<u>Title</u>: A Thermodynamic Paradigm For Using Satellite Based Geophysical Measurements For Public Health Applications

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<u>Description:</u> Vector borne diseases are emerging and re-emerging on a global scale (Fig 1. (Morens et al. 2004)). Vector-borne diseases were once a major public health concern only in tropical and subtropical areas, but today they are also an emerging threat for the continental and developed countries. Vector-borne diseases are among the most complex of all infectious diseases to prevent and control. Not only is it difficult to predict the habits of many of the vectors, but most vector-borne agents can infect animals as well. The globalization of many country's regional economies, climate variability, and civil unrest have spurred rapid movements of large human populations along with many of the disease vectors and reservoirs. Landscape scale alteration in ecosystems and land use impact the distribution of vector habitat and their interaction with human populations. *Aedes aegypti* mosquitoes, the "urbanized" vector of epidemic yellow fever, dengue, chikungunya, and Zika viruses are ideally adapted to the urban landscape (Rosenberg 2016). Extensive forest clearing for agriculture and livestock over the last 200 to 300 years allowed the adaptation of triatomines (blood sucking insects, ie Kissing Bugs), vectors of Chagas disease (*Trypanosoma cruzi)* to domestic environments using humans and domestic animals as a food source (Fig 2.) (Coura 2007). Other significant environmental public health problems result from the alteration of the landscape include heat stress in urban areas, and nutrient enrichment from agriculture and urban areas lawns that produce harmful algal blooms that impact aquatic ecosystems and availability of drinking water.

Rationale: There is a critical need to understand and quantify the environmental state and process functions that are significant in environmental public health issues and in vector borne disease life cycles. The environmental state functions include precipitation, solar radiation, the surface energy budget which drives evapotranspiration, vapor pressure deficits, air, surface, and soil temperatures; and surface hydrology (flooding and water bodies). Process functions require the quantification of the thermodynamic and functional dynamics of ecosystems. These complex science questions require measurements of leaf level photosynthesis and biochemistry processes; CO_2 exchange; leaf nutrient content; temperature, and transpiration (energy budgets). At a larger scale the determination of leaf area index; canopy structure and architecture; nutrient and water cycles; phenology; identification of key species; and landscape scale ecological functional types are critical. This whitepaper describes the rationale satellite based geophysical measurements for three public health applications; vector borne diseases, impact of urbanization and harmful algal blooms (HABS). This response falls within the purview of one of the five Earth science themes defined in the Request for Information for ESAS2017: **(III) Marine and Terrestrial Ecosystems and Natural Resource Management Biogeochemical Cycles, Ecosystem Functioning, Biodiversity, and factors that influence health and ecosystem services.**

A Thermodynamic paradigm - Satellite derived Surface Energy and Radiation Budget measurements quantify the environmental state and process functions

Surface temperature and albedo are major determinants of the surface energy budget which is critical in controlling the surface environment that significantly impacts both the rate at which vector borne disease life cycles progress and the extent of their habitat. Use of energy terms in modeling surface energy budgets allows the direct comparison of various land surfaces

encountered in complex landscape from urban, vegetated (forest and herbaceous) to non-vegetated (bare soil, roads, and buildings). These terms are also easily measured using remote sensing from aircraft or satellite platforms allowing one to examine the spatial variability of the urban surface. The partitioning of energy budget terms depends on the surface type. In natural landscapes, the partitioning is dependent on canopy biomass, leaf area index, aerodynamic roughness, and soil moisture status, all of which are influenced by the regional climate. In urban landscapes, coverage by man-made materials substantially alters the surface energy budget (Luvall et al. 1990, Luvall and Holbo 1991, Luvall and Kay 2001, Quattrochi and Luvall 2004, Luvall 2009, Comarazamy et al. 2010a, 2013b, Lee et al. 2015).

The surface radiative budget Q* (Wm^{-2}) can be measured directly using satellite data sets.

$$Q^* = K^* + L^* \qquad (1)$$

Where K* and L* are the net shortwave and longwave radiation of the surface.

Net radiation is a particularly useful term because, under most conditions, it represents the total amount of energy available to the land surface for partitioning into non-radiative processes (mass heating, evapotranspiration, biological synthesis, etc.) at the surface. In vegetated areas the amount of net radiation is dependent upon vegetation type and varies with canopy leaf area and structure.

Net radiation may be expressed as the sum of these non-radiative fluxes (Wm^{-2}):

$$Q^* = LE + H \pm G \qquad (2)$$

where:

LE = latent heat flux (both transpiration by plants & evaporation)
H = sensible heat flux
G = energy flux into or out of storage (both vegetation, urban materials, & soil)

The partitioning of LE, H, and G are dependent on the surface composition. Vegetation canopies (leaf stomata) can control transpiration rates over a wide range of soil moisture conditions and atmospheric vapor deficits. Both the physiological control of moisture loss (stomatal resistance) and leaf/canopy morphology for vegetation determines how Q^* is partitioned among LE, H, and G. In urban areas, the combination of both man-made materials and vegetation results in a spatially variable, heterogeneous mixture of surfaces that produce a complex, range of surface albedo values and significant differences in the partitioning of the surface energy budget.

Luvall and Holbo (Luvall and Holbo 1989) present a technique, Thermal Response Number (TRN) derived through remote sensing for describing the surface energy budget within a forested landscape. This procedure treats changes in surface temperature as an aggregate response of the dissipate thermal energy fluxes (latent heat and sensible heat exchange; and conduction heat exchange with biomass and soil). The TRN is therefore directly dependent on of surface properties (canopy structure, amount and condition of biomass, heat capacity, and moisture). A time interval of 15-30 minutes between remote sensing over flights of the same area using the Thermal Infrared Multispectral Scanner (TIMS) for selected forested landscapes has revealed a measurable change in forest canopy temperature due to the change in incoming solar radiation. Surface net radiation integrates the effects of the non-radiative fluxes, and the rate of change in forest canopy temperature presents insight on how non-radiative fluxes are reacting to radiant energy inputs.

The TRN provides an analytical framework for studying the effects of surface thermal response for large spatial resolution map scales. The importance of TRN is that (1) it is a functional classifier of land cover types; (2) it provides an initial surface characterization for input to various climate models; (3) it is a remotely sensed geophysical measurement; (4) it can be determined completely from a pixel by pixel measurement or for a polygon from a landscape feature which represents a group of pixels. The TRN can be used as an aggregate expression of both surface properties (forest canopy structure and biomass, age, and physiological condition; urban structures and material types) and environmental energy fluxes.

Future satellite missions need to provide hyperspectral visible and multispectral thermal data products to enable structural and functional classification of ecosystems and the measurement of key environmental parameters (temperature, soil moisture). A 60-meter spatial resolution and approximately 5-day repeat pattern greatly enhances the ability to obtain timely and adequate thermal data. A NEdT (Noise Equivalent delta Temperature) precision of < 0.2 Kelvin will produce would day-night pairs of calibrated surface temperatures for use in determining soil moisture, evaporation, and microclimate. The multispectral thermal bands will provide the capability of using wavelength dependent emissivity differences of minerals to map soil mineral composition, clay and organic matter content. The thermal measurements are particularly useful in providing approximately 5-day and day-night pairs of measurements of surface thermal environments. However, to obtain TRN from landscape scale ecosystems, repeated data collections ~ 1-2 hours apart would enhance our ability to characterize and monitor vector borne disease life cycles and habitats. Technology is available to do so through the use of constellations of cubesats.

Spectroscopy at a spectral accuracy of < 0.5nm and an absolute radiometric accuracy of > 95% from vegetation canopies for the determination of species, species functional type, biochemistry, and physiological condition along with additional characterization of surface mineralogy. Thus the combination of hyperspectral visible-shortwave infrared and multi-spectral thermal data will significantly enhance our capability to map and monitor disease vector habitats (Lee et al 2015).

Disease Vector's Habitats and Life Cycles

Satellite data products and biology-based data analysis can be integrated directly into epidemiological equations to map environmental suitability for a wide range of vector-borne diseases such as fascioliasis, schistosomiasis, leishmaniasis, dengue, malaria, and Chagas ((Raso et al. 2007); (Brooker et al. 2006); (Bavia et al. 1999); (Malone 2005); (Nieto et al. 2006); (Ceccato et al. 2012); (Yang et al. 2012)). Satellite based geophysical measurements quantify environmental state functions important to vector and disease life cycles (within vector) such as precipitation; soil moisture; surface radiant temperatures; vapor pressure deficits; solar radiation; leaf level photosynthesis and biochemistry processes; CO_2 exchange; and leaf nutrient content (Fig. 3). Satellite data also provides the spatial context and measures the interfaces as process functions: land use/cover mapping; ecological functions/structure; canopy cover; species; phenology; and aquatic plant coverage. Lastly, but perhaps the greatest strength of satellite data sets and their derived products provide a global time series of measurements that can range from days to years. The epidemiological equations (processes) can be adapted and modified to explicitly incorporate environmental factors and interfaces as illustrated below.

There is a need to understand how this dynamical shift in land use and other risk factors can change the transmission patterns of Chagas and the risk of human infection. Transmission of Chagas persists in much of the South American continent, particularly in the Orinoco Region in Colombia and Venezuela, where *Rhodnius prolixus* is the main insect vector (Guhl 2007). Palm trees that occur naturally in this region, particularly *Attalea butyracea are* widely distributed and constitute a tremendously large faunistic reserve, including many mammalian species such as *Didelphis marsupialis*, bats, rats and other rodents that play a relevant role in the natural zoonotic transmission cycle of the parasite (Gaunt and Miles 2000).

In the last 15 years, the conversion of natural ecosystems to African palm plantations (*Elaeis guineensis*) have undergone a tremendous increase in Colombia. Such large scale ecosystem alteration can potentially change transmission cycles of tropical diseases including Chagas where insect vectors are known to colonize palm tree crops, but the long-term impact has not yet been evaluated. An epidemiological approach is to measure seasonal and annual variation of the transmission cycle of Chagas disease with the aid of fieldwork, geospatial and mathematical models. A time series data obtained from the field studies combined with satellite geophysical measurements can be used to investigate the potential effect of community variation in risk, potential influences of climate change and the value of ecological niche modeling in describing the epidemiological cycle. Its critical to understand the patchy community-to-community variation in transmission that varies locally among communities even in otherwise similar climate in endemic zones. Data generated in field studies provide the basis for development of dynamical biology-based mathematical models for measuring propagation and transmission of Chagas disease in individual communities within a highly endemic region. A previous Pan American Health Organization (PAHO) funded studies, national scale ecological niche models (ENM) were used to generate risk maps of Chagas disease and the two principle triatomine vectors in Colombia (Figure 4) (Malone 2005).

Urban Heat Island - Impacts on Environmental Public Health

Extreme heat events have resulted in significant mortality and morbidity worldwide over the past 20 years. Extreme heat results in more deaths annually in the United States than severe weather (Sheridan et al. 2008). In the summer of 1996, a heatwave in Chicago resulted in an estimated 700 deaths and the European heatwave of 2003 caused an estimated 15,000 deaths in France alone (Semenza et al. 1996); (Pascal et al. 2012).

Two NASA (Project ATLANTA: Atlanta Land use Analysis: Temperature and Air quality, (1997), Heat Watch Warning System (2008) and an EPA (US EPA's Urban Heat Island Pilot Project: UHIPP, (1998) applied research projects used high resolution aircraft based remote sensing in conjunction with other data assimilated into a geographic information systems (GIS) format, to detect, observe, and measure the Urban Heat Island (UHI) for several cities across the United States (Quattrochi et al. 1998, Quattrochi and Luvall 1999), (Luvall et al. 2015). A key question posed was "can the UHI be mitigated through urban planning and proper design? The urban landscape represents a complex heterogeneous surface that strongly influences the development of the urban heat island. The urban landscape cannot be adequately characterized using traditional structural based remote sensing classification techniques (i.e., land use/cover types) because these techniques are not directly related to the physical functioning of the surface energy budget (Fig. 5a,b).

Both Project Atlanta and UHIPP used an airborne multi spectral VNIR/Thermal instrument (ATLAS) to characterize the high spatial resolution visible and thermal data (10 m) are required to quantify how artificial surfaces within the city contribute to an increase in urban heating and the benefit of cool surfaces.

Since albedo alone does not truly reflect how the urban surface partitions energy, one needs additional information to access the "urban fabric" of the city. Including surface temperature provides the needed additional information. Aircraft or satellite based remotely sensed data sets provide the needed calibrated and quantifiable data sets in physical units. Since we are working in physical units, the TRN, surface temperature and albedo classifications represents a functional classification of that surface, that have been incorporated into the surface parameterization of meteorological and air quality models (Comarazamy et al. 2010b, 2013b, 2013a).

A city has a distinctive "energy print" that is characteristic of the surface composition and how its processing energy (Figs. 6 & 7). These scattergams become a very powerful classification tool representing the functional classification of urban land surfaces. Within each city, each land use has a unique "energy print" that is directly physically related to how that surface is processing energy. These "energy prints" of the land use are unique for each city. These results again emphasize that classifications based on cover type/land use cannot be applied across a variety of cities, since they cannot represent the true energy partitioning of that surface (Luvall et al. 2015).

Harmful Algal Blooms (HABS)

Toxic blooms generated by cyanophytes are a growing concern world-wide and a serious threat to water quality. Traditional methods of identification of algae and cyanophytes are based on invasive water sampling and time consuming microscopic visual identification, or they require extensive analytical testing of water samples, which can delay remediation efforts. Chlorophyll a cannot be used as simple proxy for toxicity or the abundance of potentially toxic autotrophs because it is found ubiquitously, and its production is not directly linked to toxins such as microcystin. Hyperspectral remote sensing provides a means to characterize algal and cyanophyte blooms rapidly.

Researchers from the Department of Geology at Kent State University have developed a methodology to extract the maximum amount of independent information preserved in multi-spectral and hyperspectral visible remote sensing data (Ali et al., 2014a,b,c 2016; Ortiz et al. 2013). This method has widespread implications for several areas of interest to the Decadal Survey, included research on the *Global hydrological* cycle and water resources, *Marine and Terrestrial Ecosystems* and *Natural Resource Management and Climate Variability and Change*. Remote sensing images in the visible represents complex mixed outputs generated by the interaction of radiance signals generated by the absorption and scattering properties of the constituents present in the scene. Varimax-rotated, principle component analysis, an eigenvector-eigenvalue decompostion method can be employed to extract the underlying signals generated by these color producing agents. This approach enables the mapping of algae, cyanophytes, suspended sediment and colored dissolved organic matter in complex water. In principle, the method should be applicable to all earth surfaces, which will allow researchers to track changes in terrestrial, lacustrine and marine settings in space and time. The method has been demonstrated to be effective at mapping out the complex constituents present in the CyanoHABs that develop seasonally in the Western Basin of Lake Erie, and Sandusky Bay (Figure 8., NASA Glenn Lake Erie HAB Technical report, 2016).

The required measurements can be achieved affordably in the decadal timeframe, due to investments in response to global terrestrial/coastal coverage missions outlined in the 2007 NRC Decadal Survey (NRC 2007) and 2013 NRC sustainable land imaging report (NRC 2013) and other initiatives. The measurements would build on a legacy of airborne and space instruments including airborne: AIS (Vane et al, 1984), AVIRIS (Green et al., 1998), and AVIRIS-NG (Hamlin et al., 2011) and space: NIMS (Carlson et al., 1992), VIMS (Brown et al., 2004), Deep Impact (Hampton et al., 2005), CRISM (Murchie et al., 2007), EO-1 Hyperion (Ungar et al, 2003, Middleton et al., 2013), M3 (Green et al., 2011), ASTER, ECOSTRESS (Lee et al. 2015) and MISE, the imaging spectrometer now being developed for NASA's Europa mission.

A recently published special issue of Remote Sensing of Environment on Special Issue on the Hyperspectral Infrared Imager (HyspIRI) documents the science to achieve affordably these types of measurements (Hochberg et al. 2015).

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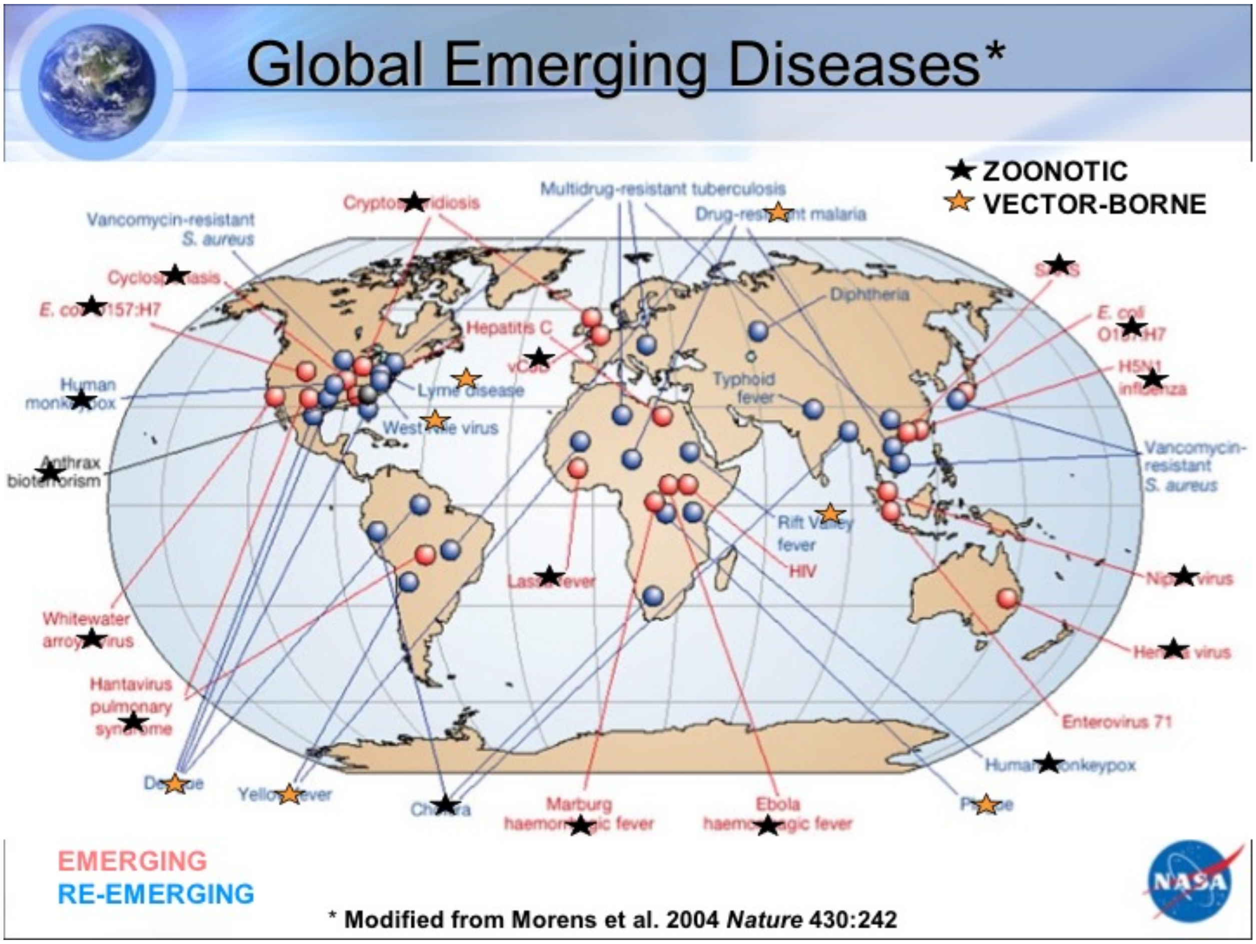


Figure 1. Emerging and re-emerging diseases are a global problem and are among the leading causes of death in the world.

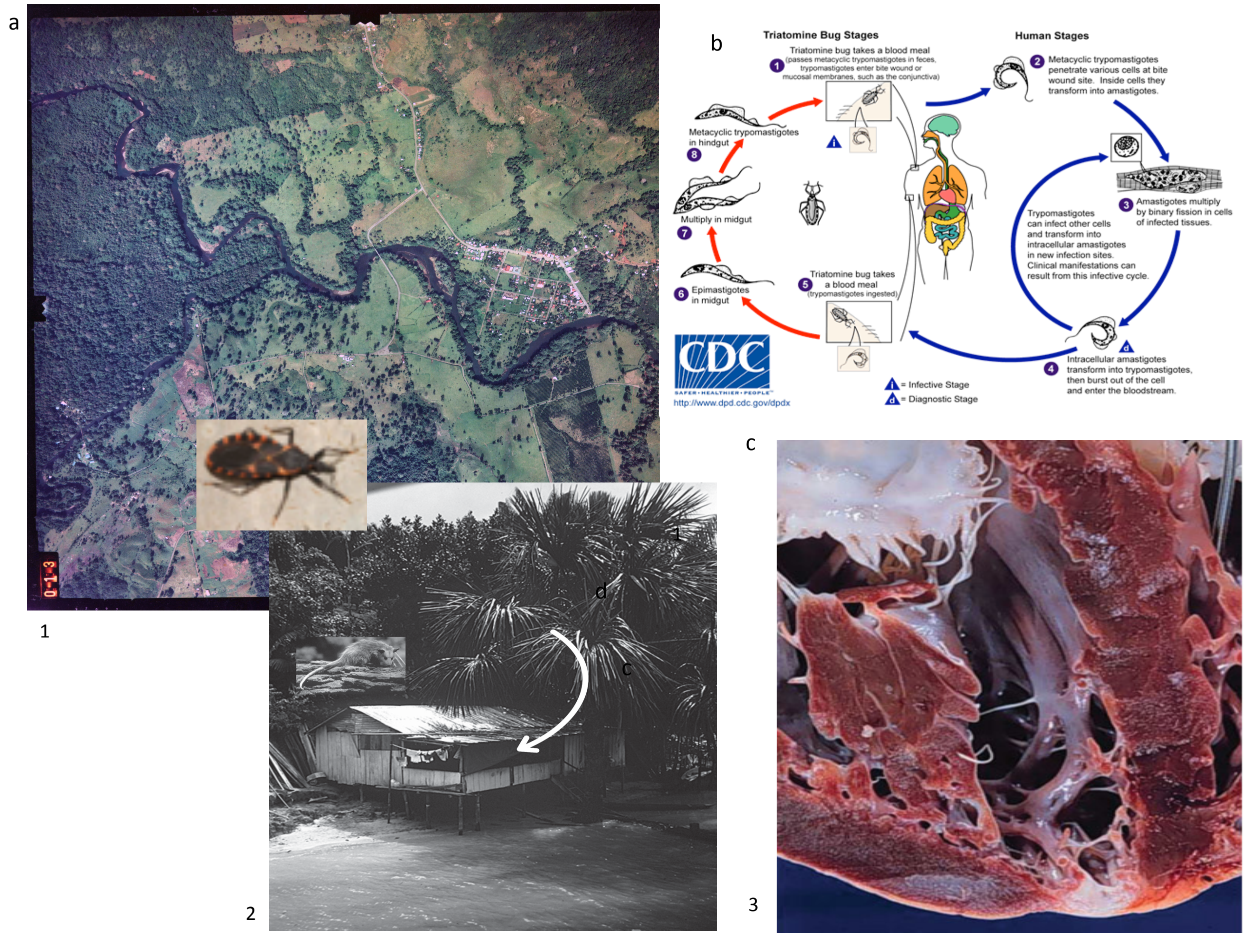


Figure 2.a) Human alteration of the landscape impacts both the habitat and the natural life cycles of many important insect disease vectors. These changes in the landscape result in close human and domesticated animal contact with insects that normally feed on non-human hosts and native wildlife species. Chagas is an example of a significant human protozoan disease (*Trypanosoma cruzi)* that emerged over the last 200-300 yrs after the destruction of its insect vector's natural forest habitat. The natural life cycle of triatomines (Kissing bug), subsequently adapted to domestic environments such as houses and farm buildings, thus bringing the kissing bug into direct contact with humans. b) An infected triatomine insect vector (or "kissing" bug) takes a blood meal and releases trypomastigotes in its feces near the site of the bite wound. Trypomastigotes enter the host through the wound or through intact mucosal membranes. In humans, the acute phase lasts for the first few weeks or months after infection. An infected individual may be symptom-free or exhibit only mild symptoms during that time period. The chronic stage develops over many years and affects the nervous system, digestive system and heart. c) Cardiac damage is severe in later chronic stages.

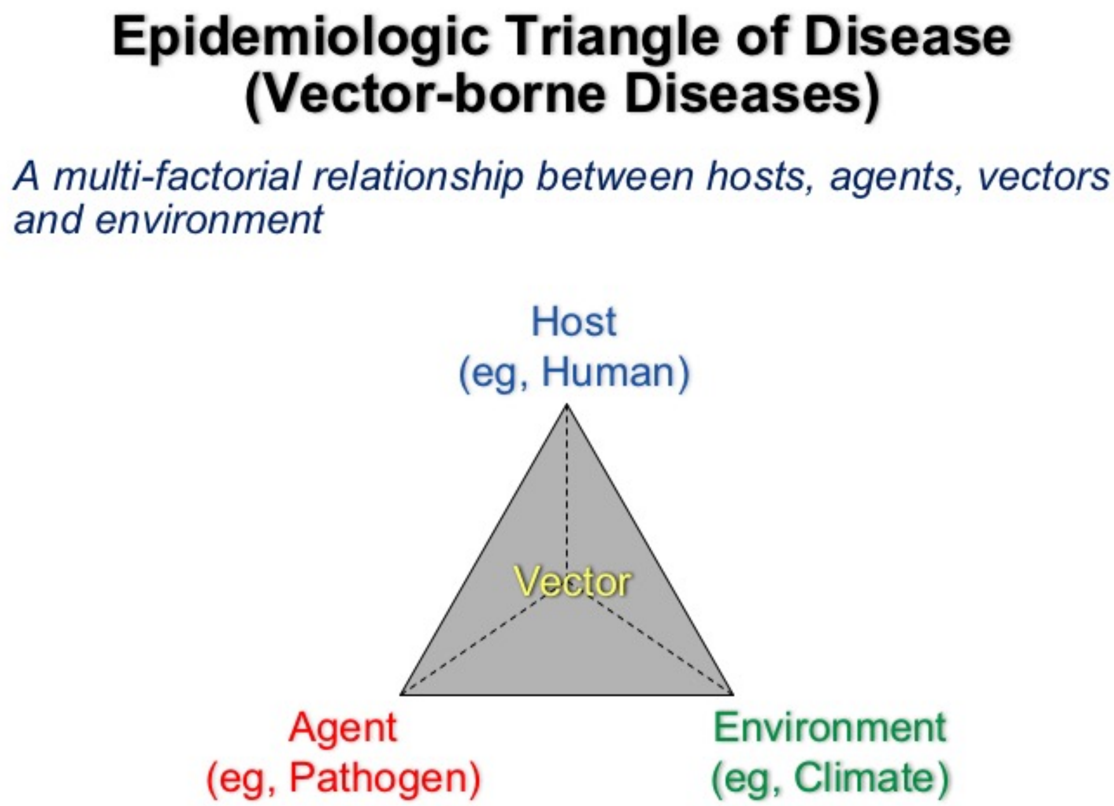


Figure 3. Satellite based geophysical measurements quantify environmental state and process functions important to understand vector and disease life cycles.

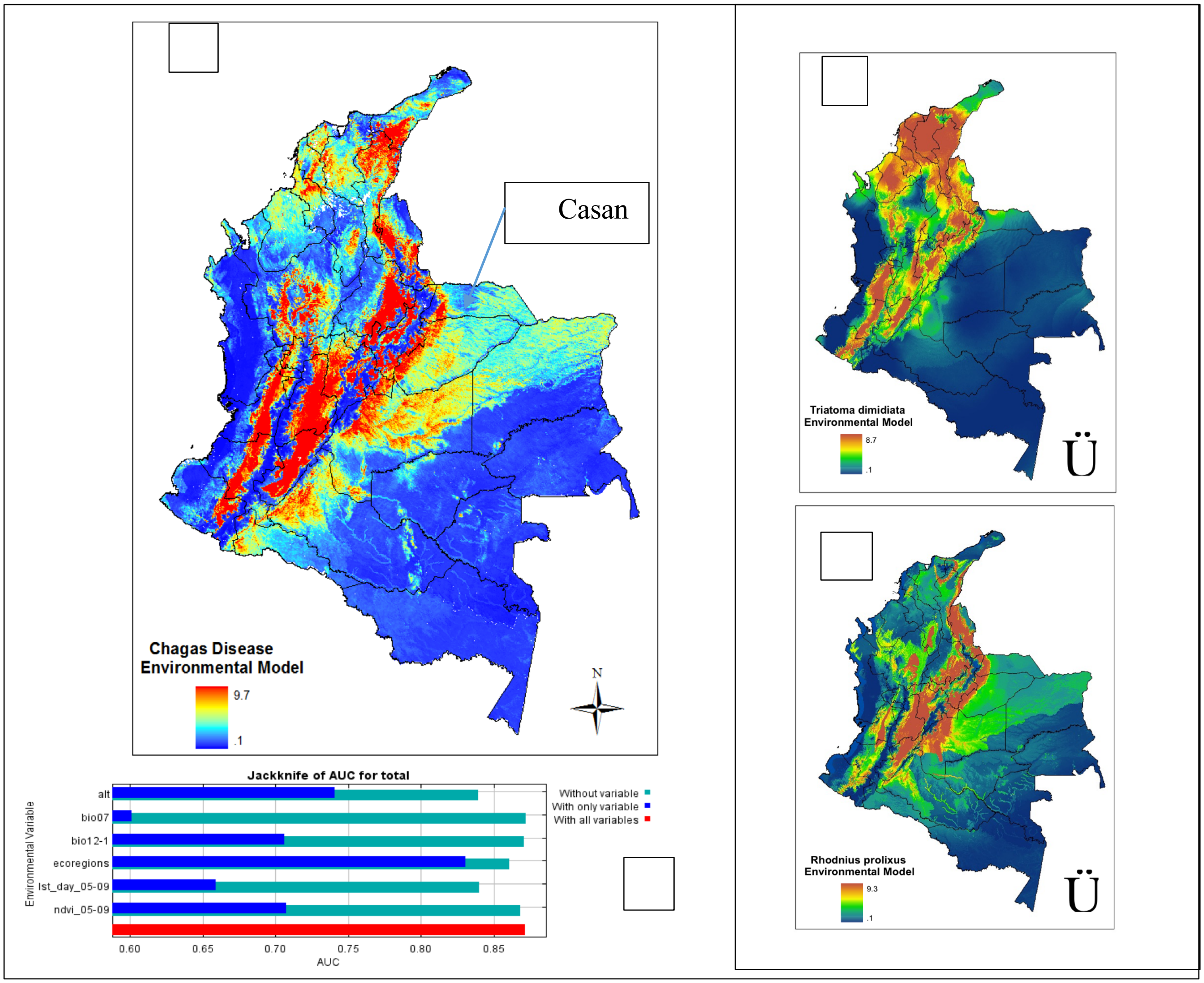
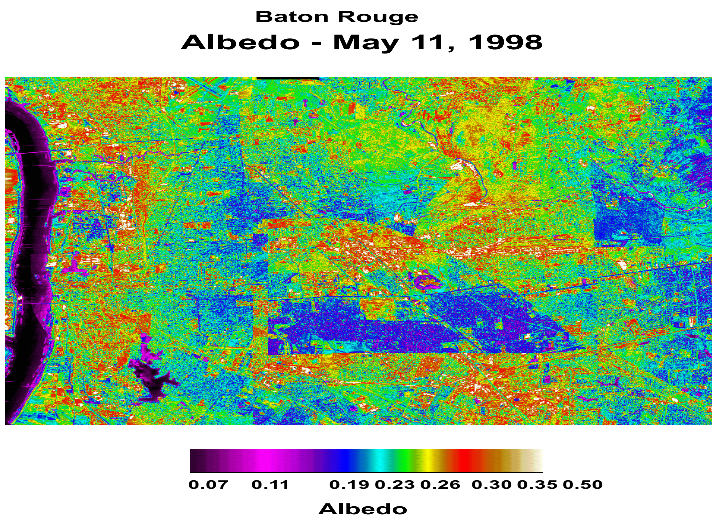


Figure 4. Maxent generated risk surfaces for Colombia generated from national scale data on Chagas disease (a) vector distribution (b, c). Note unique but overlapping geospatial ranges for Triatoma dimidiata and Rhodnius prolixus. Maxent generated Jackknife results (d) show the relative influence of the most significant environmental variables in producing probability map surfaces for Chagas disease.



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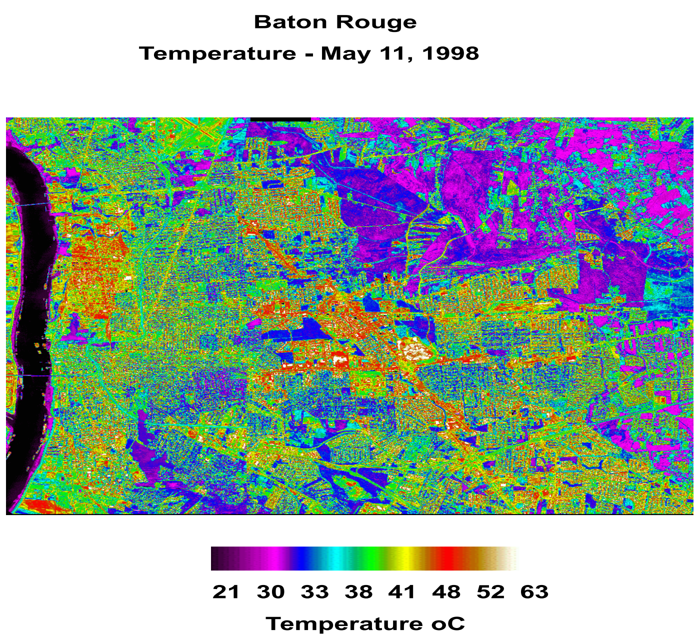

b

Figure 5. Aircraft measurements of urban areas using an airborne multispectral visible and thermal instrument at 10m resolution (ATLAS). These detailed measurements allow the characterization of various land surfaces based on the surface energy balance. (a. albedo & b. temperature).

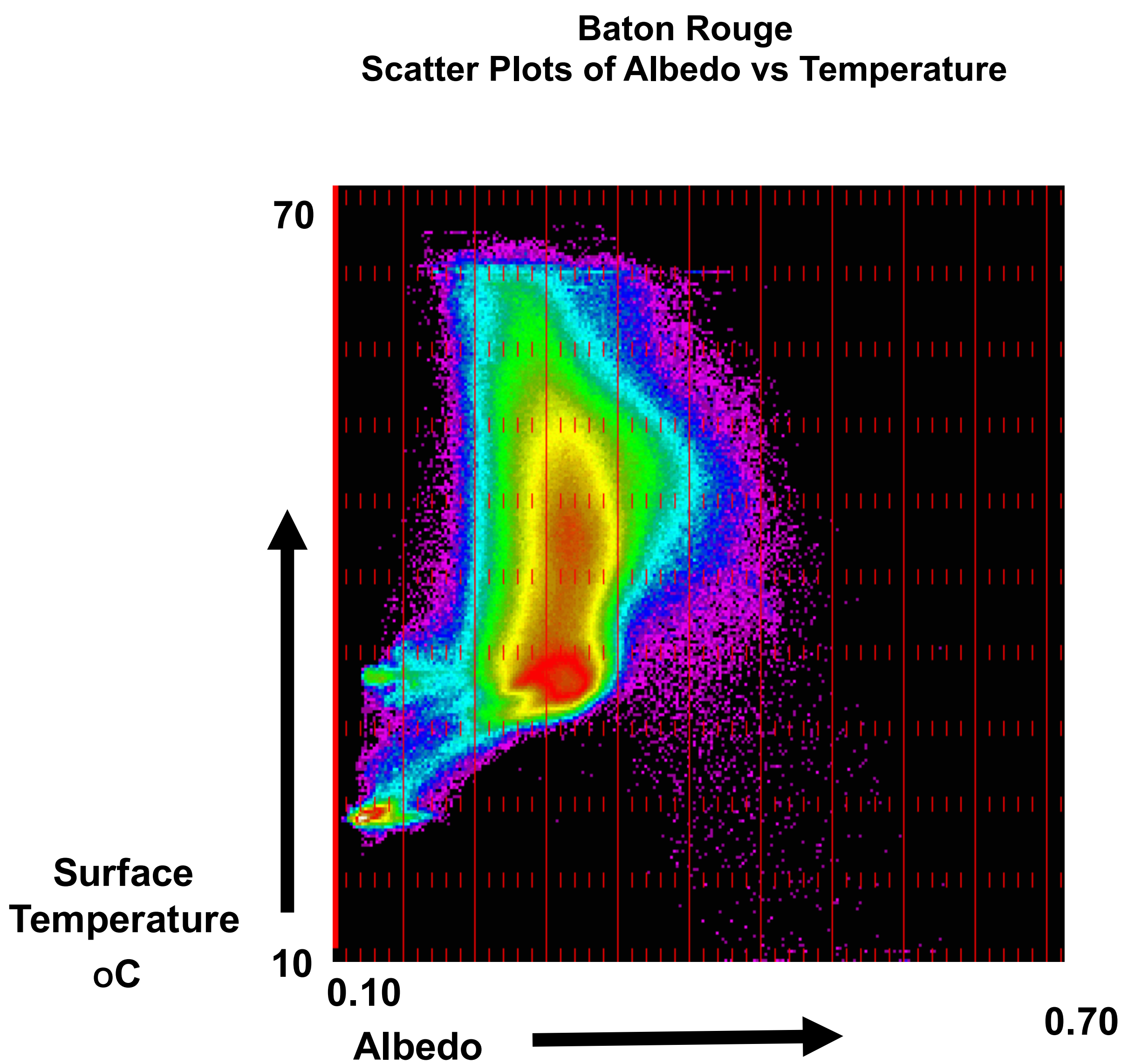

Figure 6. A scattergram of urban surfaces in Baton Rouge. The unique "energy print" represent how the surface is processing energy.

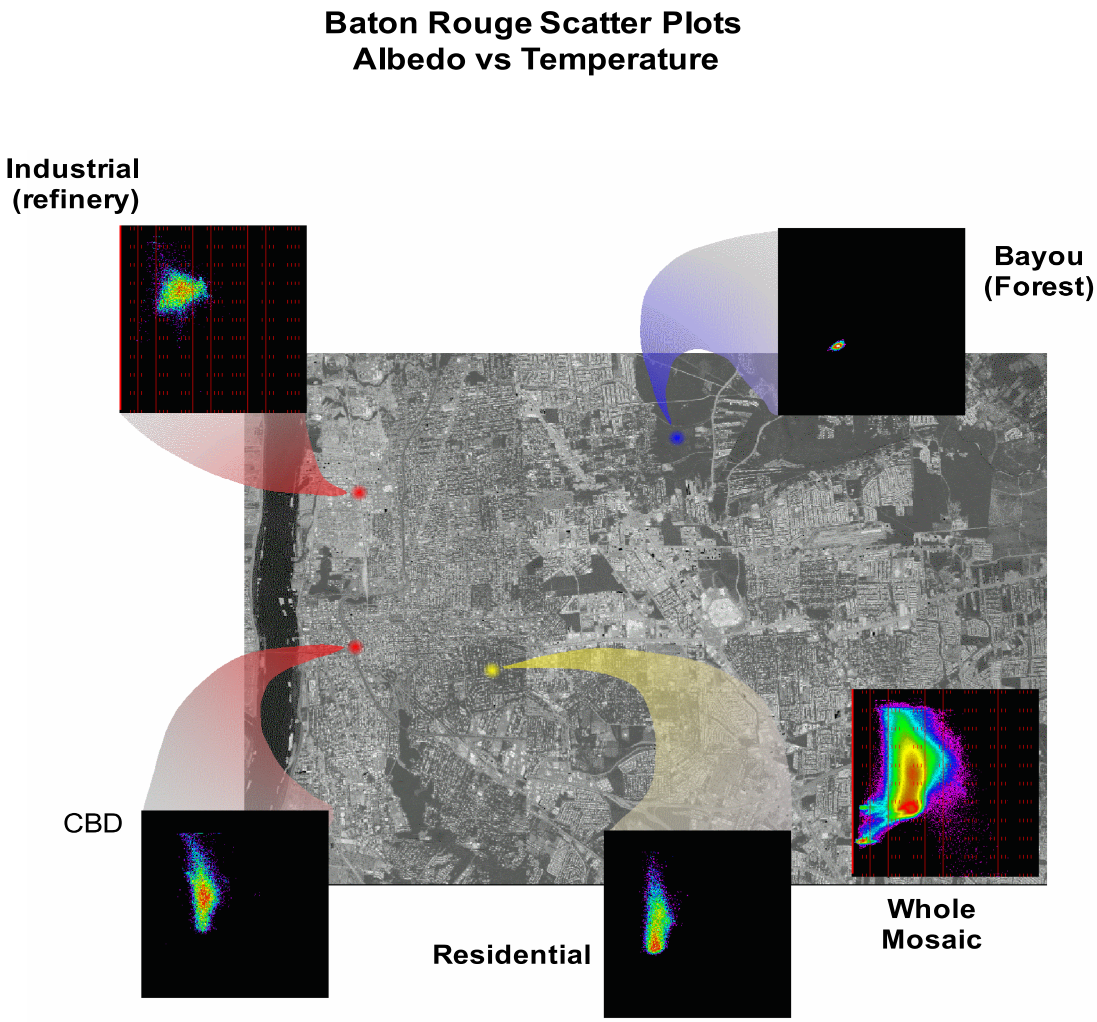

Figure 7. The energy scattergram provides a functional classification of land use patterns within an urban area.

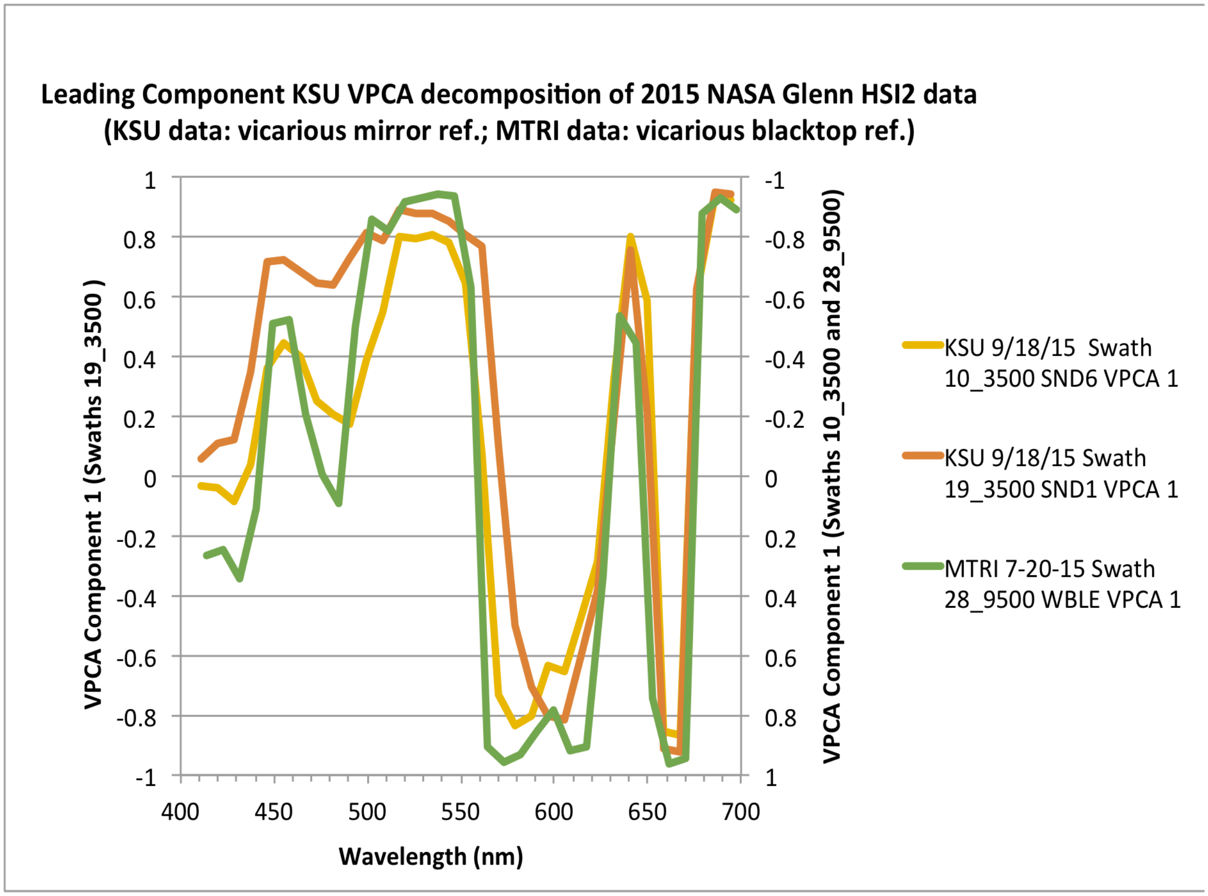

Figure 8. Spectral signatures of potentially toxic cyanobacteria in Sandusky Bay and the Western Basin of Lake Erie extracted from images swaths collected by the 2nd generation, NASA Glenn Hyperspectral Imager (HSI2) during the summer of 2015. The signals are obtained through a varimax-rotated principle component analysis of the derivative spectra correlation matrix [Source: NASA Glenn Lake Erie HAB Technical report, 2016].