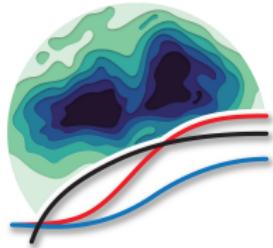


# Geospatial Methodologies in Toxicology

Linking exposure, toxicity, and disease profiles to identify U.S.  
regions at elevated health risks

Kyle P Messier, PhD

National Institute of Environmental Health Sciences - Division of Translational  
Toxicology - Predictive Toxicology Branch



Spatiotemporal Exposures  
and Toxicology (SET) Group

## Introduction

## History

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## Classical Models

## Data Sources

## Case Studies

Source-to-Outcome  
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## Conclusions

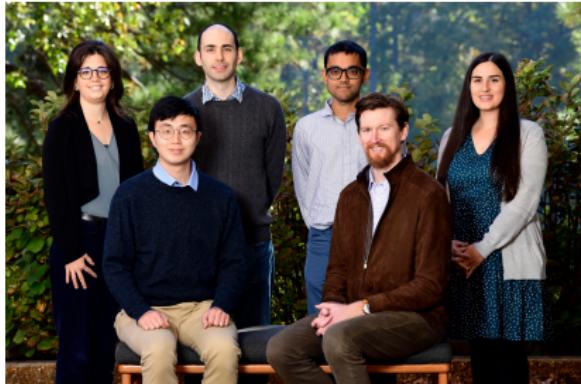
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## Introduction

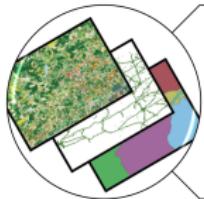
## About Us

Spatiotemporal Exposures and Toxicology {SET} group

- Spatiotemporal Exposure Mapping
  - Chemical and Stressor Mixtures Prediction
  - Mechanistically Informed Geospatial Risk Assessment

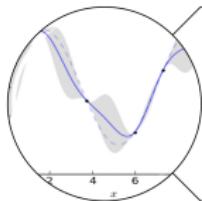


# Geospatial Methods



## Translational

- Maps
  - Integrative



## Predictive

- Interpolation
  - Uncertainty

# Objective

- Provide an overview of geospatial methods, data, applications, and future directions in toxicology and risk assessment

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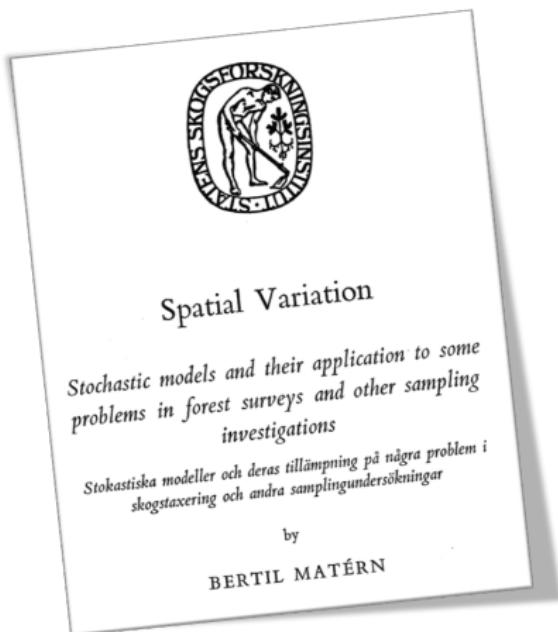
# History

# Mining



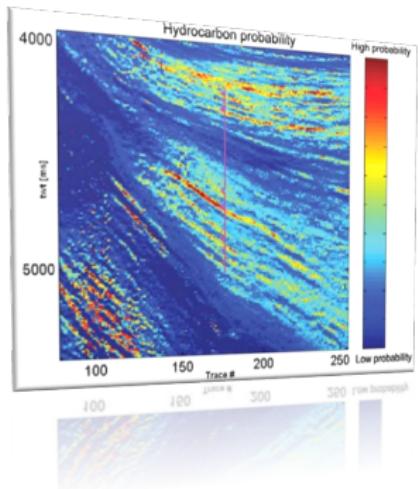
- Matheron and Krige developed geostatistical methods to predict ore content from core samples
- Matheron coined the term “Kriging” after Krige
- “Nugget” is a term used to random noise because predicting where gold nuggets were was so difficult

# Forestry



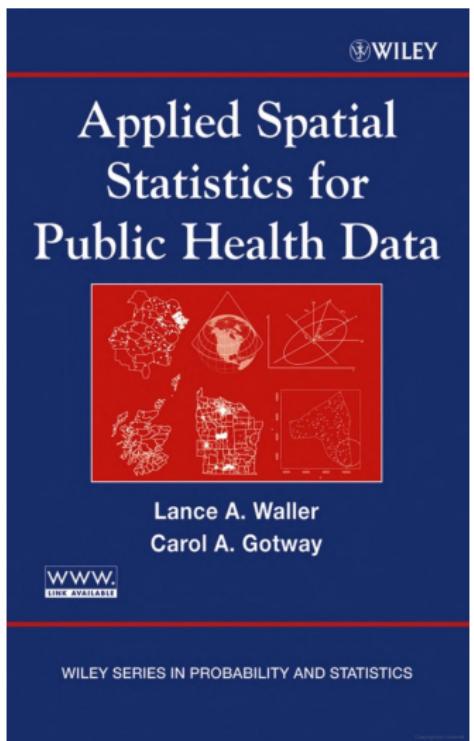
- Matérn developed correlation models for spatial variation for applications in Forestry
- To this day, we use the “Matérn” covariance function

# Petroleum Engineering



- Used to evaluate the oil and gas field reservoirs
- Uses geology and seismic data

# Public Health



- Cressie, 1990: Statistics for Spatial Data
- Waller and Gotway, 2004: Applied Statistics for Public Health Data
- Wide scale adoption for statisticians and engineers in ecological and human exposure and risk applications

# Toxicology



- **Toxicology is a new frontier for geospatial methods**
- Aggregate Exposure Pathways
- Adverse Outcome Pathway
- GeoTox
- Source-to-Outcome

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# Classical Models

## Uses in Public Health

- Estimate exposure to air pollutants, water contaminants, and other environmental stressors
- Geocode patient addresses to link to environmental exposures
- Estimate the spatial distribution of disease rates
- Estimate the spatial distribution of health risk factors

# Land Use Regression

Linear regression for spatial data

$$Y(s) = X(s)\beta + \varepsilon$$

where  $Y(s)$  is the response variable,  $X(s)$  are the predictor variables,  $\beta$  are the regression coefficients,  $\varepsilon$  is the iid error term, and  $(s)$  denotes the spatial location.

Not a terrible idea for spatial data, but it directly violates the assumption of independence of observations.

# Kriging

Kriging and spatial models provide an explicit term for spatial correlation. A reasonable approach is a random-effect model:

$$Y(s) = \mu(s) + \varepsilon + \eta(s)$$

where  $\eta \sim N_n(0, \Sigma_\theta)$

and  $\Sigma_\theta$  is a covariance matrix with parameters,  $\theta$ , that accounts for correlation between spatial and temporal locations

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# Data Sources

# Common Data Sources and Types

- U.S. Census Bureau
- U.S. Environmental Protection Agency
- U.S. Geological Survey
- National Aeronautics and Space Administration
- National Oceanic and Atmospheric Administration
- U.S. Department of Agriculture
- Land cover data
- Health statistics
- Population characteristics
- Infrastructure data
- Air quality data
- Water quality data
- Satellite imagery

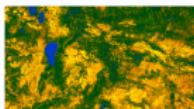
# Satellite Imagery



## Sentinel-2 Level-2A

The Sentinel-2 program provides global imagery in thirteen spectral bands at 10m-60m resolution and a revisit time of approximately five days. This dataset contains the global Sentinel-2 archive, from 2016 to the present, processed to L2A (bottom-of-atmosphere).

[Sentinel](#) [Copernicus](#) [ESA](#) [Satellite](#) [Global](#) [Imagery](#) ...



## Sentinel 1 Radiometrically Terrain Corrected (RTC)

Radiometrically terrain corrected SAR imagery derived from the Sentinel 1 Level 1 GRD product.

[ESA](#) [Copernicus](#) [Sentinel](#) [C-band](#) [SAR](#) [RTC](#)



## HREA: High Resolution Electricity Access

Settlement-level measures of electricity access, reliability, and usage derived from VIIRS satellite imagery

[HREA](#) [Electricity](#) [VIIRS](#)



## Planet-NICFI Basemaps (Analytic)

Planet's high-resolution, analysis-ready mosaics of the world's tropics

[Planet](#) [NICFI](#) [Satellite](#) [Tropics](#) [Imagery](#)



## Planet-NICFI Basemaps (Visual)

Planet's high-resolution, analysis-ready mosaics of the world's tropics

[Planet](#) [NICFI](#) [Satellite](#) [Tropics](#) [Imagery](#)



## Landsat Collection 2 Level-1

Landsat Collection 2 Level-1 data from the Multispectral Scanner System (MSS) onboard Landsat 1 through Landsat 5.

[Landsat](#) [USGS](#) [NASA](#) [Satellite](#) [Global](#) [Imagery](#)



## MODIS Burned Area Monthly

MODIS Burned Area Monthly

[NASA](#) [MODIS](#) [Satellite](#) [Imagery](#) [Global](#) [Fire](#) ...

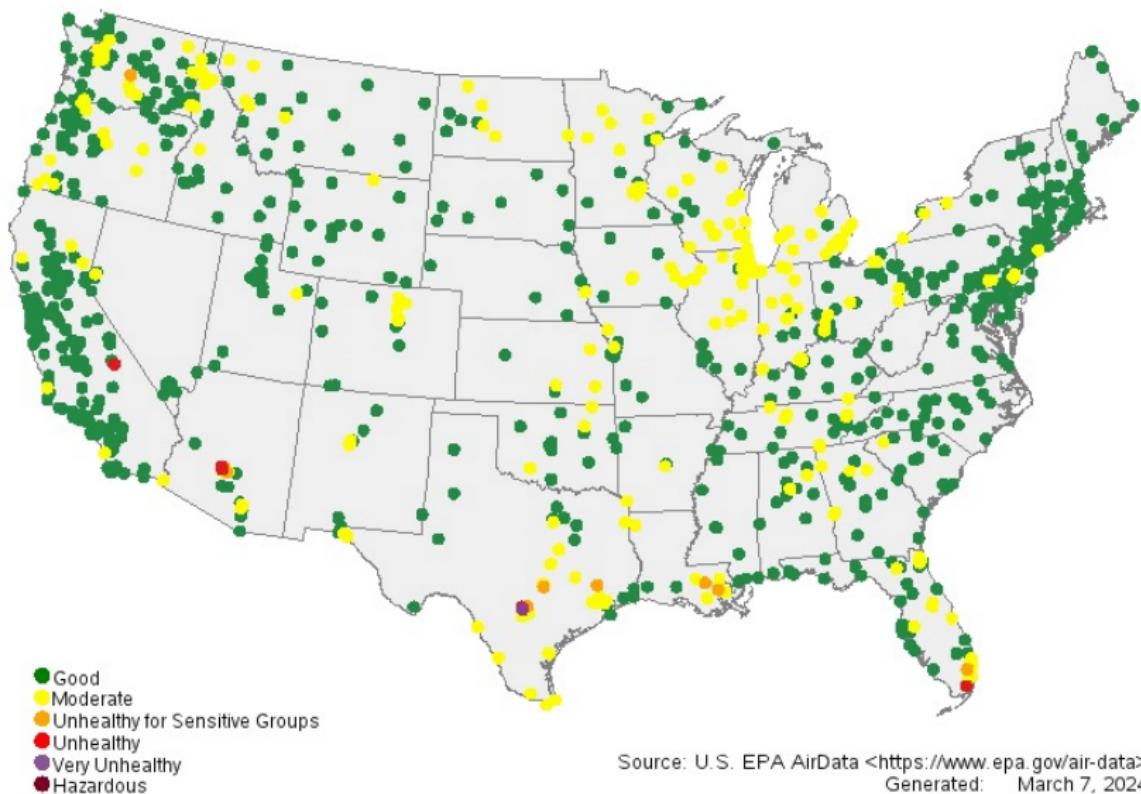


## MODIS Nadir BRDF-Adjusted Reflectance (NBAR) Daily

MODIS Nadir BRDF-Adjusted Reflectance (NBAR) Daily

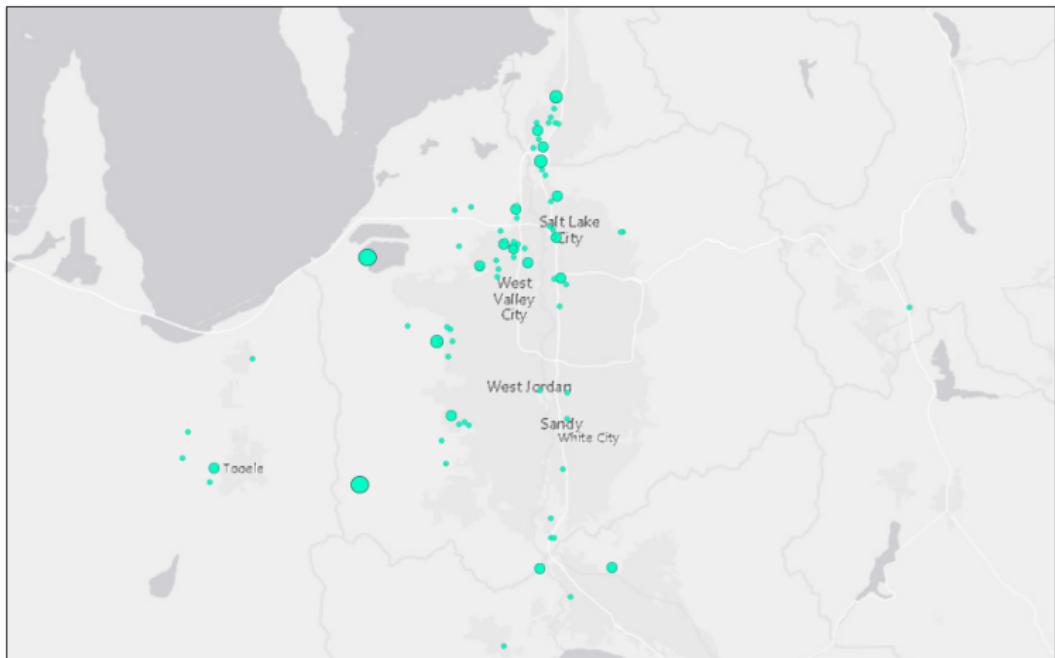
# Air Quality Data

## PM2.5 AQI Values by site on 01/01/2023



# Toxic Release Data

2021 TRI National Analysis: Where You Live



March 7, 2024

1,577,791  
0 3.75 7.5 10 15 mi  
0 5 10 20 km

EPA, HERE, NPS, Esri, HERE, GADM, USGS, EPA, NPS

https://www.epa.gov/ERIEXT

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# Health Information

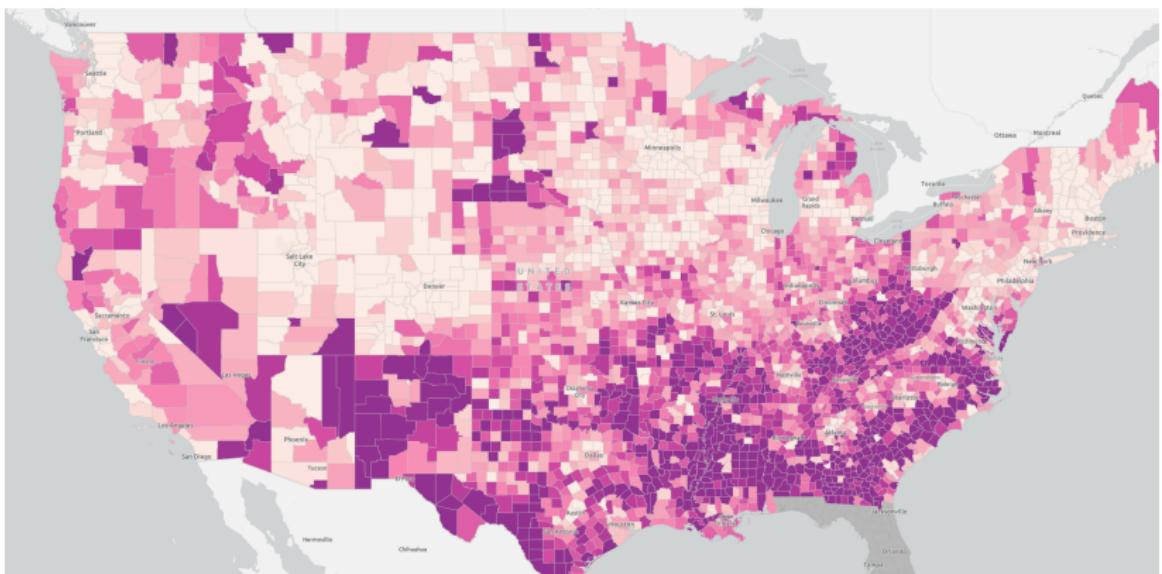


Figure 1: CDC Places Health Outcome Data: Diabetes Prevalence

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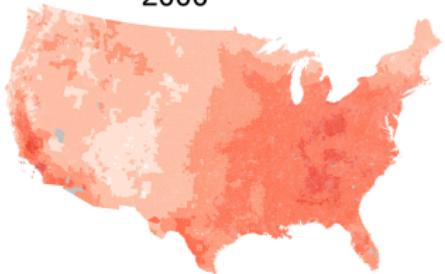
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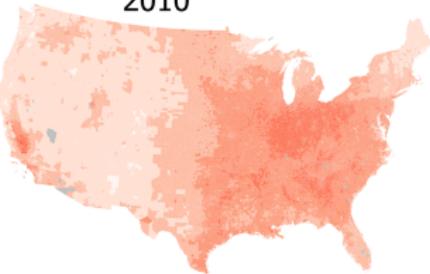
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# Air Pollution Exposure Mapping

2000

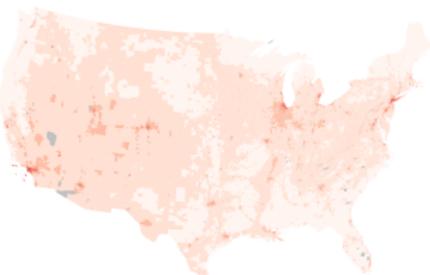
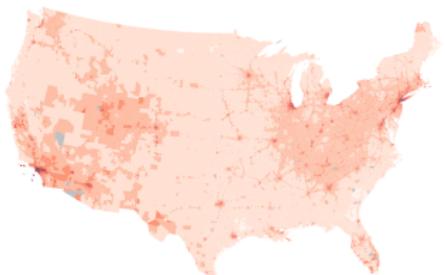


2010



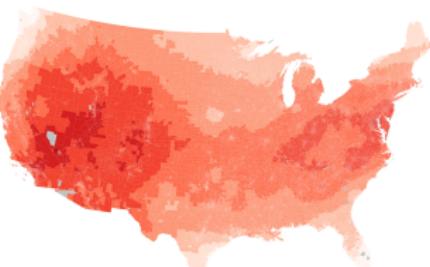
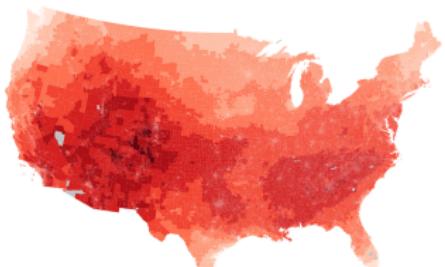
PM2.5  
(µg/m³)

- < 2.5
- 2.5 - 5
- 5 - 7.5
- 7.5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- > 30
- no data



NO2  
(ppb)

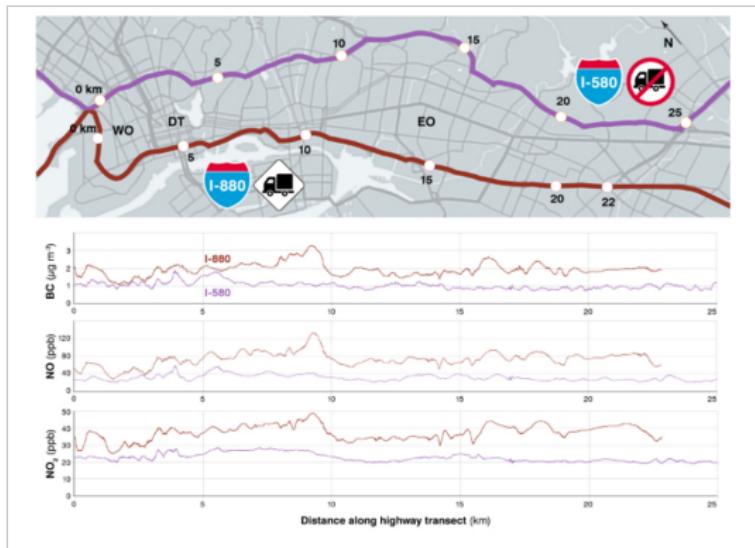
- < 3
- 3 - 6
- 6 - 9
- 9 - 12
- 12 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- > 30
- no data



Ozone  
(ppb)

- < 30
- 30 - 35
- 35 - 40
- 40 - 45
- 45 - 50
- 50 - 55
- 55 - 60
- 60 - 65
- > 65
- no data

# Tale of Two Freeways



- All measured pollutants were consistently higher on I-880 compared to I-580
- I-580 has a heavy duty truck ban
- Heavy duty trucks are forced onto I-880 to get to the Port of Oakland

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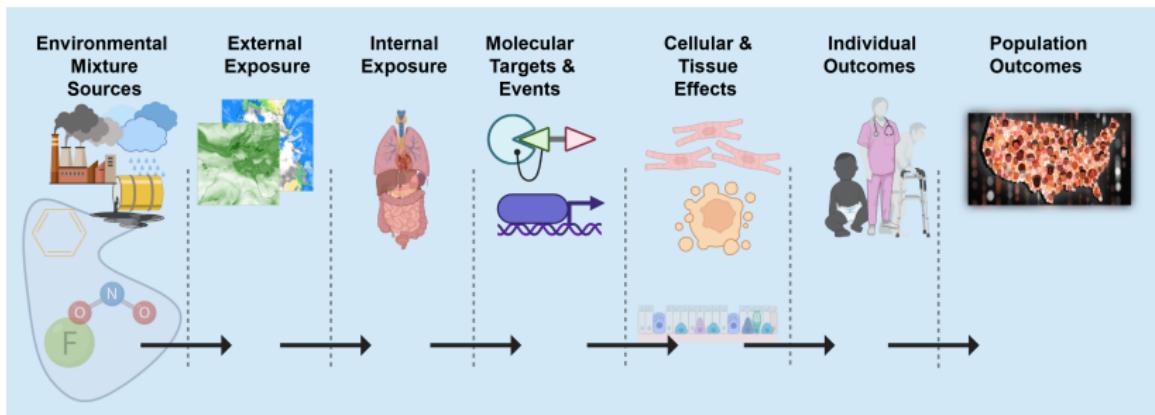
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**Source-to-Outcome**  
**●oooooooooo**

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## Source-to-Outcome

# Source-to-Outcome Modeling



# Source-to-Outcome Modeling

- Source-to-Outcome is a framework for linking environmental sources to human health outcomes
- The framework is based on the Aggregate Exposure Pathway (AEP) and Adverse Outcome Pathway (AOP) concepts

# Source-to-Outcome Modeling

- Next generation risk of cumulative and total exposomic effects on human health
- A balance between mechanistic and translational research
- A framework for integrating multiple data sources and models
- Incorporate biological and geospatial information on communities and individuals

# Getting Two Frameworks to Work Together

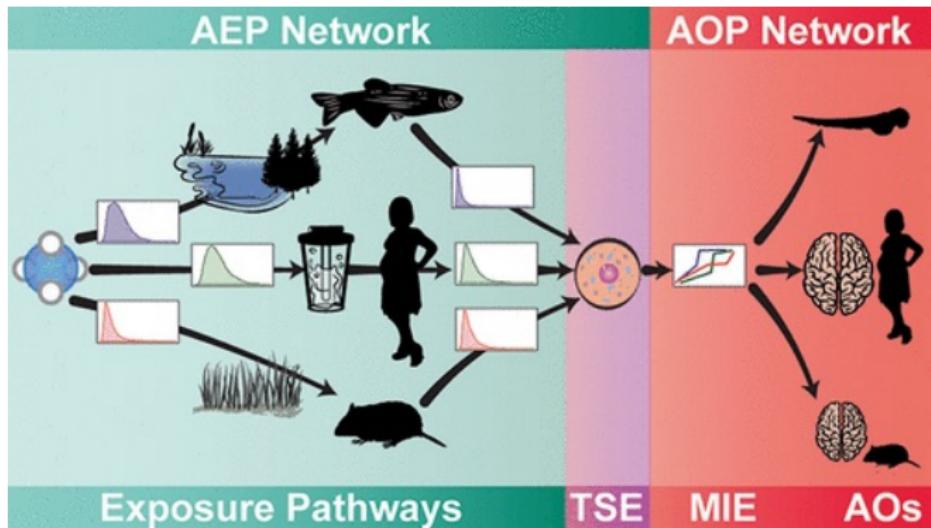
## Aggregate Exposure Pathways

- AEP is a comprehensive external analysis of source, media, and transformations

## Adverse Outcome Pathway

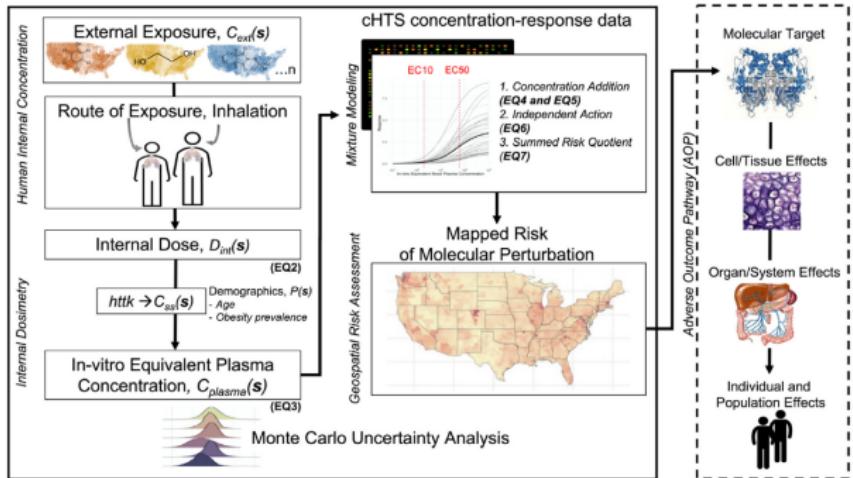
- AOPs provide a linkage specific biological target, pathway or process by a stressor and an adverse outcome(s) considered relevant to risk assessment

# AEP-AOP



Hines, D. E., Conolly, R. B., & Jarabek, A. M. (2019)

# GeoTox

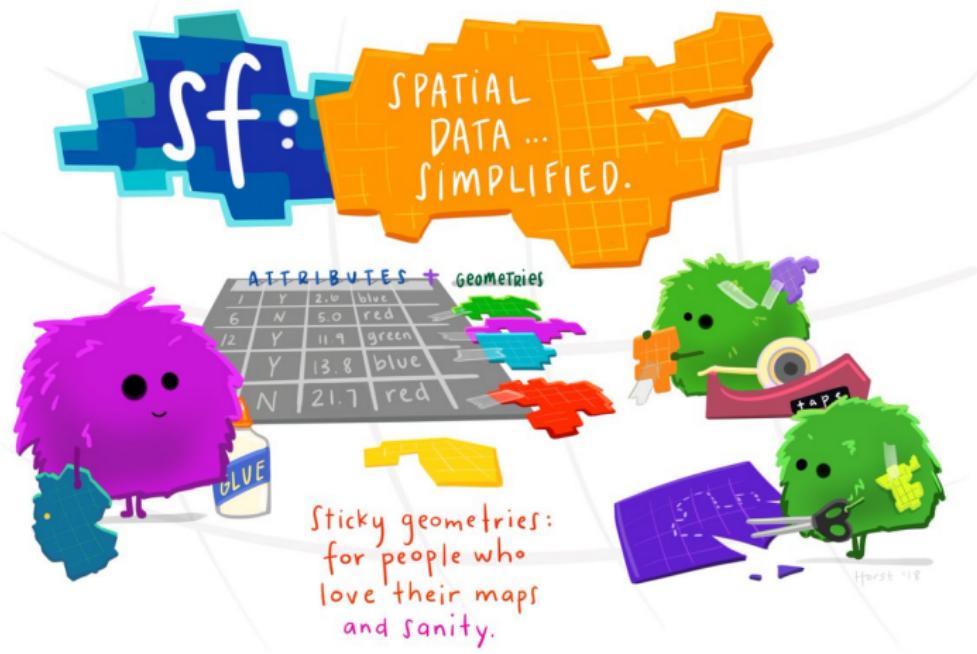


Dr. Kristin Eccles, Former Visiting Fellow in DTT  
and SET, Now at Health Canada

# GeoTox

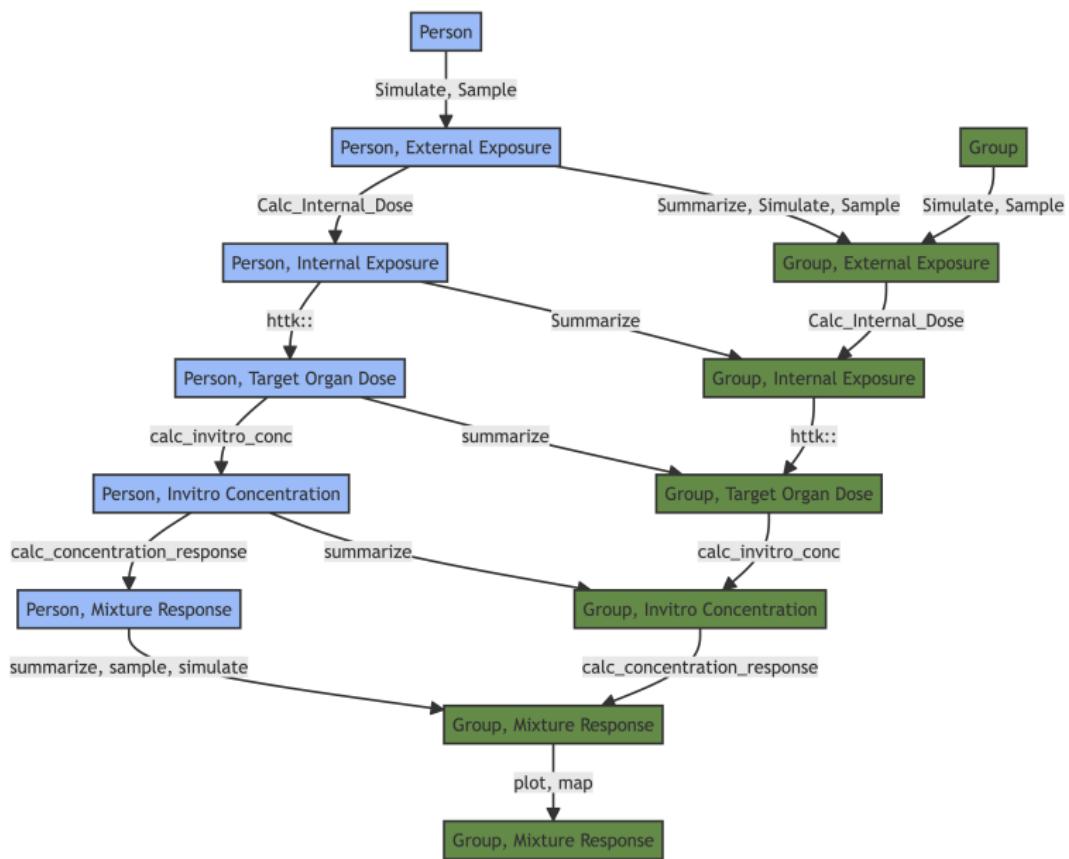
- Goal is to develop extensible, open-source software for facilitate source-to-outcome modeling (FAIR+)
- Working with Drs. David Reif and Skylar Marvel (NIEHS/DTT)
- Submitting to CRAN
- Static website hosted via {SET}group website
- Maintained, Documented, and Supported

# GeoTox



sf package for spatial data in R (Edzer Pebesma and others)  
(Illustration (c) 2018 by Allison Horst)

# GeoTox



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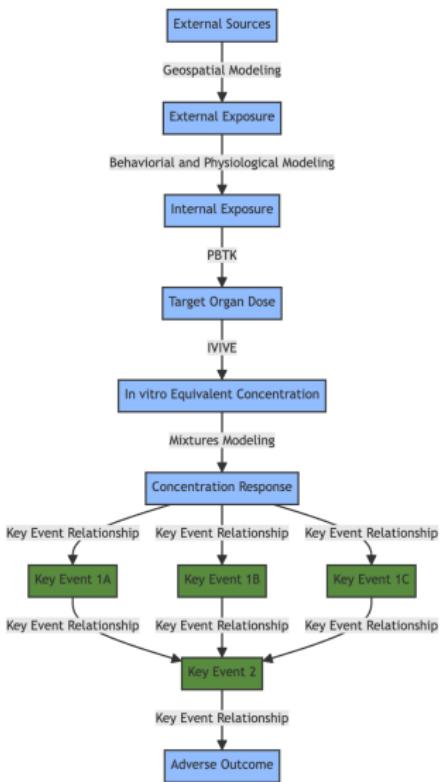
Conclusions  
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# Conclusions

## Looking Forward

- The tools for each step of the source-to-outcome modeling framework are available, but the integration is still a work in progress
- The integration of these tools will allow for the development of a comprehensive source-to-outcome modeling framework that can be used to assess the risk of cumulative and total exposomic effects on human health

# Multiple Assays Informing an AOP



## Looking Forward

- Incorporate more refined information on individual and population-level susceptibility to environmental exposures
- It is going to be a massive code and software development challenge

## Looking Forward

- Geospatial **exposures** are the foundation of a spatial, total exposome risk approach

# Acknowledgements

- Daniel Zilber
  - Mitchell Manware
  - Insang Song
  - Eva Marques
  - Ranadeep Daw
  - Mariana Alifa Kassien
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  - Alison Motsinger-Reif
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