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Geohealth: biology based mapping of vector borne disease in the Americas using NASA satellite data

Geosaúde: mapeamento da biologia das doenças vetoriais nas Américas utilizando dados de satélites da NASA

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ABSTRACT
Implementation of a geospatial surveillance and response system data resource for vector borne disease in the Americas (GeoHealth) will be tested using NASA satellite data, geographic information systems and ecological niche modeling to characterize the environmental suitability and potential for spread of endemic and epizootic vector borne diseases. The initial focus is on developing prototype geospatial models for visceral leishmaniasis, an expanding endemic disease in Latin America, and geospatial models for dengue and other *Aedes aegypti* borne arboviruses (zika, chikungunya), emerging arboviruses with potential for epizootic spread from Latin America and the Caribbean and establishment in North America. Geospatial surveillance and response system open resource data bases and models will be made available, with training courses, to other investigators interested in mapping and modeling other vector borne diseases in the western hemisphere and contributing brokered data to an expanding GeoHealth data resource as part of the NASA AmeriGEOSS initiative.

Keywords. geospatial models, geohealth, AmeriGEOSS, visceral leishmaniasis, Aedes borne arboviruses, dengue, zika, chickungunya.

RESUMO
A implementação de uma fonte de dados de vigilância e um sistema de resposta geoespacial para doenças transmitidas por vetores nas Américas (GeoHealth) será testada utilizando dados provenientes de satélites da NASA, sistemas de informações geográficas e modelagem do nicho ecológico, para caracterizar a suceptibilidade ambiental e o potencial de dispersão de doenças endêmicas e epizooticas transmitidas por vetores vetores. O foco inicial será o desenvolvimento de protótipos de modelos geoespaciais para a leishmaniose visceral, uma doença endêmica e em expansão na América Latina, e modelos geoespaciais para dengue e outros transmitidos pelo *Aedes aegypti* (zika, chikungunya), arbovírus emergentes com potencial para disseminação epizoótica pela América Latina e Caribe e estabelecimento na América do Norte. Sistemas de vigilância e resposta geoespacial e modelos de recursos em bases de dados abertas serão diponibilizados, com cursos de treinamento, para outros pesquisadores interessados em mapear e modelar outras doenças transmitidas por vetores no hemisfério ocidental e contribuir intermediando dados para uma fonte de dados GeoHealth em expansão, como parte da Iniciativa AmeriGEOSS, da NASA.

Palavras-chave. modelos geospaciais, geosaúde, AmeriGEOSS, leishmaniose visceral, doenças transmitidas pelo Aedes, zika, chickungunya.

INTRODUCTION

The growing availability of digital data for geospatial studies made possible by remote sensing and resources from influential national space agencies, such as the National Aeronautics Space Administration (NASA) (http://www.nasa.gov/) has led to the establishment of a number of multi-disciplinary scientific teams interested in geospatial health applications. This has resulted in a corresponding expanded number of publications in the geospatial health arena aimed at advancement of new knowledge on epidemiology, tele-epidemiology and geospatial modeling approaches to control of disease[1,3]. Several new journals have emerged, e.g. Geospatial Health (http://www.geospatialhealth.unina.it), the International Journal of Health Geographics (http://www.ij-healthgeographics.com), Spatial and Spatio-Temporal Epidemiology (http://www.journals.elsevier.com/spatial-and-spatiotemporal-epidemiology). The net result is that geospatial mapping and multidisciplinary modeling are becoming mainstream science in the health community at large. Amid this growth in interest, however, there is a clear need to increase new lines of collaboration and communication between research groups that are developing health applications based on the geospatial sciences. This is especially true of groups whose members come from different orientations and training and whose work is on diverse health issues. In light of this convergence of interests, it is of great potential value to cross-fertilize and reinforce linkages of diverse interest groups on health applications of the geospatial sciences. An idea proposed during a recent symposium is to join the Group on Earth Observations (GEO) mission to build the Global Earth Observation System of Systems (GEOSS) (https://www.earthobservations.org/geoss.php), under the health societal benefit area[4,5] in which health scientists working on seemingly very different health issues could work in a collaboration to further public health using a standardized, interoperable, open source global resource data portal within the concept of a 'GeoHealth' network (see box).

BOX:

MANDATE OF THE GROUP ON EARTH OBSERVATIONS HEALTH NETWORK

(**GeoHealth**) The proposed Group on Earth Observations Health Network (GeoHealth) will collaborate on activities relating to the GEO societal benefit area on Public Health and the Global Earth Observation System of Systems (GEOSS). GeoHealth will enable collaboration of governmental, inter-governmental and non-governmental organizations to organize and improve mapping and predictive modelling of the distribution of infectious, vector-borne and non contagious diseases globally and make this data, information and forecasts more readily accessible to policy and decision makers, managers, experts and other users. The GeoHealth network aims to progress from a Community of Practice to an Initiative and then a Flagship in the GEO Work Plan. It is a voluntary partnership that is guided by a steering committee comprising key stakeholders, initially the ISPRS VIII/2 Working Group, and the International Society of Geospatial Health-GnosisGIS (www.gnosisgis.org) and would actively recruit other organizations to join. GeoHealth draws on GEO's work on data-sharing principles to promote full and open exchange of data, and on the GEOSS common infrastructure to enable interoperability through adoption of consistent standards. To assist both holders and users of health information to engage with GeoHealth, an active website will contain links to information resources, activities, GeoHealth documents, meetings and other resources relevant to the GeoHealth mandate. We propose that GnosisGIS, ISPRS VIII/2, the American Society of Tropical Medicine and Hygiene, and other groups interested in Geospatial Health will join and fully commit to the global vision of GEO.

Is it possible to develop a dynamical 3-dimensional (3-D) or even 4-D (adding the temporal dimension) models of disease, such as a bi-weekly global leishmaniasis or dengue report? We propose we are on the cusp of succeeding in this endeavor, facilitated by global earth observation satellite systems, big data, climatology advances, and new sensors such as the global precipitation model (GPM), soil moisture ocean salinity (SMOS), Landsat 8 data that continues a record of 40 years of Landsat legacy data, and the new ESA Sentinel 1, 2 and 3 programs. Perhaps most crucially for community risk assessment is the sub-meter resolution environmental data now available from Worldview-2 and Worldview-3[6]. Add to this the elective value-added potential of low-altitude sensors on drone airborne vehicles as a source of very high resolution data collection within a user-set agenda[7].

The public health community is behind on use of earlier EO systems, and will be even further behind with the emergence of currently planned systems. Future NASA satellite missions such as HyspIRI (http://hyspiri.jpl. nasa.gov/) will provide further enhanced capability to map vector-borne and other environmentally sensitive diseases based on global hyperspectral visible and multispectral thermal data products (60 m^2, 5 day thermal and 19-day, 30 m^2 hyperspectral repeat intervals) that will enable structural and functional classification of ecosystems and the measurement of key environmental parameters (temperature, soil moisture). The planned ECOSTRESS instrument (May 2018) on the International Space Station (ISS) (http://www.nasa.gov/jpl/nasas-ecostress) will monitor plant health using surface temperature measurements (and derived evapotranspiration values) with minimum 3-5 day diurnal pair coverage, 38 x 57m spatial resolution at varying times during the day due to the ISS processing orbit. Timely adoption of these data resources in health surveillance and response systems will require close cooperation of NASA earth system scientists and public health scientists. In addition, very high resolution satellite data from Digital Globe managed satellites (GeoEye-1, Worldview1-4, Quickbird-2) are available for both historical and current time periods. These advances finally allow seamless mapping and modeling of diseases, not only at continental scales (1 km^2) and local community-agricultural field scales (30 m^2), but for the first time also at the habitat-household scale (<1 m^2) within individual communities.

What is now needed is an open source, inter-operable platform that is freely accessible by the global health community to link public health workers with the most current potential earth observation resources from the geospatial sciences community. We propose that geospatial data resources from NASA, INPE, JAXA, ESA, USGS, and the Centers for Disease Control in the USA, the European Centre for Disease Prevention and Control (ECDC) and other national agencies can be organized through GEOSS to make this possible. We anticipate that other organizations with an interest in geospatial health issues will join us in this commitment. The statement (box) describing the potential aims, organization and structure of GeoHealth is offered as a framework for initial effort as a vehicle for translational research, dissemination and implementation in national public health systems in collaboration with GEO.

MATERIAL AND METHODS

A geospatial surveillance and response system resource for vector borne disease in the Americas (GeoHealth) will be implemented using NASA satellite data, geographic information systems and ecological niche modeling to characterize the environmental and socioeconomic suitability and the potential for spread of selected endemic and epizootic vector borne diseases in the Americas. The initial focus will be on developing prototype geospatial models on visceral leishmaniasis, an expanding endemic disease in Latin America, and models for dengue and other emerging *Aedes aegypti* borne viruses (dengue, zika, chikungunya) that have potential for epizootic spread from Latin America and the Caribbean and establishment in North America. Use of the geospatial surveillance and response system open resource data bases and models will be made available, with training courses, to other investigators interested in mapping and modeling other vector borne diseases, leading to a continually growing archive of brokered data.

Specific Objectives

1. Construct a geospatial health resource data portal (GeoHealth) compatible with the interoperable, open access standards of the Global Earth Observation System of Systems (GEOSS);

2. Map and model the distribution and spatial variation in epidemiological risk of visceral leishmaniasis in Brazil using GeoHealth data portal resource data;

3. Develop geospatial models for mapping arbovirus transmission and emergence prediction in the Americas using GeoHealth data portal resource data;

4. Provide a platform for processing massive big data resources;

5. Implement dissemination and training programs to promote geospatial mapping and modeling for vector borne diseases as envisioned by GEOSS.

Objective 1 - Construction of the GeoHealth geospatial resource data portal

Implementation of GeoHealth will require initial effort to compile, design, and construct interoperable data structures anticipated to be useful for vector borne disease surveillance and response systems based on the project investigators' experience, literature reports and availability.

We propose GeoHealth common resource data for potential users will reduce redundancy of effort in developing surveillance and response systems and evolution of a GeoHealth data portal to incorporate new project resources and results as new data systems (eg. NASA HyspIRI, ECOSTRESS) become globally available. All data will be resampled and projected in geographic formats compatible with other GeoHealth project data parameters and available in ASCII form needed for use in Maxent[8] or Bayesian (OpenBUGS) mapping and modeling software. Data portal construction methods will be similar to that reported for a prior PAHO funded project on mapping and modeling 6 neglected tropical diseases in Latin America and the Caribbean region[9].

The architecture of the GeoHealth data portal will be designed in collaboration with LSU Electrical Engineering and Computer Science, to ensure interoperability and use of data formats needed for big data analysis.

The overall aim is to utilize available global data from advanced climate data monitoring systems, satellite remote sensing data, and data on natural or man-made environmental change (eg land use, deforestation, climate change) to evaluate their influences on disease occurrence and potential mitigation. Currently available global data are underutilized by medical researchers. This may be due to lack of ability to bridge barriers to awareness, prioritization, or training deficits needed for interdisciplinary interaction of medical scientists with environmental scientists. Development of GeoHealth will facilitate and encourage research to utilize and implement currently available geospatial analysis tools and new global data systems in surveillance and response systems for vector-borne diseases. The GeoHealth portal will be constructed and made available for mapping and modeling vector borne diseases at three scales:

Regional Scale

Climate Data

Worldclim - Precipitation, Temperature maximum/minimum, Potential Evapotranspiration;
monthly Bioclim (1km2) = 50 year long term normal climate data)
NCEP/NCAR CDAS Re Analysis data (50km2); daily
Global Precipitation Measurement Mission (GPM) – 3 hour/daily

Earth Observing Satellite data

MODIS 8day-16day NDVI, LST, other products (1km^2)
SRTM Shuttle Radar Topography Mission
SMOS ESA Soil Moisture Ocean Salinity (50km2); resample to 1km using MODIS

Feature data

DIVA Political boundaries, World Wildlife Fund Ecosystems
Hydrology – Rivers, streams, lakes; Watersheds
Landscan – global population data; Census tract population data

Community Scale

Landsat 8; Landsat Legacy data; ASTER (including Topography)
ESA Harmonized Landsat/Sentinel-2 (HLS) v. 1.2
Land Use, Soil Type

Habitat-Household Scale

Worldview 2, Worldview 3

To economize on the size of data storage requirements, data available for multiple years (eg. USGS Landsat Legacy data) will be acquired and archived in the data portal archive at only 5-year intervals (2005, 2010 and 2015). Products from more recently launched satellite data systems (e.g., ESA SMOS data) will be made available for only years available. A step-by-step tutorial on how investigators can download additional data in the same format from the entire observation period as needed for specific applications. Thus investigators will be able to examine data to evaluate usefulness using limited example data, with instructions on how to obtain similar additional complete data on specific time frames and scales as needed from open-source archives linked to specified internet sites (e.g., EROS Data Center).

Data from the GeoHealth common resource data portal will be used to demonstrate the feasibility of improved disease risk assessment models in prototype surveillance and response system models as compared to previously reported models for vector-borne diseases that have a fundamentally different epidemiology: 1) visceral leishmaniasis, an endemic, expanding sand fly transmitted zoonotic childhood disease in Brazil, and 2) Dengue and other *Aedes aegypti* transmitted arboviruses (chikungunya, zika) at reported epidemic outbreak sites in Latin America and the Caribbean region. These models will be developed as described for VL under Objective 2. Models for arboviruses are only briefly described under Objective
3. Health Data used will be existing data obtained from previous and current projects of Brazilian collaborators, including: Case report data; Vector-CDC Trap collection data; Surveys/Questionnaire data.

Laboratory and field data will be compiled to relate to thermal-moisture regimes that define the life cycle drivers and environmental preferences and limits of tolerance of the parasite-vector system in a given environment. Candidate GeoHealth environmental data sets will be selected for mapping and modeling analysis from the GeoHealth data portal that directly measure (eg., mean NCEP/NCAR CDAS Re-Analysis climate data) or indirectly measure (e.g., MODIS satellite LST and NDVI) thermal-hydrological, landform (e.g., topography) or landuse features of the environment that determine the distribution and abundance, temporal development rate and seasonality of pathogen-vector systems.

Objective 2 - Map and model the distribution and spatial variation in risk of visceral leishmaniasis (VL) in Brazil using GeoHealth data portal parameters

We hypothesize it is possible to develop geospatial development rate models that can simulate and display 'snapshot' temporal progression (eg. each 8-days) of vector-parasite life cycles and geospatial risk based on comprehensive daily climate re-analysis data, Global Precipitation Measurement Mission (GPM) data, SMOS soil moisture, and MODIS land surface temperature (LST) and vegetation indices (NDVI, NDMI, NDWI) in the context of topography, landuse and population patterns in Brazil. A major gap in past has been environmental moisture data. This can now be addressed using newly available sensor systems data.

Disease and vector occurrence data available at national, statewide and local community scale from earlier leishmaniasis studies in Brazil[10] will serve as input for disease and vector data for re-analysis using comprehensive high temporal resolution GeoHealth climate and satellite-derived environmental data at regional scale (1 km^2 spatial resolution), statewide scale (15-30-60 m^2 spatial resolution) and individual community scales (sub-meter spatial resolution). High frequency climate and satellite sensor data can be made available in near real time by access to GeoHealth data archives or Internet linkages to active program data.

Selection of relevant environmental parameters to include in geospatial models will be based on results of regression analysis of disease and vector occurrence data, with variance inflation factor analysis to eliminate autocorrelation bias, according to the method of Mischler et al[9] (**Figure 1a, b, c**).

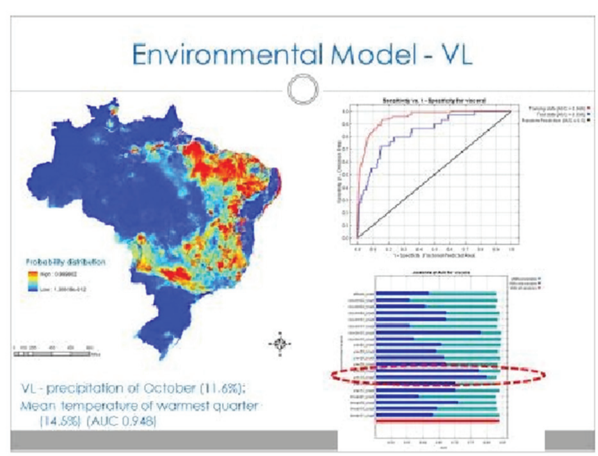

Figure 1a. Maxent risk surface and jackknife statistics output for VL in Brazil.

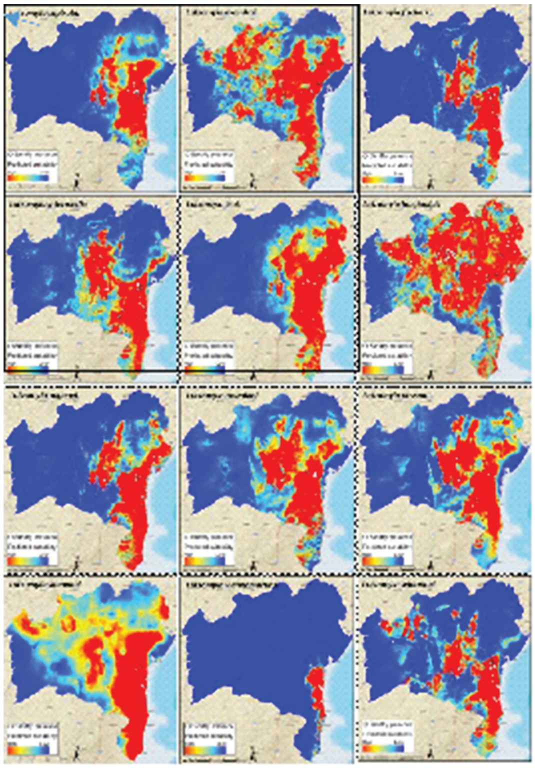

Figure 1b. Maxent predicted distribution based on MODIS variables and sand fly species collected in Bahia State. Red areas indicate higher distribution probability.

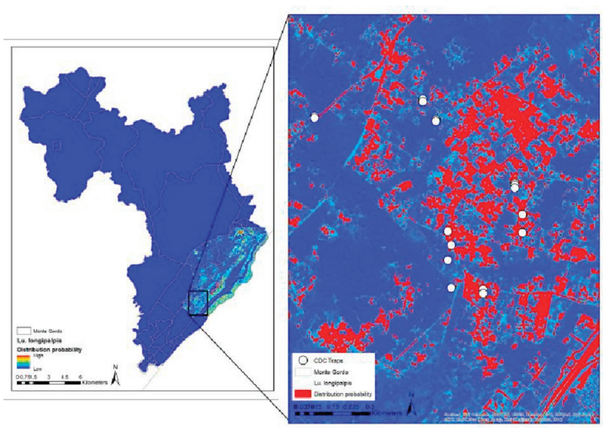

Figure 1c. Maxent predicted suitability for Lutzomyia longipalpis in the Monte Gordo community based on CDC trap data points and environmental variables from sub-meter spatial resolution Worldview 3 imagery using Maxent.

Significantly associated GeoHealth potential risk factors will be included in Maxent as variables and run with known vector and disease occurrence point data to develop probability risk surface maps that can be generated and incorporated as data layers in ArcGIS 10.4 mapping and modeling software. The relative contribution of each environmental (or socioeconomic) variable in generating geospatial risk maps will be evaluated by jackknife statistics generated as part of the Maxent software package.

Despite the existence of sustained national ministry of health recommended control programs for VL in Brazil for decades, little progress has been made in reducing VL childhood disease and fatality rates due to gaps in understanding the complex spatial and temporal interactions of environmental factors, suitable conditions for sand fly vectors and the role of dogs as the primary reservoir host. The disease in fact is spreading to new foci in urbanizing environments and new approaches to develop effective control strategies are needed. We propose that high resolution, biology-based geospatial mapping and modeling methods can be developed and implemented by government agencies as the key to more rational, targeted control in surveillance and response systems that can interrupt and reverse expansion of VL to new endemic areas.

Objective 3 - Geospatial modeling for arbovirus transmission and emergence prediction

Within the last several decades, arboviruses have emerged as significant sources of human morbidity and mortality, and have created substantial stress on the public health infrastructure of both developed and developing nations[11]. Of significance is the ongoing problem of dengue (DENV) transmission in Central and South America and repeated introductions into the southern United States[12], the emergence of both chikungunya (CHIKV) and zika (ZIKV) viruses in the Western hemisphere[13]. While many studies have investigated factors associated with transmission of these arboviruses, there are still gaps in the knowledge about what environmental and ecological factors alter transmission patterns and render conditions right for emergence of these arboviruses. Quantitative tools such as mathematical, statistical, and geospatial models have been developed to try to predict patterns of transmission as well as introduction and emergence. We will address the current need for broadly applicable models for fast and generalizable predictions across large geographic areas for concerted and standardized methods for control and mitigations.

Objective 4 - Development of data storage and processing infrastructure

In collaboration with LSU Electrical Engineering and Computer Science, classical modeling with limited data content will be expanded to enable comparison of results to big data analysis using more comprehensive, multivariable environmental data covering longer time periods and to validate and extend mapping and modeling results generated by analysis of more limited data by classical statistics.

Objective 5 - Implement dissemination and training programs to promote geospatial mapping and modeling for vector borne diseases as envisioned in the GEOSS initiative

Short courses will be offered on-site and via the Internet to promote use of GeoHealth resources and recruit contributions of brokered new data. A course on eco-epidemiological aspects of GIS/RS and vector borne disease will be developed, including use of mathematical models, computer simulations and GIS tools. Project results will be shared with health agencies in endemic countries to promote use of geospatial surveillance and response systems.

ANTICIPATED RESULTS

The main achievement of the current project will be launch of GeoHealth in the health societal benefit area in keeping with the interoperable, open-source GEOSS program goals in Latin America, North America and the Caribbean. The project will not generate new field data. The aim is to further develop existing data and predictive models from earlier results by access to a comprehensive geospatial resource for data needed to map and model vector-borne diseases. Organizations interested in geospatial health will be enlisted to serve as contributors of new data and applications in a dynamic, expanding interoperable data GEOSS resource. Training opportunities for health scientists in the public health community will be available on best use of earth observing satellite data through tutorials and short courses. GeoHealth data and models will be made available via the Internet for use by researchers and health agencies in the USA, Brazil and elsewhere in the Americas.

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