRMM/TMI       |           | M        | daac.gsfc.nasa.gov/CAMPAIGN_DOCS/hydrology/                 |
|                    | Terra/DAS²     | 1°        | 8-day    | eos-am.gsfc.nasa.gov                                         |
|                    | GOES/Sounder   | 10 km     | hr       | www.nndc.noaa.gov/phase3/productacm.htm                      |
| Precipitation rate | Terra/DAS²     | 2°        | 8/day    | eos-am.gsfc.nasa.gov                                         |
| Precipitation amount| TOVS/MSU      | 0.5°      | D, M, Y  | ghr.eumetsat.de/en                                           |
| Moisture           | GOES/Imager    | 8 km      | hr       | www.nndc.noaa.gov/phase3/productacm.htm                      |
| Relative humidity  | Terra/DAS²     | 2°        | 4/day    | eos-am.gsfc.nasa.gov                                         |
| Surface temperature| Terra/MODIS    | 1 km      | D        | eos-am.gsfc.nasa.gov                                         |
| Surface temperature| Terra/MODIS    | 1°        | D, 8-day, M | eos-am.gsfc.nasa.gov                                    |
| Surface temperature| Terra/DAS²     | 2°        | 8/day    | eos-am.gsfc.nasa.gov                                         |
| Surface temperature| Envisat/AATSR  | 17 km     | D        | envisat.estec.esa.nl/envisat-welcom.html                    |
| Surface temperature| Envisat/AATSR  | 50 km     | D        | envisat.estec.esa.nl/envisat-welcom.html                    |
| Surface temperature| ERS/ATSR       | 1 km      | W        | earth1.esrin.esa.int/ERS                                   |
| Surface temperature| Meteosat/VISSR | 5 km      | 48/day   | www.eumetsat.de/en                                          |
| Surface temperature| GOES/Imager    | 4 km      | hr       | www.nndc.noaa.gov/phase3/productacm.htm                      |

Notes:
- See Appendix A for explanation of sensor acronyms.
- hr, hourly; D, daily; W, weekly; M, monthly; Y, yearly.
- Future launch.
- Data Assimilation System.