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Mapping and Forecasting Mosquito-Borne Disease Risk

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Week 5

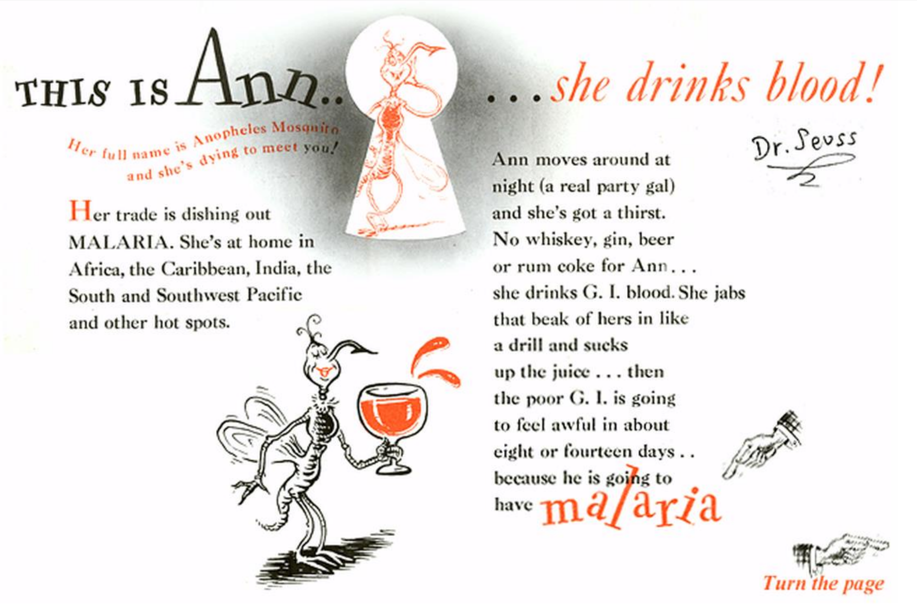
Presentation Overview

- Mosquito Ecology and Mosquito-Borne Diseases
- Remotely-Sensed Data for Monitoring Mosquito-Borne Disease Transmission
- Remote Sensing Applications to Support Mosquito-Borne Disease Control and Elimination
- Summary and Take-Home Messages

Mosquito Ecology and Mosquito-Borne Diseases

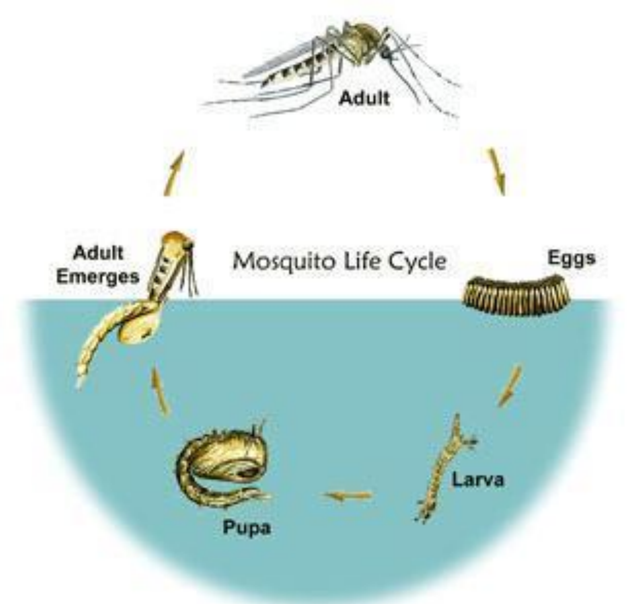
Mosquitos kill more humans than any other animal – including humans!

- More than 3,000 species, although only a small portion of these transmit disease to humans
- Life cycle includes both aquatic (juvenile) and terrestrial (adult) stages
- Nearly all mosquito species take blood meals from a variety of hosts, including humans
- Most mosquitos feed selectively on a narrow range of host species



The various mosquito life stages have distinctive ecologies

- Juvenile
  - Require stagnant water to develop
  - Eggs laid directly on water or in moist areas
  - Larvae feed on various microorganisms and are preyed upon by many other species
  - Pupae remain at the surface and do not feed
- Adult
  - Require protected areas for resting habitats
  - Feed on nectar for energy
  - Females need a blood meal to lay eggs



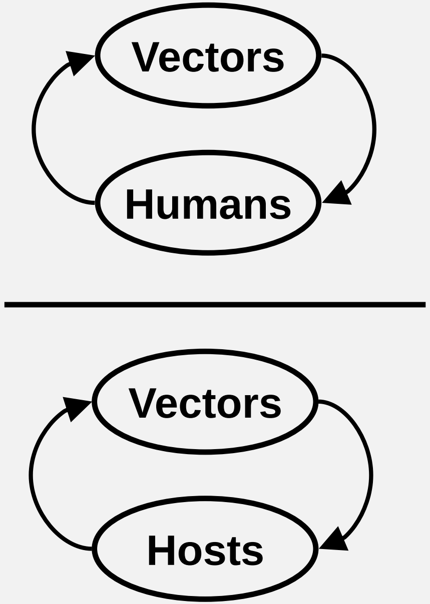
Source: American Mosquito Control Association

Two main families of mosquitoes are responsible for transmitting most of the pathogens that cause disease in humans

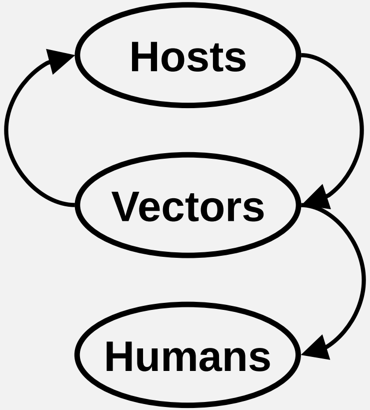
- Anopheline Mosquitoes (Anophelinae)
  - Species in the genus *Anopheles*
  - Vectors of malaria and filarial parasites
  - Dominant malaria vector species vary geographically
    - *Anopheles gambiae* (Africa)
    - *Anopheles darlingi* (South America)
    - *Anopheles culicifacies* (India)
    - *Anopheles minimus* (Southeast Asia)

- Culicine mosquitoes (Culicinae)
  - Species in multiple genera of which *Culex* and *Aedes* are the most common vectors
  - Global vectors of multiple arboviruses
    - *Aedes aegypti* (Chikungunya, Dengue, Yellow Fever, Zika)
    - *Aedes albopictus* (Chikunguna, Dengue, Zika?)
  - For other diseases like West Nile, dominant vectors vary geographically
    - *Culex pipiens* (Eastern US)
    - *Culex quinquefasciatus* (Southern US)
    - *Culex tarsalis* (Central and Western US)

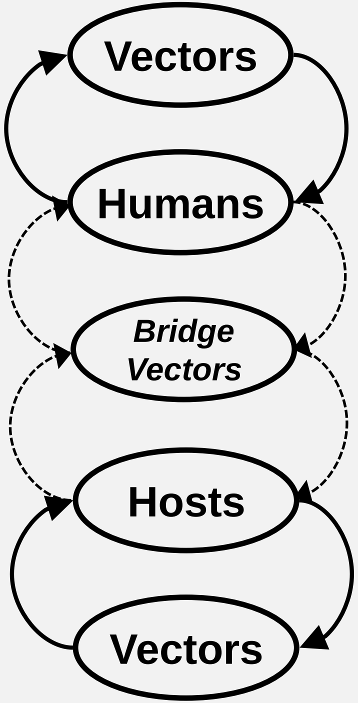
Mosquito-borne disease transmission cycles often involve one more *non-human host species*



Dengue, Malaria

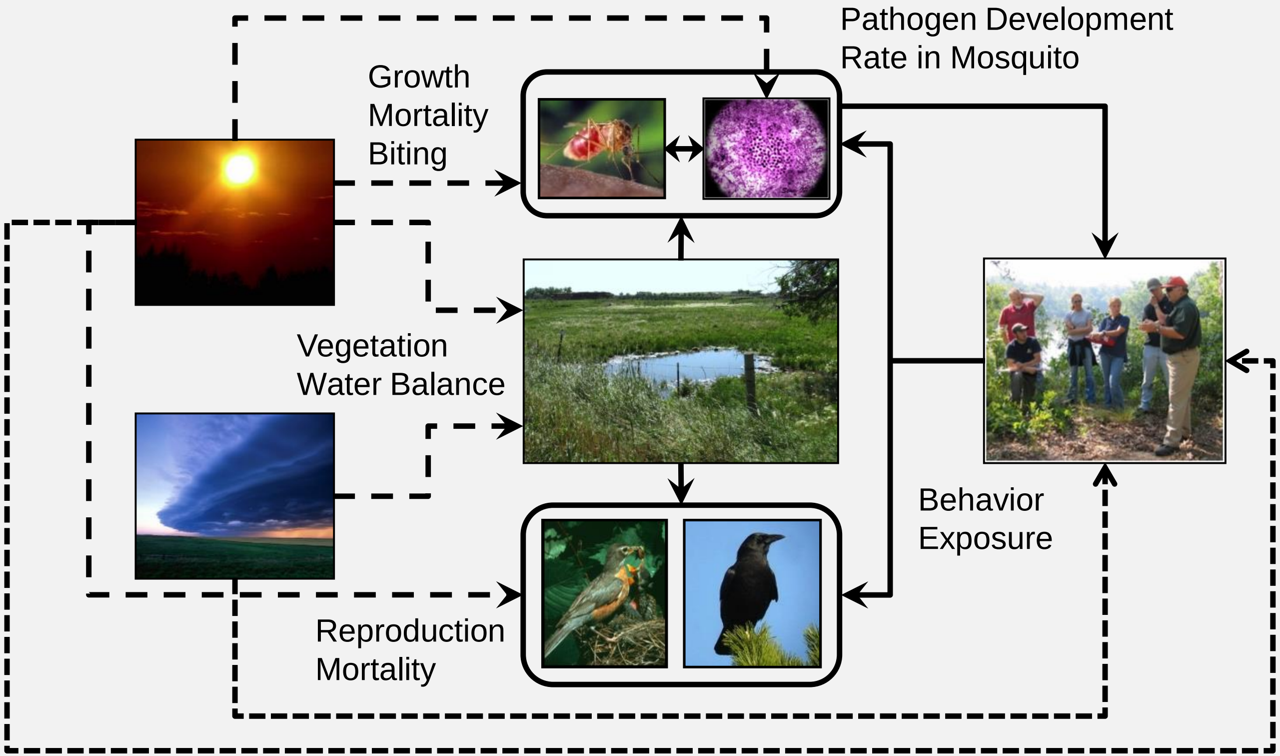


West Nile Virus



Yellow Fever, Chikungunya

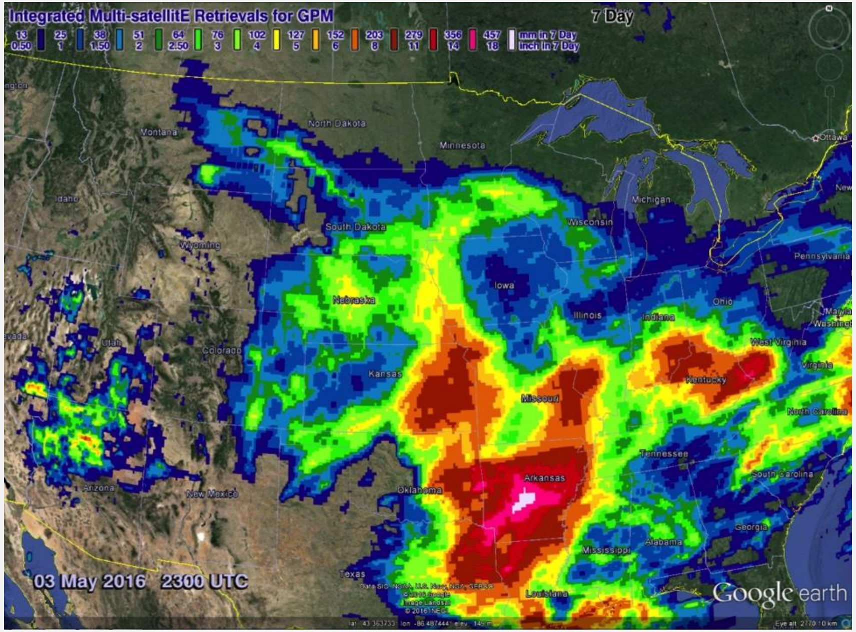
Meteorological variables and land cover influence mosquito-borne diseases through multiple pathways and can be monitored by earth-observing satellites



Remotely-Sensed Data for Monitoring Mosquito-Borne Disease Transmission

Precipitation is the ultimate source of water for the aquatic habitats of mosquito species

- Satellite estimates synthesize multiple information sources to estimate rainfall
- Some products also incorporate ground measurements from meteorological stations
- Generally available at fairly coarse spatial resolutions (~100 km) with a relatively high measurement frequency

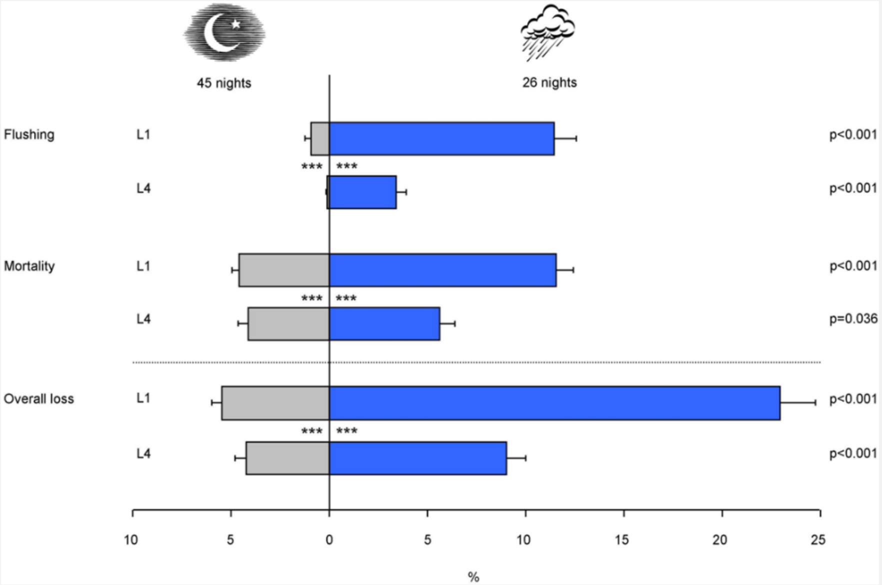


Relevant NASA Precipitation Products

- TRMM/TMPA – 0.25 degree grid
  - http://pmm.nasa.gov/data-access/downloads/trmm
  - 3B42: TRMM and Other Satellites (3-hourly, daily, monthly), > 1 month latency
  - 3B43: TRMM and Other Data Sources (monthly), > 1 month latency
  - 3B42RT: TRMM and Other Satellites Real Time (3-hourly, daily), < 1 day latency
  - Will continue to be produced through mid-2017
- Global Precipitation Mission (GPM) – 0.1 degree grid
  - http://pmm.nasa.gov/data-access/downloads/gpm
  - IMERG: Intercalibrates, merges, and interpolates satellite precipitation estimates across the TRMM and GPM eras
    - Various temporal resolutions (3-hourly, daily, 7-day, monthly)
    - Various latencies (6-hour, 18-hour, 4 months)

However, the direct effects of precipitation are highly varied and are not always positive

- Indirect effects of cloudiness on solar radiation and temperature
- Heavy rains can cause flooding, which can result in high levels of larval mortality
- Rainfall effects on breeding habitats are highly contingent upon local conditions
  - Soil Characteristics
  - Soil Saturation
  - Topography
  - Land Use

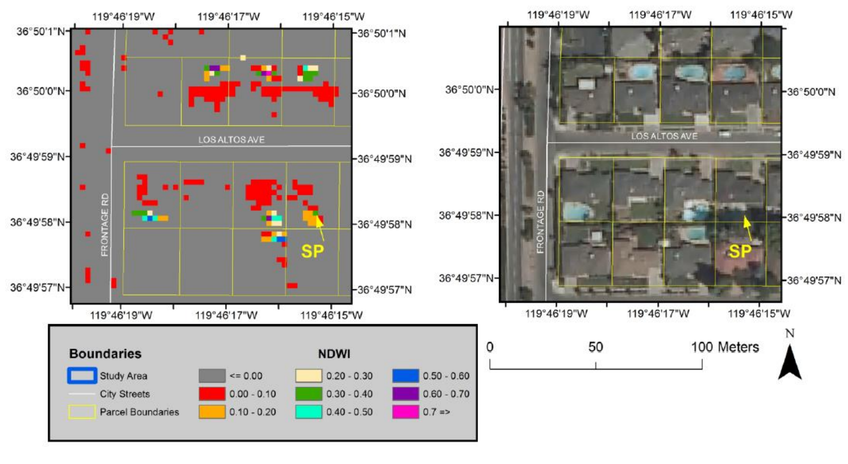


Paaijmans et al. (2007) Unexpected high losses of *Anopheles gambiae* larvae due to rainfall. *PLOS One* **11**: e1146.

Geomorphology, hydrology, and humans all influence the abundance and distribution of mosquito breeding habitats

Many earth-observing satellites can measure surface water

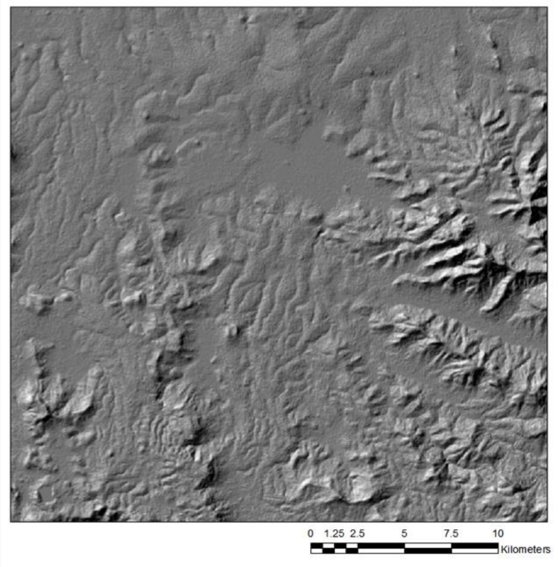
- Advantages
  - Water bodes can be detected reliably using optical remote sensing
  - Provides the most direct remotely-sensed measurement of breeding habitat
- Disadvantages
  - Repeat measurements needed to detect ephemeral water bodies
  - Many important breeding habitats are small – just a few meters in size – and are not detectable using moderate-resolution image such as Landsat (30 m pixel size)

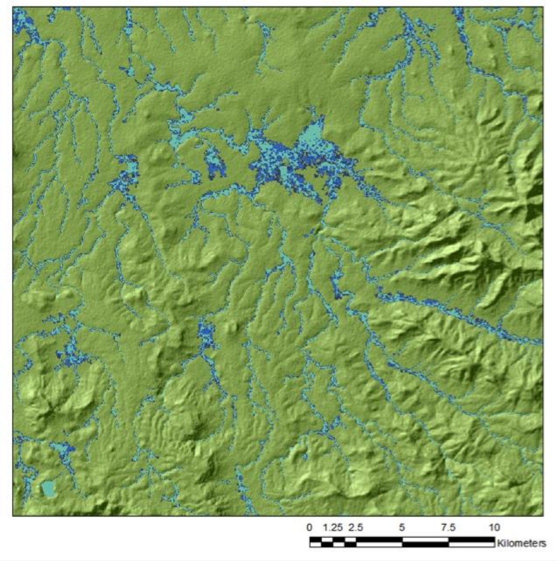


McFeeters (2013) Using the Normalized Difference Water Index (NDWI) within a Geographic Information System to Detect Swimming Pools for Mosquito Abatement: A Practical Approach. *Remote Sensing* 5: 3544-3561

Digital elevation models from the Shuttle Radar Topographic Mission (SRTM) and other sources provide information about where breeding sites may occur

- Simple topographic indices
  - Topographic moisture index (TMI)
  - Height above nearest drainage (HAND)
- More complex hydrological models



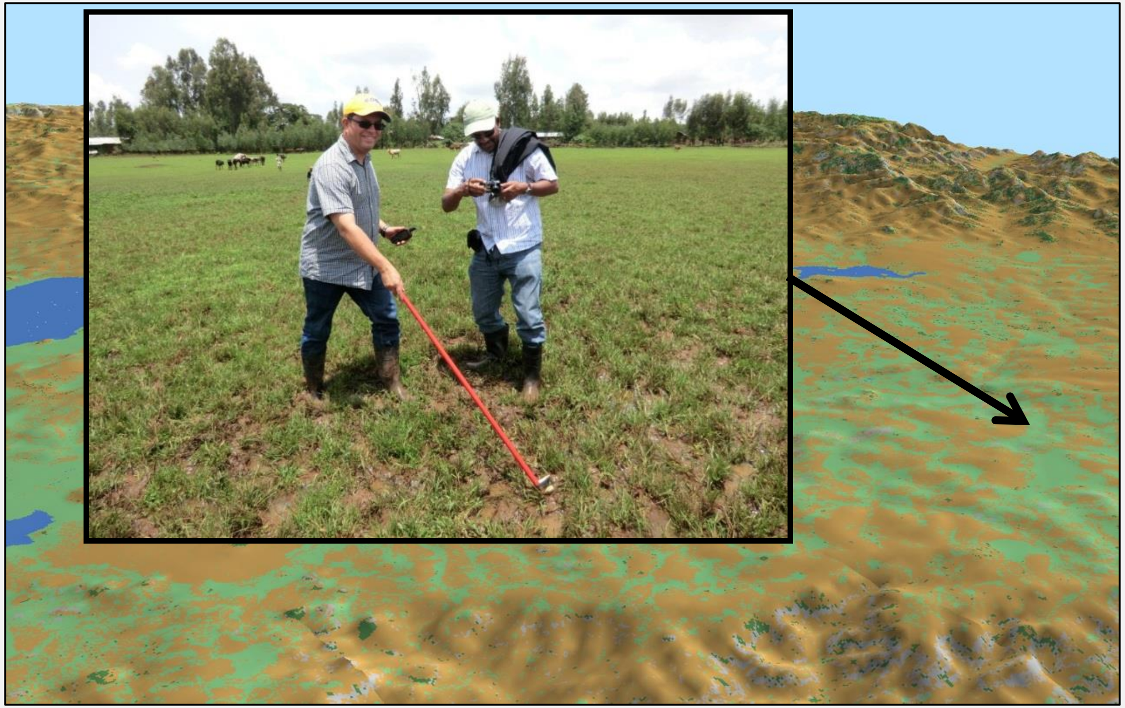


Sources of Digital Elevation Data

- The National Map http://nationalmap.gov/
  - Coverage for the contiguous United States plus Alaska and Hawaii
  - Available at a range of spatial resolutions
    - 1 arc-second (30 m) for all of the United States and Canada
    - 1/2 arc-second (10 m) for the contiguous United States
    - 1/9 arc-second (3 m) for portions of the contiguous United States
- The Shuttle Radar Topography Mission (SRTM) https://lta.cr.usgs.gov/SRTM
  - STRM Void Filled: 3 arc-second (90 m) outside of the United States
  - STRM 1 Arc-Second Global: 1 arc-second (30 m) outside of the United States

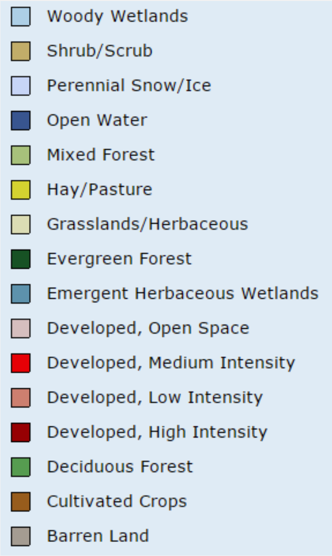
Land cover and land use maps derived from Landsat imagery can provide information about larval habitats

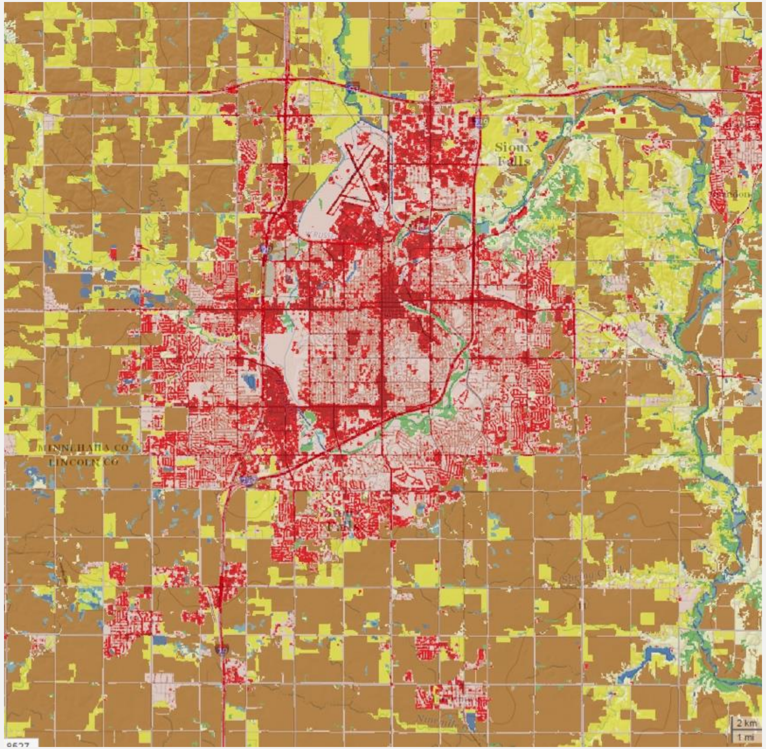
- In the Amhara region of Ethiopia, lowland pastures are important breeding sites for anopheline mosquitoes.
- As a result, landscapes with a high proportion of these wetlands have high malaria incidence

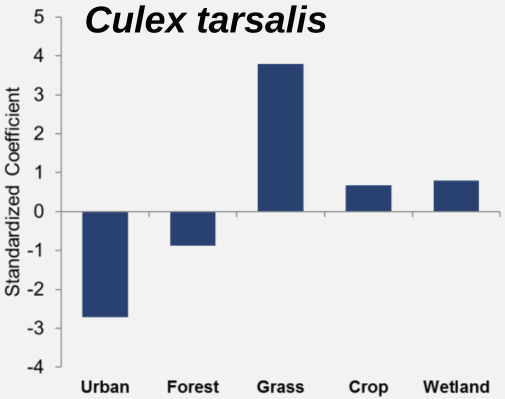


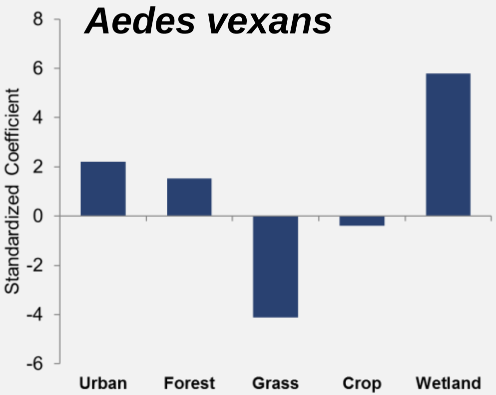
Midekisa et al. (2014) Multisensor earth observations to characterize wetlands and malaria epidemiology in Ethiopia. *Water Resources Research* 50*:* 8791–8806.

Different mosquito species are often associated with different land cover characteristics



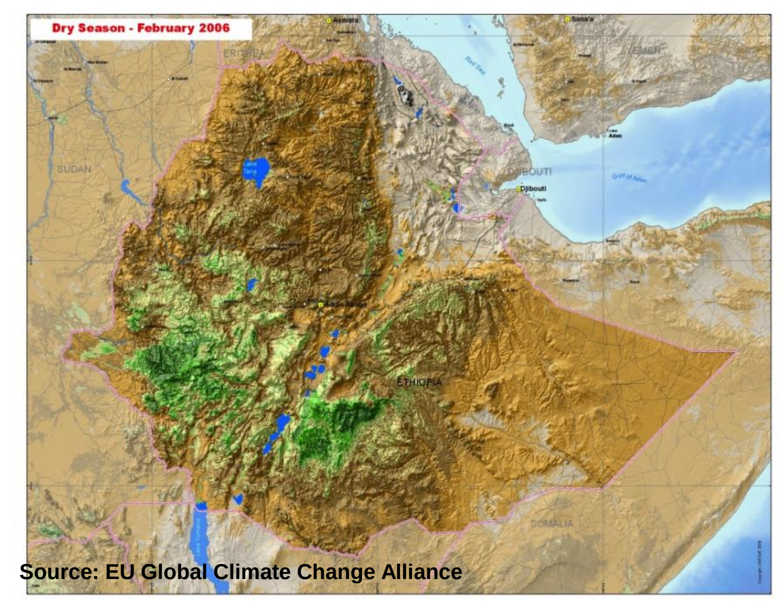




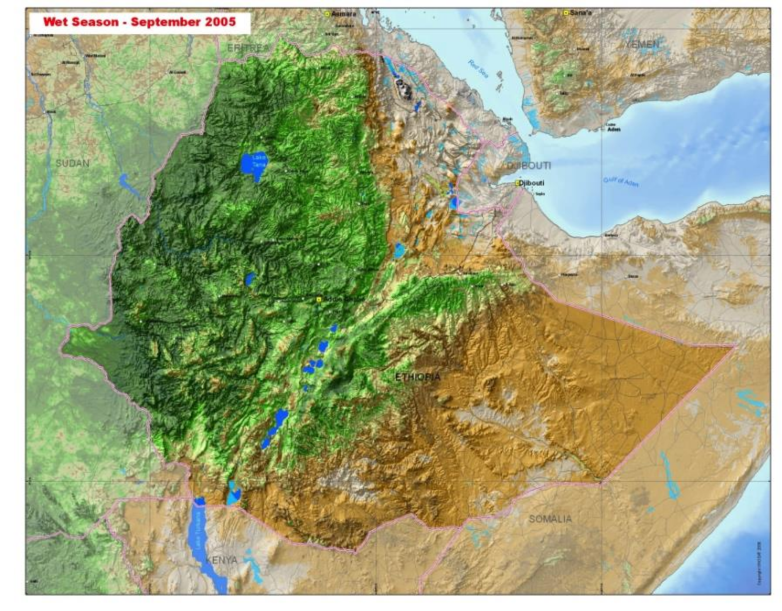


Chuang et al. (2011) Weather and land cover influences on mosquito populations in Sioux Falls, South Dakota. *Journal of Medical Entomology* 48: 669-679.

Spectral indices such as NDVI measure green vegetation and can provide a proxy for soil moisture



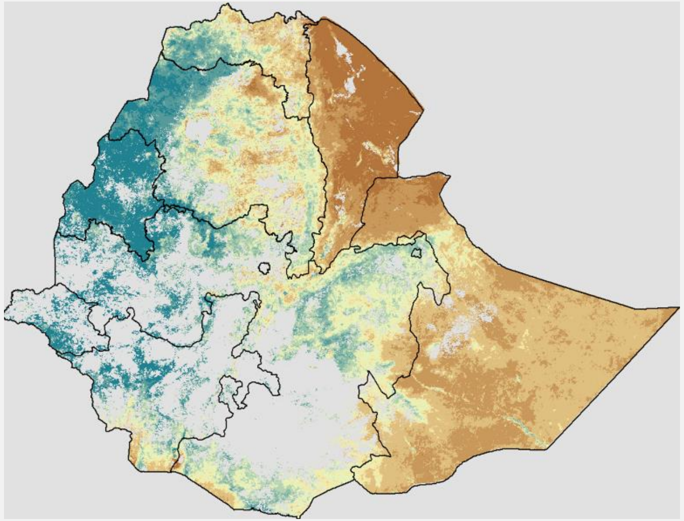
Source: EU Global Climate Change Alliance



A potential advantage of this approach is that this data is available at a finer spatial resolution (500-1000 m) than rainfall products.

Commonly-used spectral indices for mosquito-borne disease applications

- Normalized Difference Vegetation Index (NDVI)
  NIR – Red / NIR + Red
- Enhanced Vegetation Index (EVI)
  NIR – Red / NIR + 6 Red – 7.5 Blue + 1
- Normalized Difference Moisture Index (NDMI)
  NIR – MIR / NIR + MIR
- Limitations for mosquito-borne disease applications
  - Cloud cover
  - Respond to multiple environmental factors
    - Soil Moisture
    - Vegetation Type
    - Human Land Use



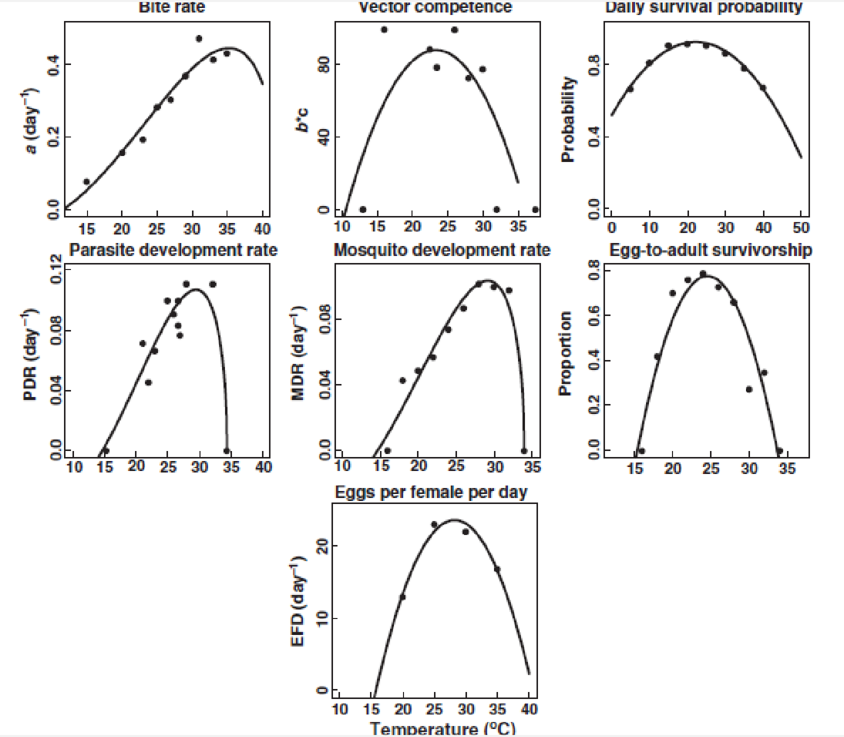
July 2003 NDVI calculated from MODIS BRDF-Adjusted reflectance

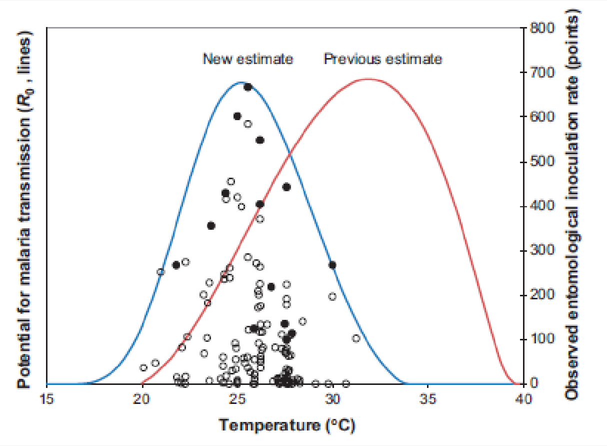
Sources of Vegetation Index Data

https://lpdaac.usgs.gov

- MODIS Vegetation Indices
  - Separate products for Terra (MOD13) and Aqua (MYD13)
  - 250, 500, 1000, and 5600 m resolution
  - 16-day composites (also monthly at 1000 and 5600 m)
  - Includes NDVI and EVI
- MODIS BRDF-Adjusted Reflectance
  - Combined Terra/Aqua product (MCD43)
  - 500 and 1000 m resolution
  - 16 day sliding composites (updated daily in collection 6)
  - Reflectance bands can be used to compute NDVI, EVI, NDMI, and other spectral indices

Temperature affects mosquito life cycles and disease transmission through multiple pathways



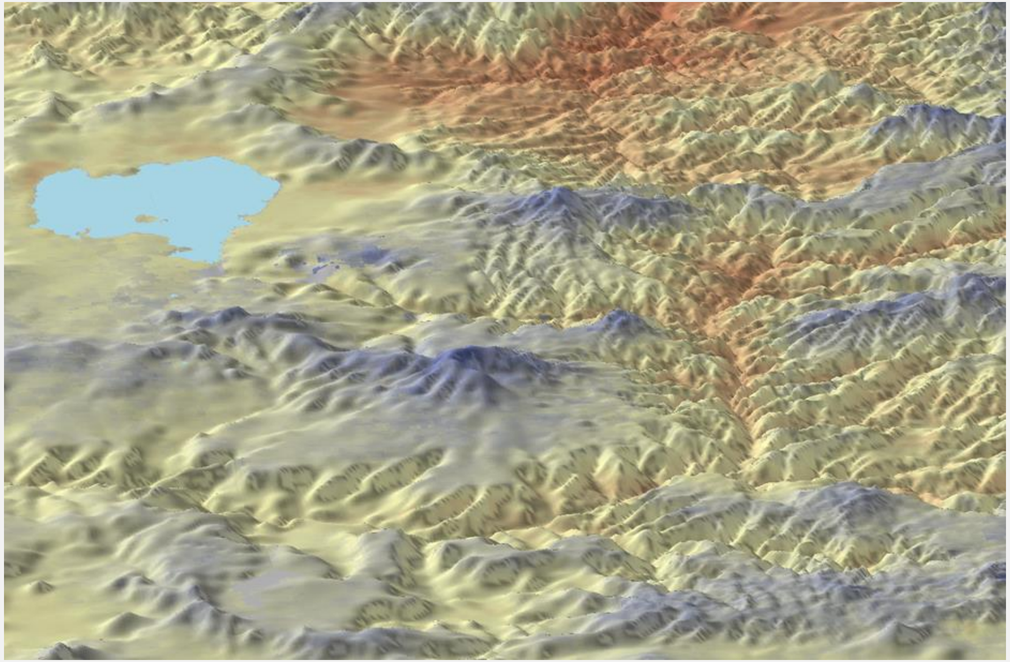


As the result of these combined effects, there are different optimum temperature ranges for the transmission of different mosquito-borne diseases in various ecological contexts.

Mordecia et al. (2013) Optimal temperature for malaria transmission is dramatically lower than previously predicted. *Ecology Letters* 16: 22-30

Remotely-sensed land surface temperature (LST) is often used as a proxy for air temperature

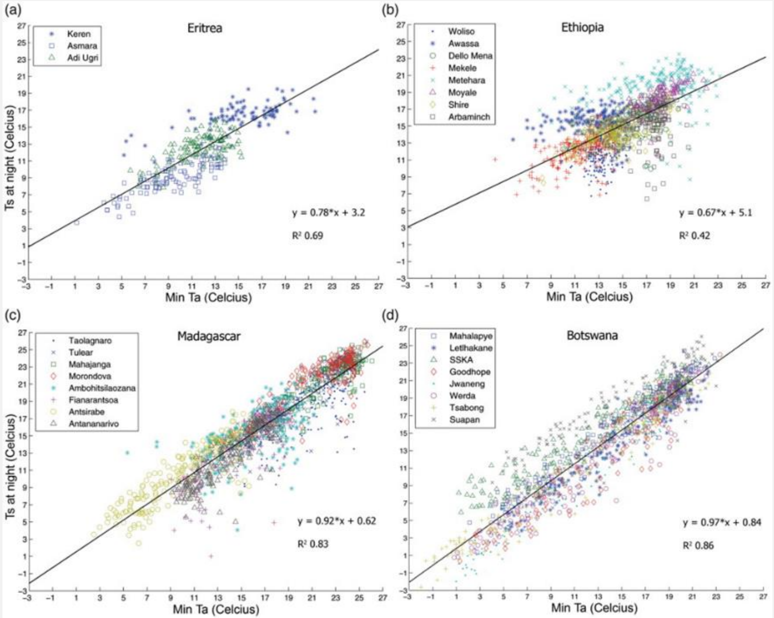
- Temperature of the uppermost layer of the earth's surface (vegetation, soil, impervious surfaces)
- Computed based on radiance in the thermal infrared portion of the spectrum (~ 8-14 μm)
- Available at relatively fine spatial resolutions (e.g., 1000 m MODIS products)



MODIS Terra land surface temperature in the Amhara region of Ethiopia, September 2003. Red=Warm, Blue=Cool.

However, there are a number of limitations to the use of LST for mosquito-borne disease applications

- Nighttime LST has is associated with minimum diurnal temperature
- Daytime LST is strongly affected by solar radiation and the surface energy balance and has a weaker association with maximum diurnal temperature
- But mosquitoes respond to temperature effects throughout the entire day
- Probably safest to use LST as a metric of relative variability through time rather than an absolute measure of accumulated degree days

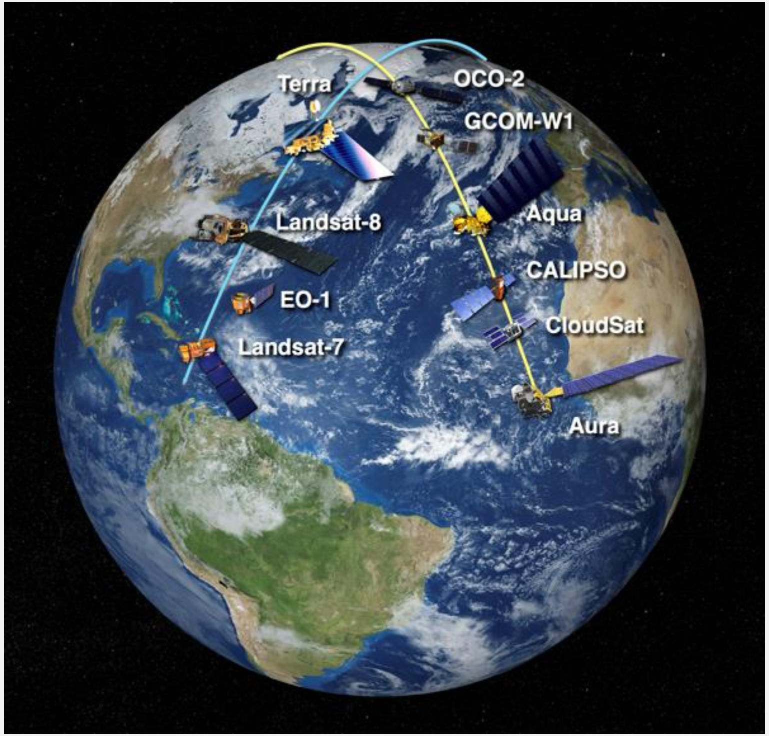


VanCutsem et al. (2010) *Evaluation of MODIS land surface temperature data to estimate air temperature in different ecosystems over Africa*. Remote Sensing of Environment 114: 449-465.

Sources of Land Surface Temperature Data

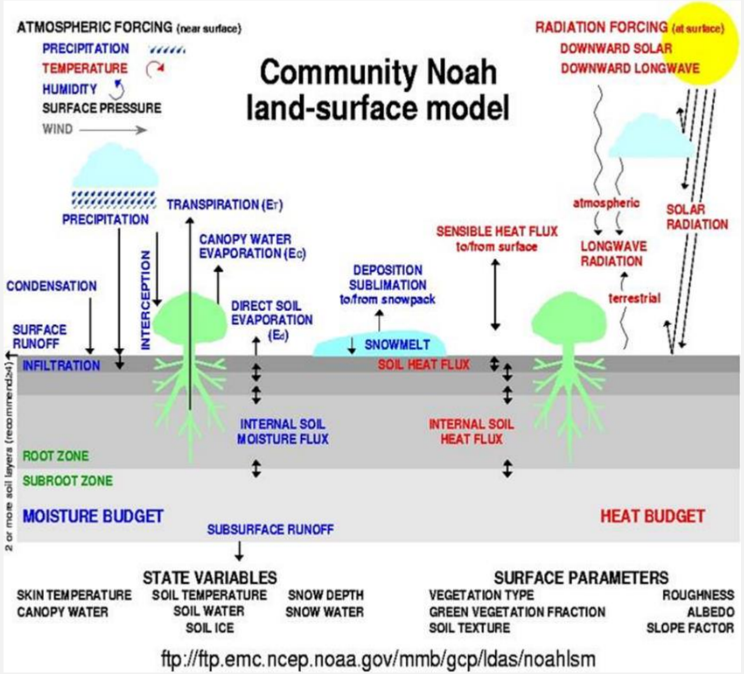
https://lpdaac.usgs.gov

- MODIS products
  - 1000 m and 5600 m spatial resolution
  - 8-day composite
  - Clouds are less of a problem than with optical-IR remote sensing products, but there can still be substantial issues in tropical regions with missing data during the rainy season
- Terra (MOD11)
  - Available from 2000-present
  - Overpass times between 10-12 a.m. and p.m.
- Aqua (MYD11)
  - Available from 2002-present
  - Overpass times between 1-3 a.m. and p.m.



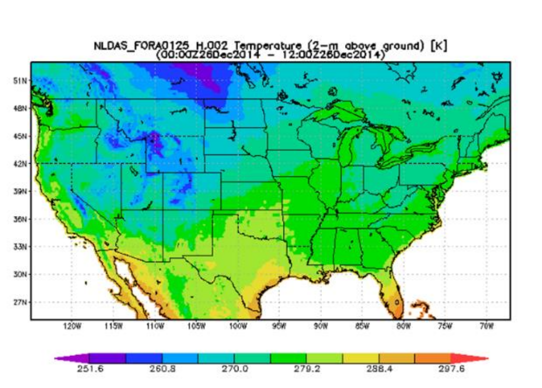
There are also a number of gridded meteorological and hydrometeorological datasets that are useful for mosquito-borne disease applications

- NASA Land Data Assimilation System (LDAS)
  - Gridded observations of temperature, precipitation, wind, humidity, and radiation are created by assimilating and rescaling data from a variety of sources, including satellite observations
  - The observations are then used to force macroscale land surface models that simulate land surface water and energy balance
  - These models produce a variety of outputs that are relevant to mosquito-borne disease, including soil moisture and soil temperature

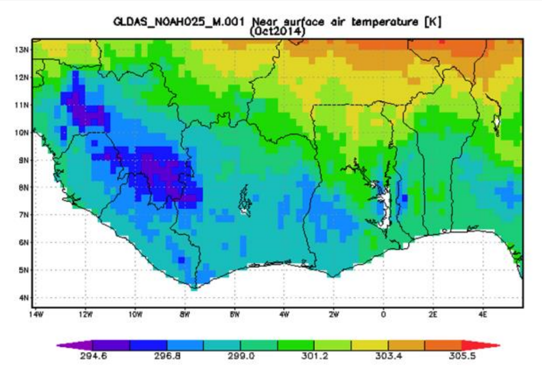


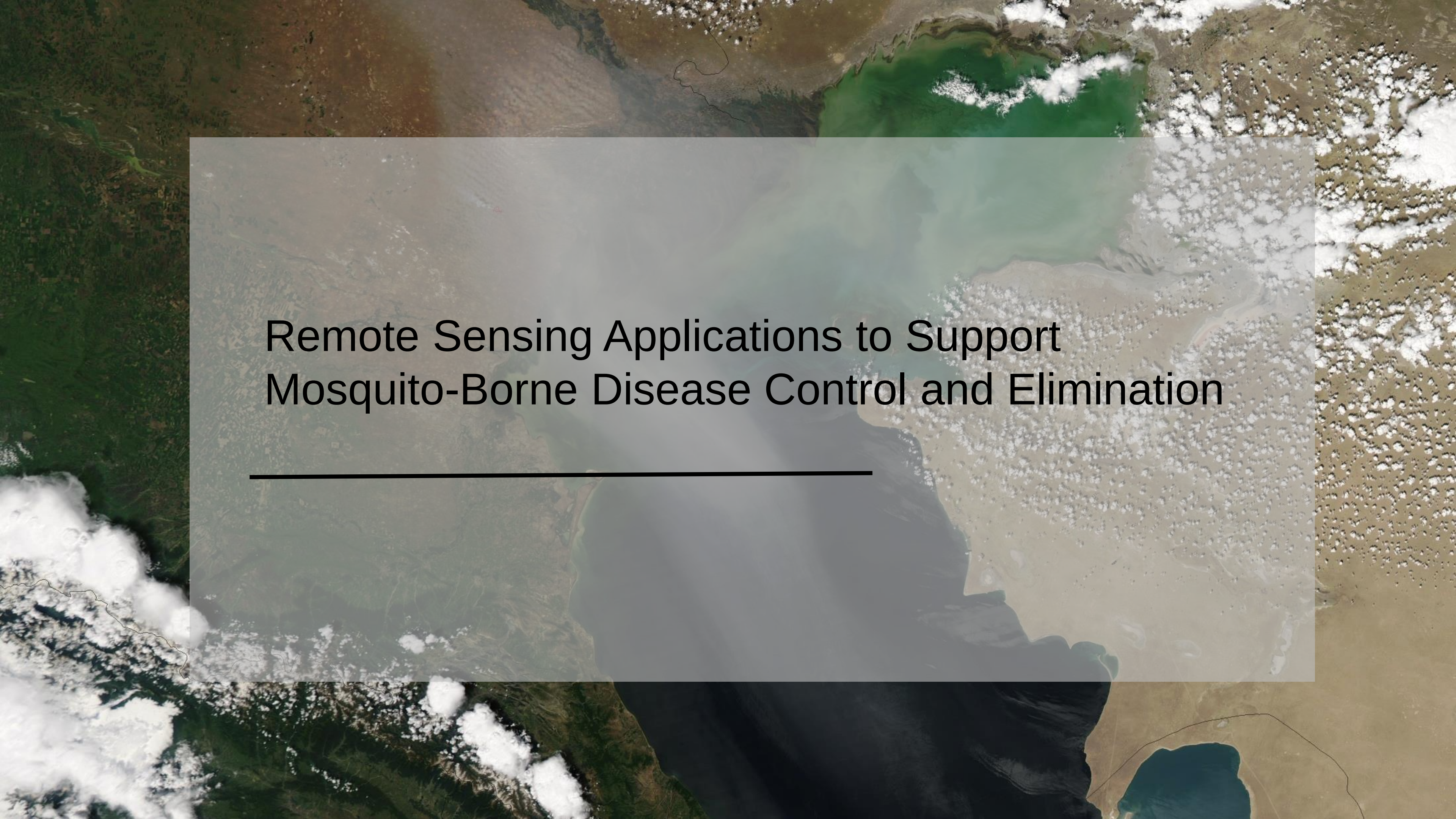
National (United States) and global products are available

- National Land Data Assimilation System (NLDAS)
  - 0.125 degree grid
  - Hourly time step (monthly product available)
  - Relatively short latency (3-4 days)



- Global Land Data Assimilation System (GLDAS)
  - 1 degree and 0.25 degree spatial resolutions
  - 3-hourly time step (monthly product available)
  - Longer latency (1-2 months)



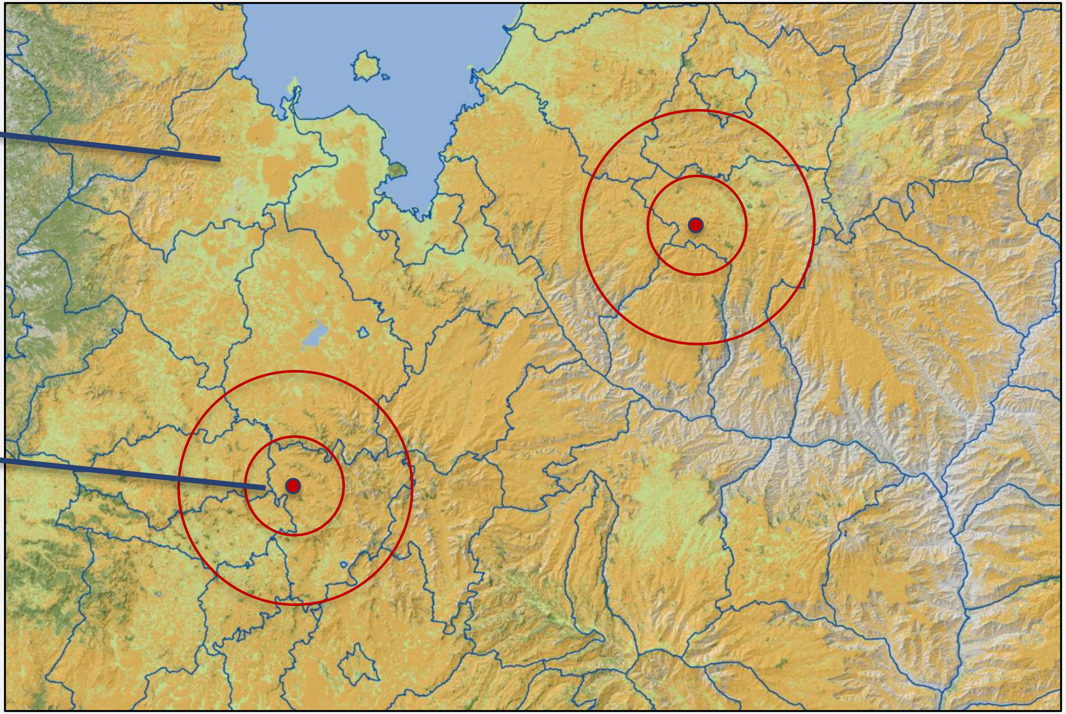


Remote Sensing Applications to Support Mosquito-Borne Disease Control and Elimination

Remote sensing data can be associated with case data and mosquito data via overlay of polygons or points in a GIS

Polygons represent the counties, districts, or other administrative boundaries within which epidemiological data are summarized

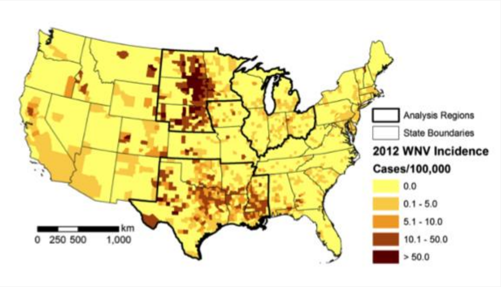
Points represent mosquito traps or individual villages. A surrounding buffer zone is typically used to summarize remotely-sensed environmental data.



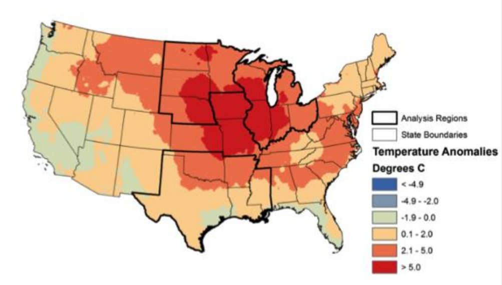
We can combine remotely-sensed environmental data with data on disease cases and mosquitoes to help us better understand the environmental drivers of disease outbreaks

- Was climatic variability a driver of the reemergence of West Nile virus in the United States in 2012?
- Used partial least squares regression (PLSR) to examine the influences of NLDAS temperature and precipitation on reported cases of WNV at the county level
- Examined three zones with large WNV clusters
  - Upper Midwest
  - Northern Great Plains
  - South Central

2012 WNV Incidence Rates

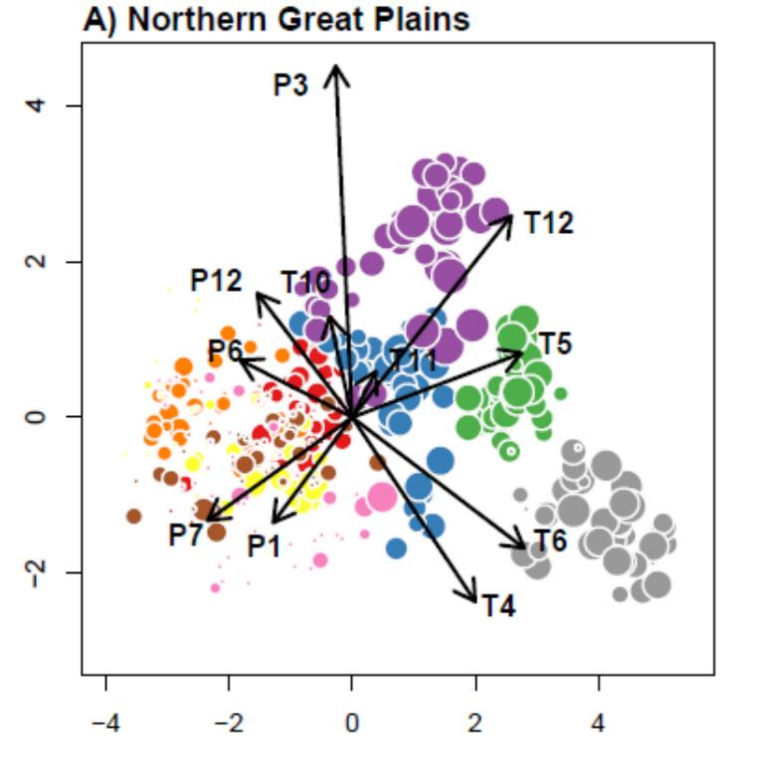


July Temperature Anomalies



PLSR biplots display relationships between climatic variability and WNV outbreaks

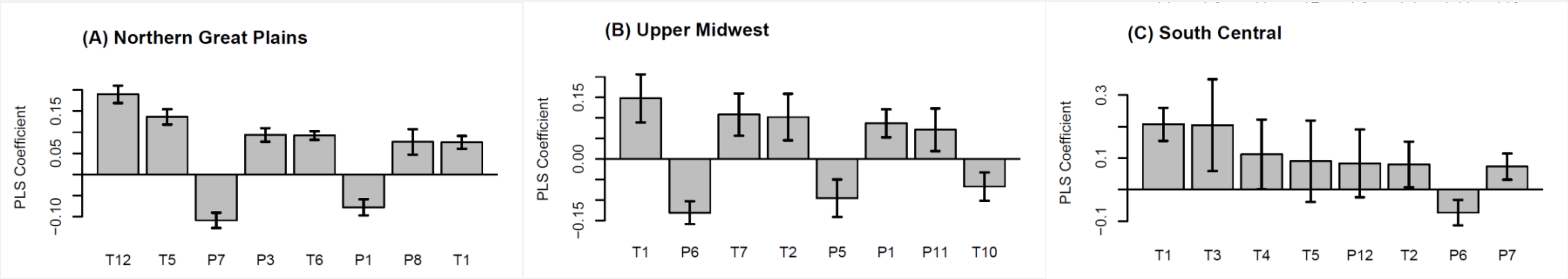
- Points close together have similar climatic anomalies and point size reflects the relative WNV rate for each county/year
- Arrows represent correlations of climatic variables with each component.
  - T=Temperature
  - P=Precipitation
  - Month=1-12



Wimberly et al. (2014) Regional variation of climatic influences on West Nile virus outbreaks in the United States. *American Journal of Tropical Medicine and Hygiene* 91: 677-684.

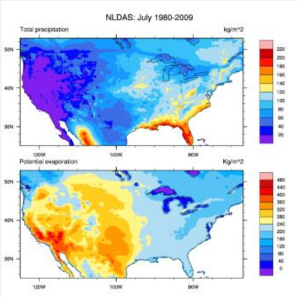
Standardized PLSR coefficients reflect the relative importance of each variable in each region.

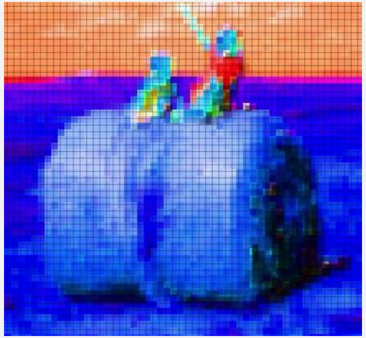
T=Temperature, P=Precipitation, Month=1-12



Wimberly et al. (2014) Regional variation of climatic influences on West Nile virus outbreaks in the United States. *American Journal of Tropical Medicine and Hygiene* 91: 677-684.

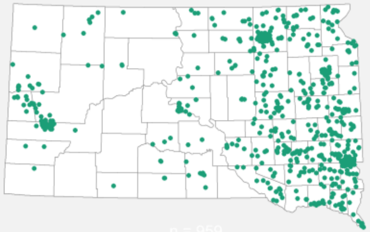
Environmental relationship can be applied to generate disease risk maps by smoothing noisy measurements of disease cases and filling in data gaps



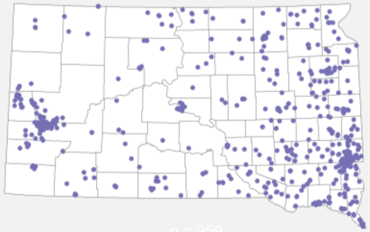


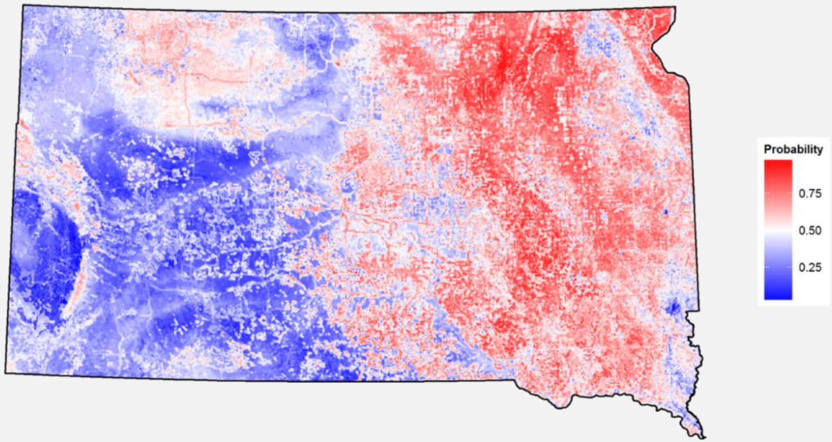
A preliminary WNV risk map for South Dakota shows statewide patterns related to climate and land cover.

WNV Cases



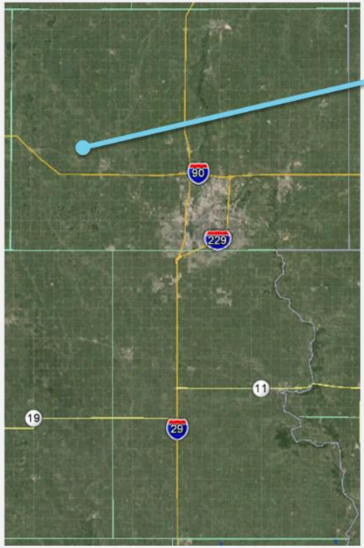
Control Points

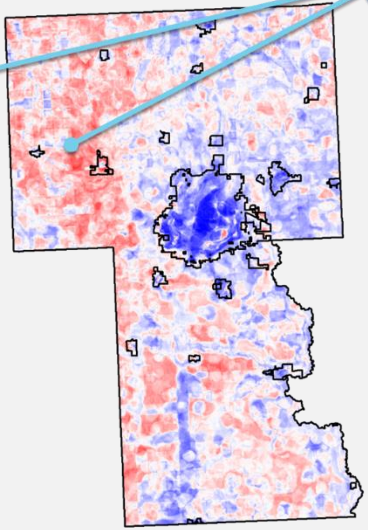




The map was based on a random forests model with NLDAS climate, NLCD land cover, and SUURGO soil data as the main predictor variables

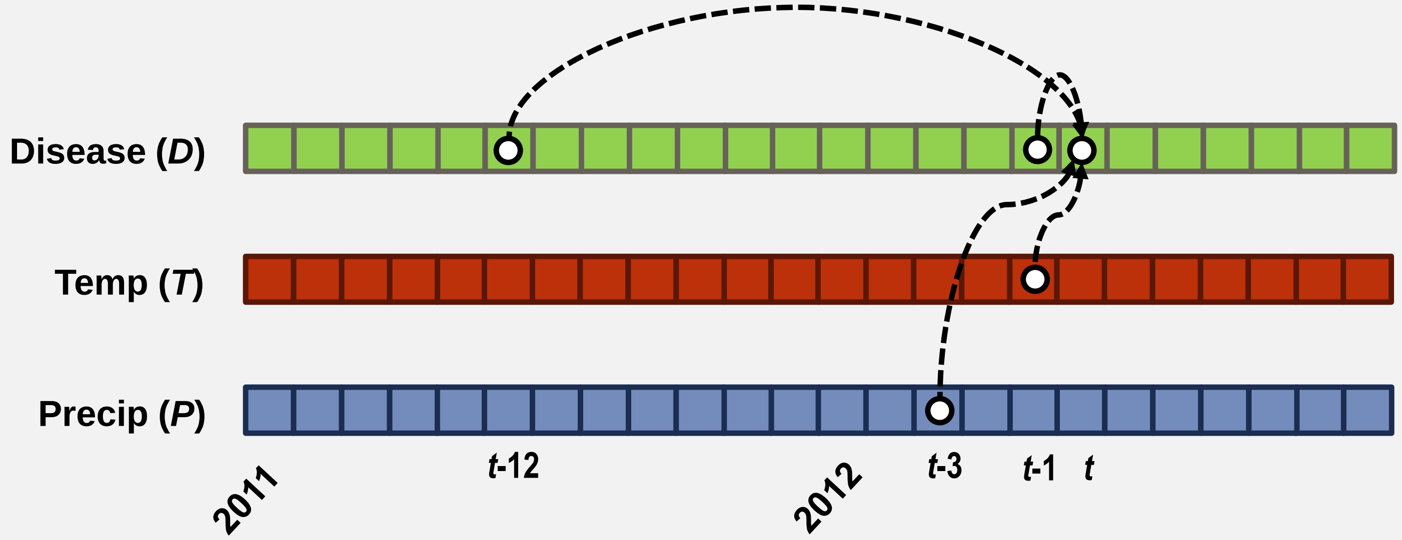
At more localized scales, the map reveals spatial patterns of WNV risk related to land use and soil drainage





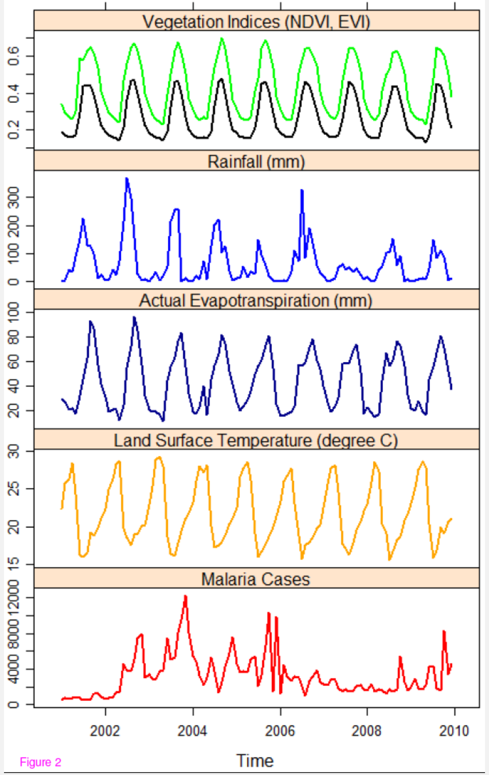
Higher risk in areas with poorly drained soils and more grass cover, lower risk in more developed areas

Malaria risk in humans exhibits lagged responses to environmental variability, providing a basis for forecasting future malaria risk using environmental variables



Time series models were used to association malaria outbreaks with remotely sensed environmental variables in Ethiopia

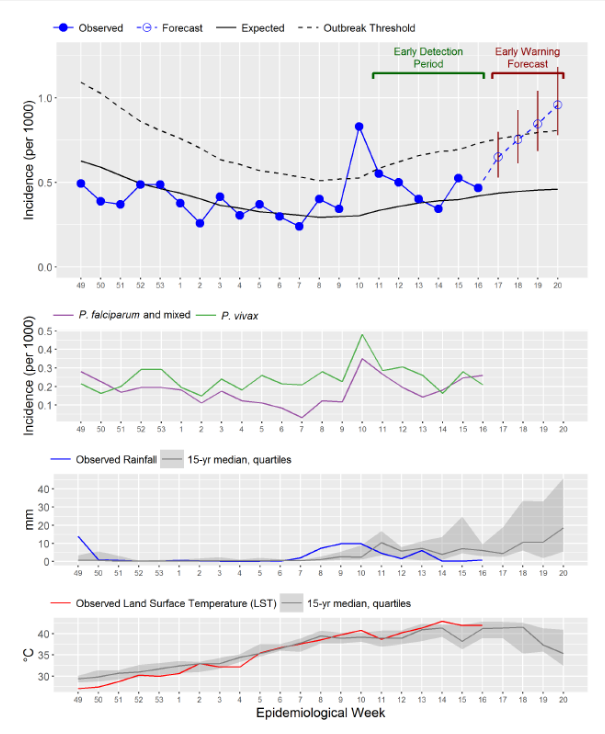
- Short-term (1 month) effects of land surface temperature
- Longer-term (1-3 month) effects of moisture variables
  - Precipitation
  - Actual evapotranspiration
  - Vegetation indices
- Moisture more important in warmer and drier climates at lower elevations



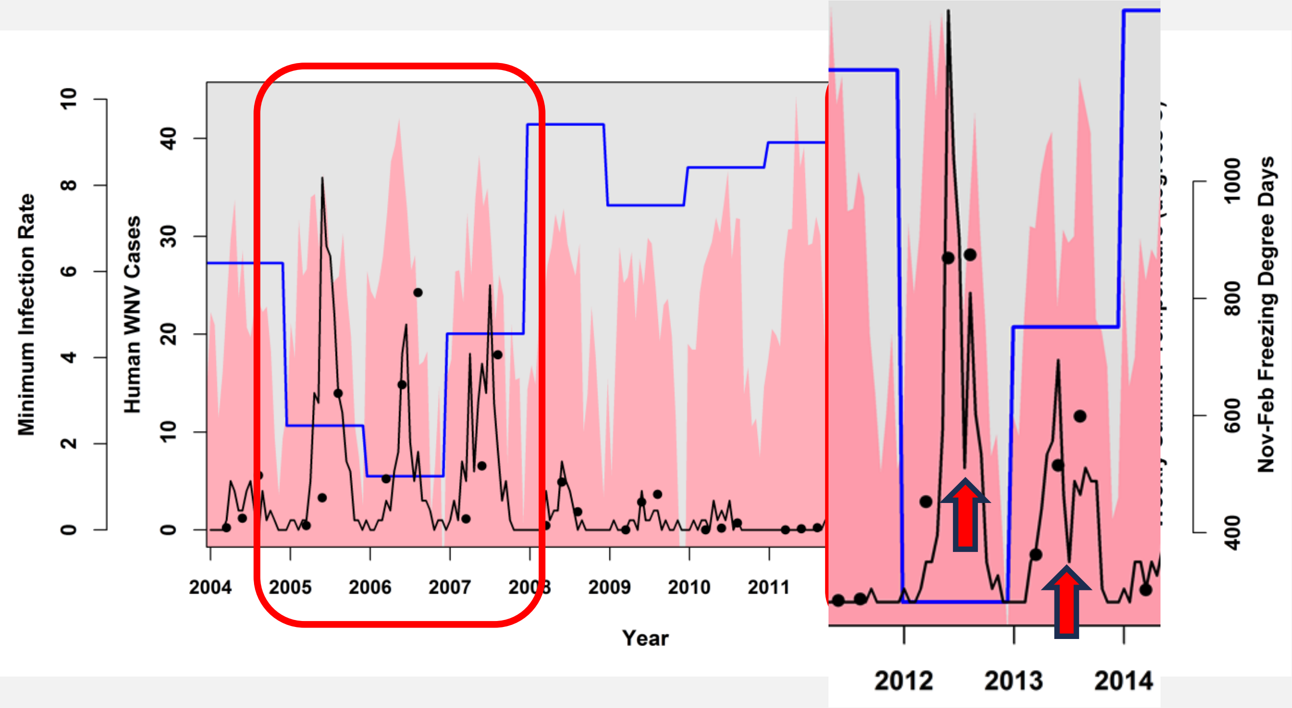
Midekisa et al., 2012. Remote sensing-based time series models for malaria early warning in the highlands of Ethiopia. *Malaria Journal* 11: 165.

We have extended these results to develop the EPIDEMIA malaria forecasting system

- Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment
- The example on the right is a weekly forecast for Dembecha District, Amhara Region of Ethiopia, April 2016
- A dynamic linear model implemented using the Kalman filter assimilates data on land surface temperature, precipitation, vegetation indices, and historical malaria cases.
- For more information visit https://epidemia.sdstate.edu/



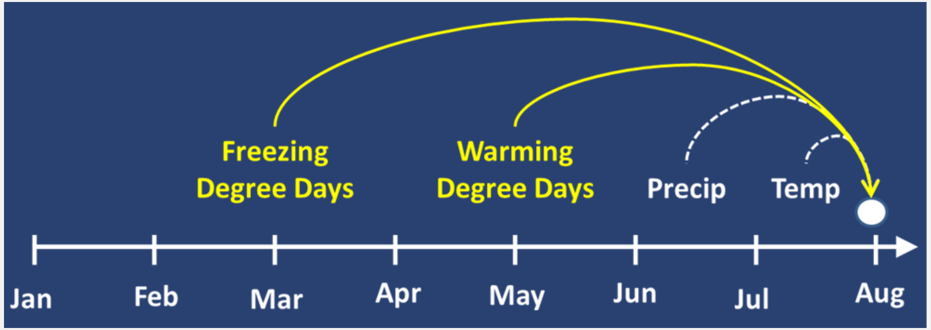
In South Dakota, WNV outbreak years are characterized by high mosquito infection rates, warm winters, and hot summers.

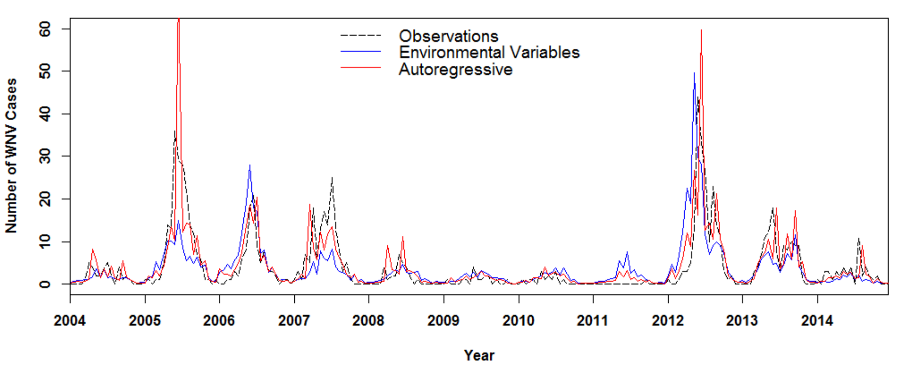


Time series truncated to the WNV transmission season (May-October)

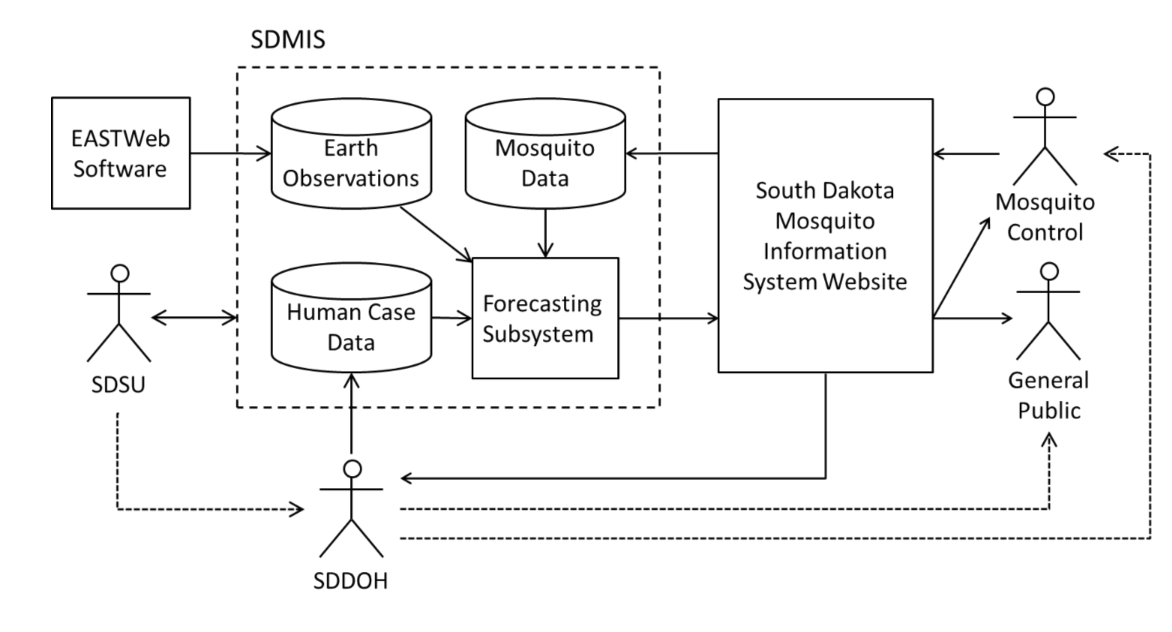
As a result, it is possible to forecast WNV outbreak years using lagged environmental data

- Predictions for eastern South Dakota from a generalized linear autoregressive model
- Temperature and precipitation data from NLDAS
- Seasonal lags from the preceding winter and spring
- 1-4 week lags of summer precipitation and temperature





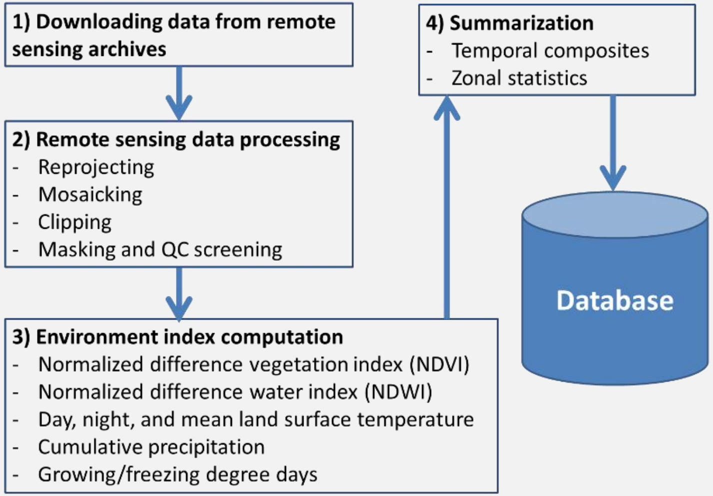
The South Dakota Mosquito Information Systems (SDMIS) project is using these relationships to produce forecasts of WNV risk in South Dakota

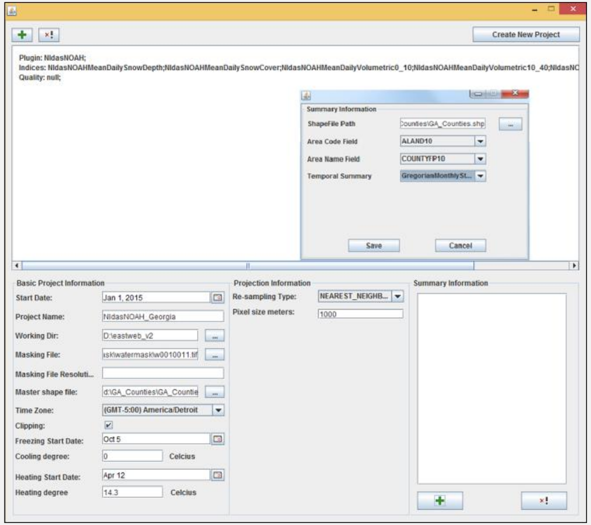


Check out this video on our NASA Applied Science Project: https://www.youtube.com/watch?v=ag-Zo0izSNg

The EASTWeb software is used to automatically acquire and process environmental monitoring data from multiple sources.

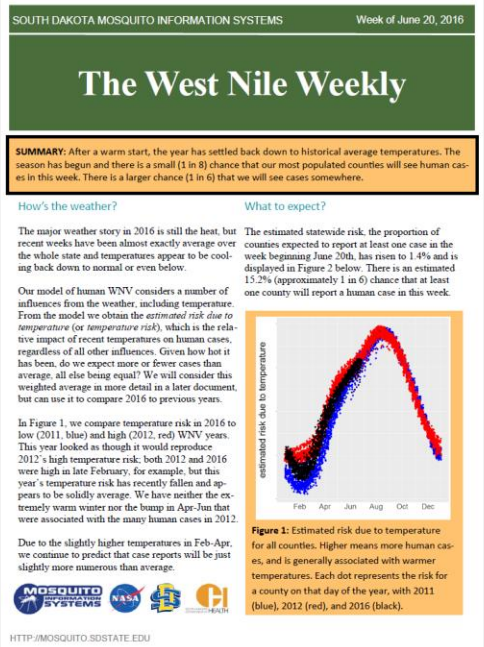
Supported by the NASA Advancing Collaborative Connections for Earth System Science (ACCESS) program, cooperative agreement NNX14AI37A https://epidemia.sdstate.edu/eastweb/





Liu et al. (2015) Software to Facilitate Remote Sensing Data Access for Disease Early Warning Systems. *Environmental Modeling and Software* 74: 247-257.

The project website allows public health partners to upload mosquito data and provides access to weekly reports



SOUTH DAKOTA MOSQUITO INFORMATION SYSTEMS — Week of June 20, 2016

The West Nile Weekly

SUMMARY: After a warm start, the year has settled back down to historical average temperatures. The season has begun and there is a small (1 in 8) chance that our most populated counties will see human cases in this week. There is a larger chance (1 in 6) that we will see cases somewhere.

How's the weather?

The major weather story in 2016 is still the heat, but recent weeks have been almost exactly average over the whole state and temperatures appear to be cooling back down to normal or even below.

Our model of human WNV considers a number of influences from the weather, including temperature. From the model we obtain the *estimated risk due to temperature* (or *temperature risk*), which is the relative impact of recent temperatures on human cases, regardless of all other influences. Given how hot it has been, do we expect more or fewer cases than average, all else being equal? We will consider this weighted average in more detail in a later document, but can use it to compare 2016 to previous years.

In Figure 1, we compare temperature risk in 2016 to low (2011, blue) and high (2012, red) WNV years. This year looked as though it would reproduce 2012's high temperature risk; both 2012 and 2016 were high in late February, for example, but this year's temperature risk has recently fallen and appears to be solidly average. We have neither the extremely warm winter nor the bump in Apr-Jun that were associated with the many human cases in 2012.

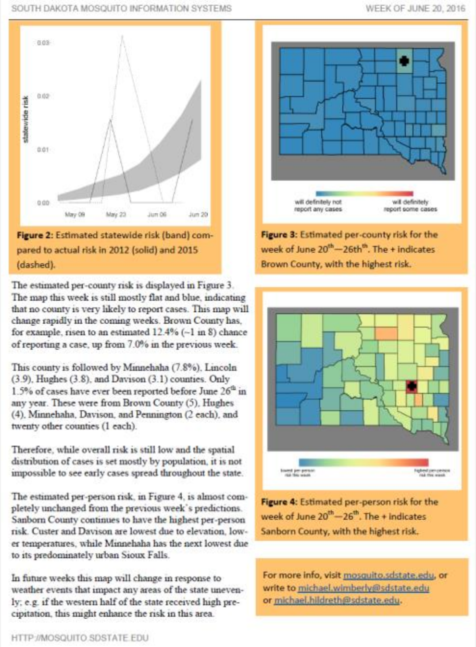
Due to the slightly higher temperatures in Feb-Apr, we continue to predict that case reports will be just slightly more numerous than average.

What to expect?

The estimated statewide risk, the proportion of counties expected to report at least one case in the week beginning June 20th, has risen to 1.4% and is displayed in Figure 2 below. There is an estimated 15.2% (approximately 1 in 6) chance that at least one county will report a human case in this week.

Figure 1: Estimated risk due to temperature for all counties. Higher means more human cases, and is generally associated with warmer temperatures. Each dot represents the risk for a county on that day of the year, with 2011 (blue), 2012 (red), and 2016 (black).

HTTP://MOSQUITO.SDSTATE.EDU



SOUTH DAKOTA MOSQUITO INFORMATION SYSTEMS — WEEK OF JUNE 20, 2016

Figure 2: Estimated statewide risk (band) compared to actual risk in 2012 (solid) and 2015 (dashed).

Figure 3: Estimated per-county risk for the week of June 20th—26th. The + indicates Brown County, with the highest risk.

The estimated per-county risk is displayed in Figure 3. The map this week is still mostly flat and blue, indicating that no county is very likely to report cases. This map will change rapidly in the coming weeks. Brown County has, for example, risen to an estimated 12.4% (~1 in 8) chance of reporting a case, up from 7.0% in the previous week.

This county is followed by Minnehaha (7.8%), Lincoln (3.9), Hughes (3.8), and Davison (3.1) counties. Only 1.5% of cases have ever been reported before June 26th in any year. These were from Brown County (5), Hughes (4), Minnehaha, Davison, and Pennington (2 each), and twenty other counties (1 each).

Therefore, while overall risk is still low and the spatial distribution of cases is set mostly by population, it is not impossible to see early cases spread throughout the state.

The estimated per-person risk, in Figure 4, is almost completely unchanged from the previous week's predictions. Sanborn County continues to have the highest per-person risk. Custer and Davison are lowest due to elevation, lower temperatures, while Minnehaha has the next lowest due to its predominately urban Sioux Falls.

In future weeks this map will change in response to weather events that impact any areas of the state unevenly; e.g. if the western half of the state received high precipitation, this might enhance the risk in this area.

Figure 4: Estimated per-person risk for the week of June 20th—26th. The + indicates Sanborn County, with the highest risk.

For more info, visit mosquito.sdstate.edu, or write to michael.wimberly@sdstate.edu or michael.hildreth@sdstate.edu.

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Summary and Take-Home Messages

Key Take Home Messages

Remote Sensing Data for Mosquito-Borne Diseases

- Ecological details matter!
  - Different mosquito species vector different diseases and are sensitive to different environmental factors
  - Don’t overlook the importance of avian and mammalian hosts!
  - Local geography is also important – environmental effects are strongly mediated by natural landscape features and human land use
- When selecting remotely-sensed environmental data to work with, consider how the characteristics of these data match up with the important ecological details
  - Spatial resolution (grid cell size)
  - Temporal resolution (time between re-measurements)
  - What is actually being measured?
    - Land surface temperature versus air temperature
    - Rainfall versus soil moisture versus vegetation greenness

Key Take Home Message

Development of Public Health Applications Using Satellite Remote Sensing

- Data access and processing is a key limitation
- Automation is essential to facilitate early warning and related time-sensitive applications
- Need for workflows and products specifically tailored for public health applications
- Integration of earth observations with existing systems for surveillance of mosquitoes and human disease is essential
- Integrating forecasting with disease surveillance and environmental monitoring allows for continual evaluation of the underlying models and improvement of our scientific understanding of mosquito-borne disease epidemiology