Rev Inst Adolfo Lutz
www.ial.sp.gov.br/ial/publicacoes/

REVISTA DO INSTITUTO ADOLFO LUTZ
Resumo Expandido/ Expanded Abstract

Simpósio Internacional
"Leishmaniose Visceral: Desafios para o Controle no Contexto da Diversidade dos Cenários"

A thermodynamic paradigm for using satellite based geophysical measurements in public health applications

Um paradigma termodinâmico para o uso de medidas geofísicas baseadas em satélites e suas aplicações em saúde pública

RIALA6/1761

Jeffrey C LUVALL*

*Correspondence to: ZP11 Earth Science Office, NASA, Marshall Space Flight Center, Huntsville, AL 35812. Tel: +1 256 961 7886, Fax: +1 256 961 7788. Email: jluvall@nasa.gov

Recebido: 17.09.2018 - Aceito para publicação: 28.12.2018

ABSTRACT

A thermodynamic paradigm for studying disease vector's habitats & life cycles using NASA's remote sensing data is being proposed. NASA's current and planned satellite missions provide measurements of the critical environmental measures environmental state functions important to vector & disease life cycles such as precipitation, soil moisture, temperature, vapor pressure deficits, wet/dry edges, and solar radiation. Satellite data provide landscape scale process functions represented by land use/cover mapping and actual measurements of ecological functions/structure: canopy cover, species, phenology, and aquatic plant coverage. These measurements are taken in a spatial context and provide a time series of data to track changes in time. Global public health is entering a new informational age through the use of spatial models of disease vector/host ecologies driven by the use of remotely sensed data to measure environmental and structural factors critical in determining disease vector habitats, distributions, life cycles, and host interactions. The vector habitat microclimates can be quantified in terms of the surface energy budget measured by satellites. The epidemiological equations (processes) can be adapted and modified to explicitly incorporate environmental factors and interfaces required by a specific disease and its vector/host cycle. Remote sensing can be used to measure or evaluate or estimate both environment (*state functions*) and interface (*process functions*). It is critical that the products of remote sensing must be expressed in a way they can be integrated directly into the epidemiological equations.

Keywords. disease vectors, thermal remote sensing, habitat, life cycles, epidemiological equations.

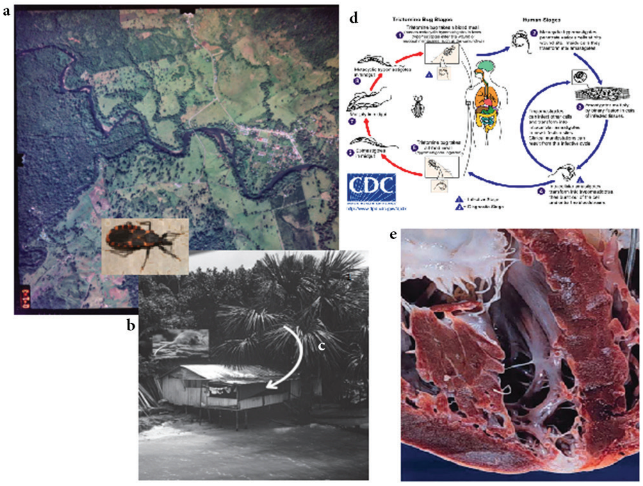
RESUMO

Um paradigma termodinâmico para estudar os habitats e ciclos de vida dos vetores de doenças utilizando dados de sensoriamento remoto da NASA está sendo proposto. As missões atuais e planejadas para os satélites da NASA fornecem medições das funções críticas ambientais e funções do estado ambiental, importantes para os ciclos de vida de vetores e doenças, como precipitação, umidade do solo, temperatura, déficits de pressão do vapor, bordas úmidas/secas e radiação solar. Os dados de satélite fornecem as funções dos processos na escala da paisagem, representada pelo mapeamento do uso/cobertura da terra e medições reais das funções/estruturas ecológicas: cobertura do dossel, espécies, fenologia e cobertura de plantas aquáticas. Essas medições são feitas em um contexto espacial e fornecem uma série temporal de dados para rastrear dinâmica das mudanças. A saúde pública global está entrando em uma nova era informacional através do uso de modelos espaciais para vetores/hospedeiros de doenças, impulsionados pelo uso de dados de sensoriamento remoto, para medir fatores ambientais e estruturais críticos na determinação de habitats de vetores de doenças, distribuições, ciclos de vida e interações com o hospedeiro. Os microclimas dos habitats vetoriais podem ser quantificados em termos do orçamento de energia superficial, medidos por satélites. As equações epidemiológicas (processos) podem ser adaptadas e modificadas para incorporar explicitamente fatores e interfaces ambientais requeridos por uma doença específica e o ciclo do seu vetor/hospedeiro. O sensoriamento remoto pode ser usado para medir ou avaliar, ou mesmo estimar tanto o ambiente (funções do seu estado) quanto a interface (funções de seus processos). É fundamental que os produtos de sensoriamento remoto sejam expressos de forma a integrá-los diretamente às equações epidemiológicas.

Palavras-chave. doenças vetoriais, sensoriamento remoto termal, hábitat, ciclos de vida, equações epidemiológicas.

INTRODUCTION

Vector borne diseases are emerging and re-emerging on a global scale[1]. 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[2]. 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 (**Figures 1a,b,c,d,e**)[3]. Other significant environmental public health problems result from the alteration of the landscape include heat stress in urban areas.



Figures 1. a) Human alteration of the landscape impacts both the habitat and the natural life cycles of many important insect disease vectors. **b)** 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. **c)** Chagas is an example of a significant protozoan disease (*Trypanosoma cruzi*) that emerged over the last 200–300 years through deforestation through the adaptation of triatomines (Kissing bug) to domestic environments. **d)** 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. The acute phase lasts for the first few weeks or months of infection and maybe symptom-free or exhibits only mild symptoms. The chronic stage develops over many years affects the nervous system, digestive system and heart. **e)** Cardiac damage is severe in later chronic stages. [1]NASA [2]Coura JR, 2007. "Chagas disease: what is known and what is needed - A background article." Memórias do Instituto Oswaldo Cruz 102: 113-122. [3]Fauci et al. Harrison's Principles of Internal Medicine.

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 (**Figure 2**).

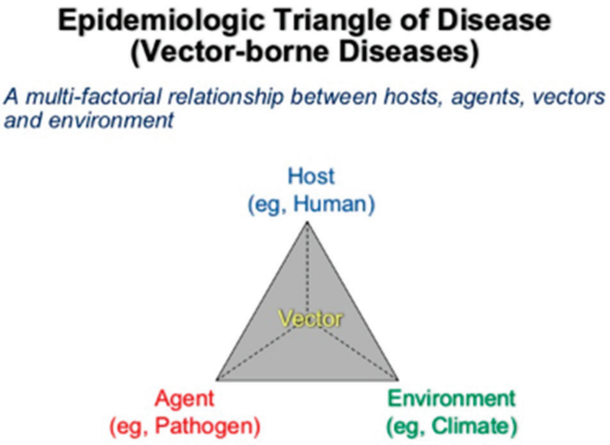


Figure 2. Satellite based geophysical measurements quantify environmental state and process functions important to understand vector and disease life cycles

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.

MATERIAL AND METHODS

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[4, 6].

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}):

$$Q^* = LE + HG \qquad (2)$$

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 present a technique, Thermal Response Number (TRN) derived through remote sensing for describing the surface energy budget within a forested landscape[7].

The ratio of net radiation to change in temperature can be used to define a surface property referred to as the Thermal Response Number (TRN).

$$TRN = \sum_{t_1}^{t_2} Rn\Delta t \,/\, \Delta T (\text{in kJm-2 K}) \qquad (3)$$

Where $\sum_{t_1}^{t_2} Rn\Delta t$ represents the total amount of net radiation (Rn) for that surface over the time period between flights ($\Delta t = t_2 - t_1$) and Δt is the change in mean temperature of that surface.

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.

RESULTS AND DISCUSSION

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[8,13]. 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. 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.

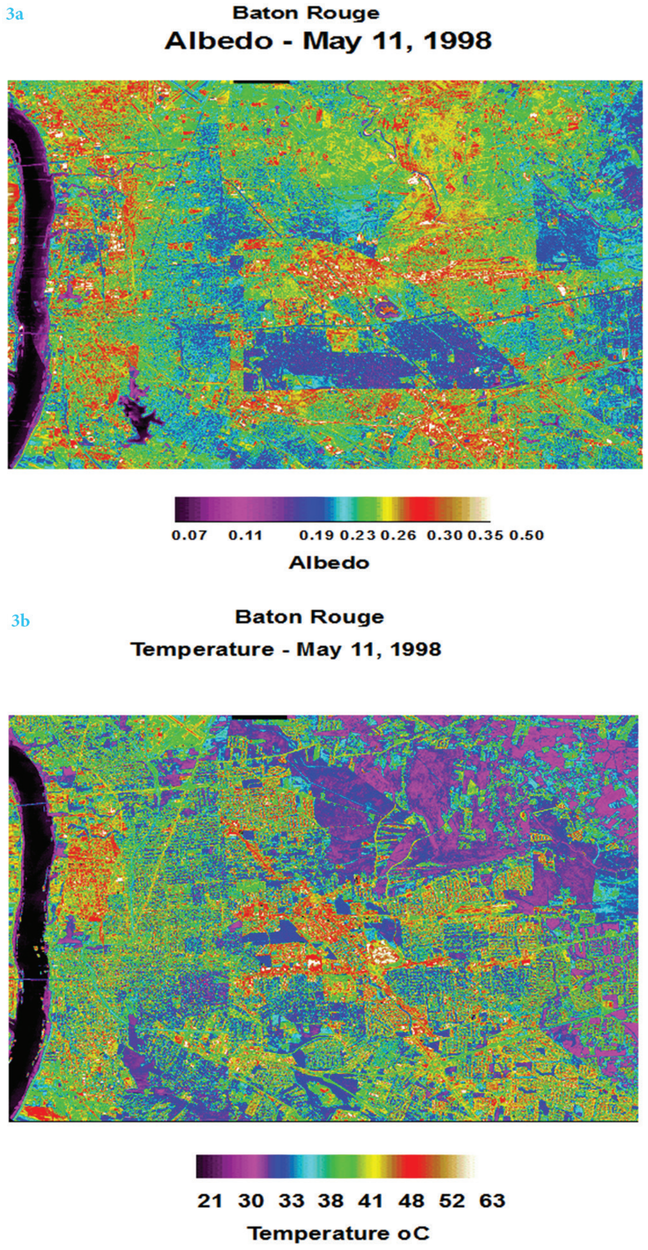
There is a need to understand how this dynamical shift in land use and other risk factors can change the transmission patterns of Chagas and the risk of human infection. Transmission of Chagas persists in much of the South American continent, particularly in the Orinoco Region in Colombia and Venezuela, where *Rhodnius prolixus* is the main insect vector[14]. 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[15].

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[16].

The Urban Heat Island effect (UHI) results from elevated temperature over urban areas due to thermal energy characteristics of urban surface materials that absorb incoming shortwave solar radiation and re-emit this energy as longwave radiation from surfaces common to the city landscape (e.g., pavement, rooftops)[17]. The UHI may increase heat-related impacts by raising air temperatures in cities approximately 1-6 ºC in the surrounding suburban and rural areas due to absorption of heat by dark paved surfaces and buildings; lack of vegetation and trees; heat emitted from buildings, vehicles; and air conditioners; and reduced air flow around buildings[18].

The increased air temperatures caused by the UHI effect can significantly impact potential disease transmission. Christofferson and Mores[19] where a ~ 4 ºC increase in temperature at 26 °C would result in significant differences in the dissemination of the dengue virus[19]. Morin et al[20] reviewed many studies demonstrating the importance of temperature in the ecology of dengue in both virus replication and the transmission of dengue. Morin et al[21] presents a series of meteorologically driven simulations of dengue epidemics in San Juan, PR. They concluded that "the simulations further indicate that rainfall strongly modulates the timing of dengue (e.g., epidemics occurred earlier during rainy years) while temperature modulates the annual number of dengue fever cases. Our results suggest that meteorological factors have a time-variable influence on dengue transmission relative to other important environmental and human factors".

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 (ie, land use/cover types) because these techniques are not directly related to the physical functioning of the surface energy budget (**Figures 3a, b**).



Figures 3 a, b. Aircraft measurements of Baton Rouge, LA 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).

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.

A city has a distinctive "energy print" that is characteristic of the surface composition and how its processing energy (**Figure 4**).

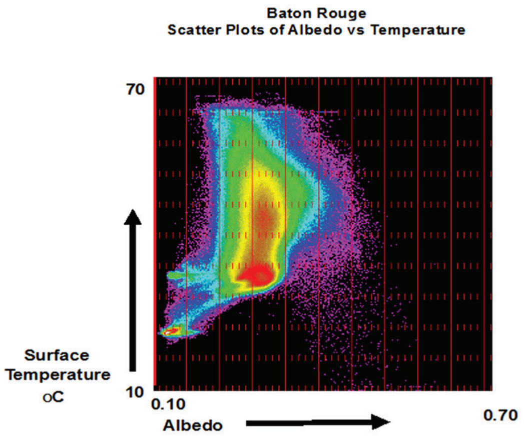


Figure 4. An "energy finger print" of urban surfaces in Baton Rouge. The unique "energy print" represent how the surface is processing energy and can be used to provide a functional classification of urban surfaces which drive the microclimate

These "scattergams" or "energy finger prints" 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 (Figure 5). 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[6].

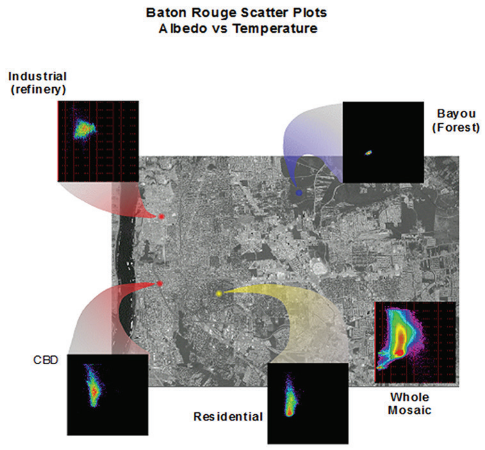


Figure 5. The Baton Rouge, LA energy finger print provides a functional classification of land use patterns within an urban area that is related to the microclimate and land use/cover of an urban area

CONCLUSION

A thermodynamic paradigm for studying disease vector's habitats & life cycles using NASA's remote sensing data is being proposed. NASA's current and planned satellite missions provide measurements of the critical environmental measures environmental state functions important to vector & disease life cycles such as precipitation, soil moisture, temperature, vapor pressure deficits, wet/dry edges, and solar radiation. 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[22].

Research funding: Supported by the NASA ROSES 2016 Group on Earth Observations (GEO) Work Programme, 305 Grant # 80 NSSC 18K0517.

REFERENCES

1. Morens DM, Folkers GK, Fauci AS. The challenge of emerging and re-emerging infectious diseases. Nature. 2004;430(6996):242-9. Available in: https://www.nature.com/articles/nature02759

2. Rosenberg R. Threat from emerging vectorborne viruses. Emerg Infect Dis. 2016;22(5):910–1. http://dx.doi.org/10.3201/eid2205.160284

3. Coura JR. Chagas disease: what is known and what is needed--a background article. Mem Inst Oswaldo Cruz. 2007;102 Suppl 1:113–22. http://dx.doi.org/10.1590/S0074-02762007000900018

4. Luvall JC, Holbo HR. Thermal Remote Sensing Methods in Landscape Ecology. In: Turner MG, Gardner RH, editors. Quantitative Methods in Landscape Ecology. Series: Ecological Studies. Springer; 1991. p.127–52.

5. Quattrochi DA, Luvall JC. Thermal remote sensing in land surface processes. 1. ed. CRC Press; 2004.

6. Luvall JC, Quattrochi DA, Rickman DL, Estes Jr MG. Boundary layer (atmospheric) and air pollution: urban heat islands. In: Encyclopedia of Atmospheric Sciences. Amsterdam: Elsevier; 2015. p. 310–8. http://doi.org/10.1016/B978-0-12-382225-3.00442-4

7. Luvall JC, Holbo RH. Measurements of short-term thermal responses of coniferous forest canopies using thermal scanner data. Remote Sens Environ. 1989;27:1–10. Available in: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.468.8438&rep=rep1&type=pdf

8. Raso G, Vounatsou P, McManus DP, Utzinger J. Bayesian risk maps for Schistosoma mansoni and hookworm mono-infections in a setting where both parasites co-exist. Geospat Health. 2007;2(1):85–96. http://dx.doi.org/10.4081/gh.2007.257

9. Brooker S, Clements ACA, Bundy DAP. Global epidemiology, ecology and control of soil-transmitted helminth infections. Adv Parasitol. 2006;62:221–61. https://doi.org/10.1016/S0065-308X(05)62007-6

10. Bavia ME, Hale LF, Malone JB, Braud DH, Shane SM. Geographic information systems and the environmental risk of schistosomiasis in Bahia, Brazil. Am J Trop Med Hyg. 1999;60(4):566–72.

11. Nieto P, Malone JB, Bavia ME. Ecological niche modeling for visceral leishmaniasis in the state of Bahia, Brazil, using genetic algorithm for rule-set prediction and growing degree day-water budget analysis. Geospat Health. 2006;1(1):115-26. https://doi.org/10.4081/gh.2006.286

12. Ceccato P, Vancutsem C, Klaver R, Rowland J, Connor SJ. A vectorial capacity product to monitor changing malaria transmission potential in epidemic regions of Africa. J Trop Med. 2012;2012:595948. https://doi.org/10.1155/2012/595948

13. Yang GJ, Tanner M, Utzinger J, Malone JB, Bergquist R, Yy Chan E. Malaria surveillance-response strategies in different transmission zones of the People's Republic of China: Preparing for climate change. Malar J. 2012;11:426. https://doi.org/10.1186/1475-2875-11-426

14. Guhl F. Chagas disease in Andean countries. Mem Inst Oswaldo Cruz. 2007;102 Supp l:29–37. http://dx.doi.org/10.1590/S0074-02762007005000099

15. Gaunt M, Miles M. The ecotopes and evolution of triatomine bugs (Triatominae) and their associated trypanosomes. Mem Inst Oswaldo Cruz. 2000;95(4):557–65. http://dx.doi.org/10.1590/S0074-02762000000400019

16. Malone JB. Biology-based mapping of vector-borne parasites by Geographic Information Systems and Remote Sensing. Parassitologia. 2005;47(1):27–50.

17. Dominguez A, Kleissl J, Luvall JC, Rickman DL. High-resolution urban thermal sharpener (HUTS). Remote Sens Environ. 2011;115(7):1772–8: http://dx.doi.org/10.1016/j.rse.2011.03.008

18. Government US. United States Environmental Protection Agency. Reducing Urban Heat Islands: Compendium of Strategies; 2016.

19. Christofferson RC, Mores CN. Potential for extrinsic incubation temperature to alter interplay between transmission potential and mortality of

dengue-infected Aedes aegypti. Environ Health Insights. 2016;10:119-23. http://dx.doi.org/10.4137/EHI.S38345

20. Morin CW, Comrie AC. Regional and seasonal response of a West Nile virus vector to climate change. Proc Natl Acad Sci. 2013;110(39):15629-5. http://dx.doi.org/10.1073/pnas.1307135110

21. Morin CW, Monaghan AJ, Hayden MH, Barrera R, Ernst K. Meteorologically driven simulations of dengue epidemics in San Juan, PR. PLoS Negl Trop Dis. 2015;9(8):e0004002. http://dx.doi.org/10.1371/journal.pntd.0004002

22. Lee CM, Cable ML, Hook SJ, Green RO, Ustin SL, Mandl DJ. An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities. Remote Sens Environ. 2015;167:6–19. http://dx.doi.org/10.1016/j.rse.2015.06.012