Challenges in Evaluating Drinking Water Quality in Agricultural Areas

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Overview

- **Private wells/small systems**
  - Regulations in US and EU
  - Water quality issues

- **Exposure assessment approaches: examples from the USA:**
  - Arsenic in New England
  - Nitrate in Iowa and North Carolina

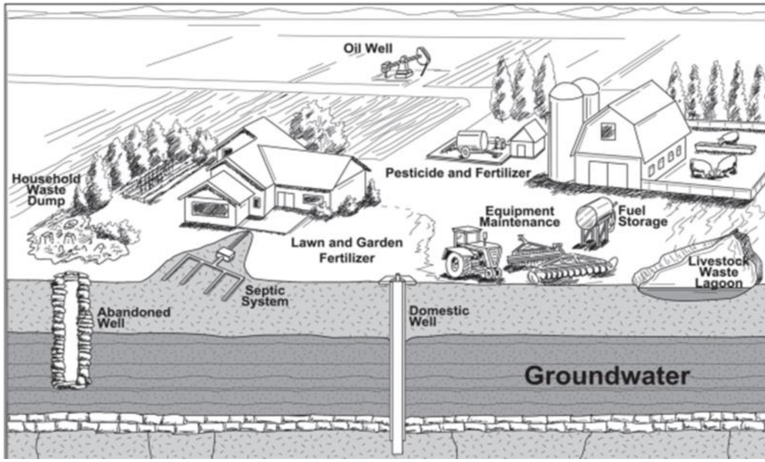
- **Considerations for future studies**

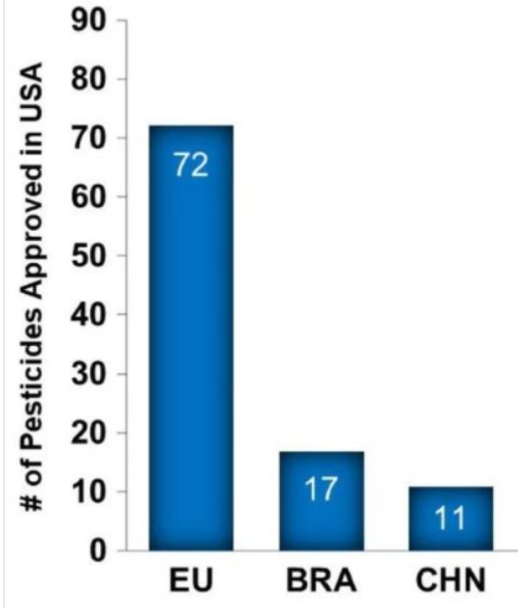
U.S. Drinking Water Regulations

- **Regulated by U.S. EPA under Safe Drinking Water Act (SDWA) since 1974**
  - **Community water supplies (serving 25+ or 15+ connections)**

- **Private wells & very small systems exempt**
  - **Monitoring data sparse**
  - **Located in rural/agricultural areas**
  - **Affected by non-point source pollution**
    - **Fertilizer applications, manure**
    - **Pesticide applications (herbicides, seed treatments)**
    - **Septic systems often close to wells**

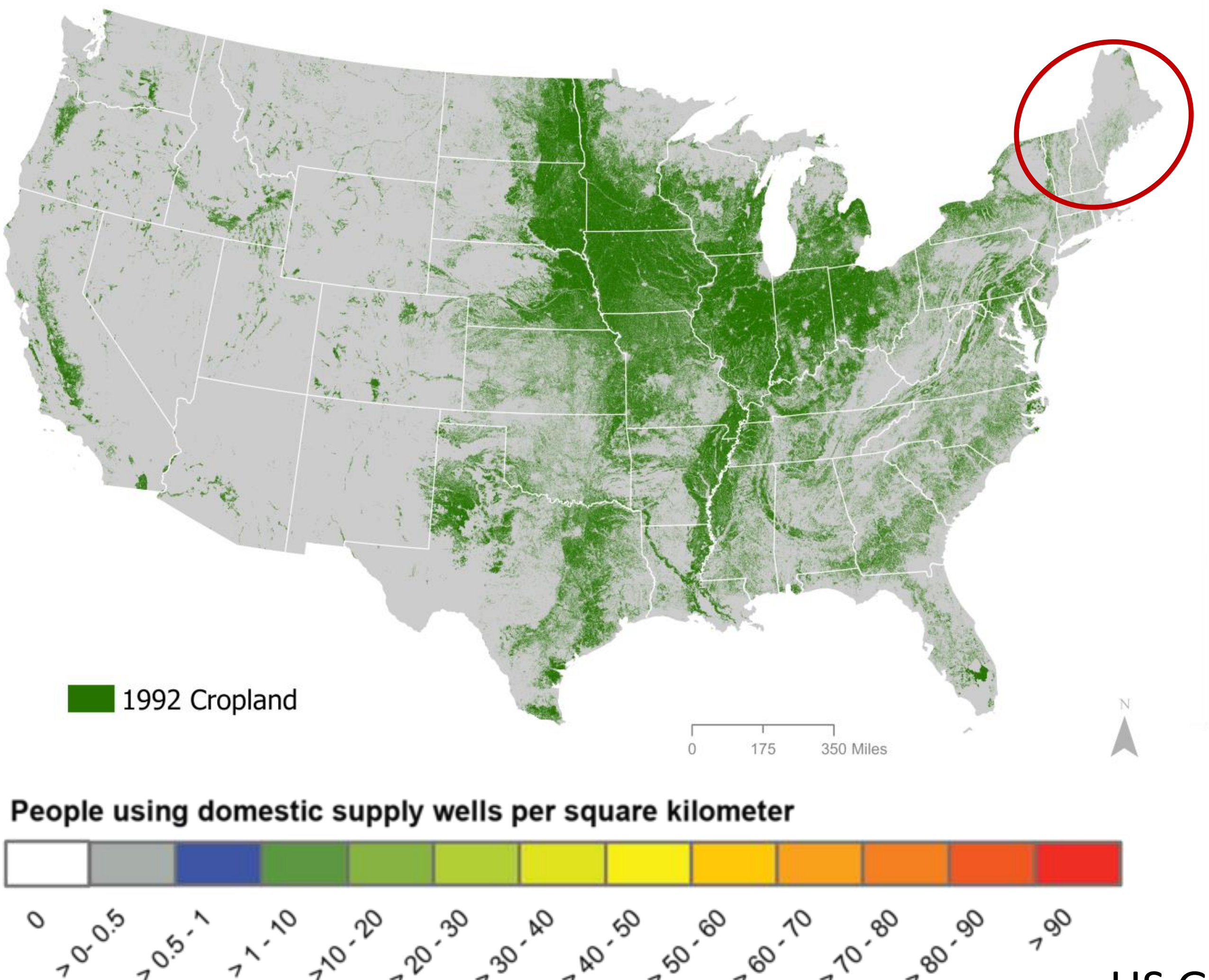
- **Agricultural chemicals less regulated than EU**
  - **Nutrient reduction strategy is voluntary**
  - **72 pesticides used in U.S. banned in the EU**
    - **>25% of agricultural pesticide use**





Donley Env Health; 2019

Density of private drinking water wells (1990)



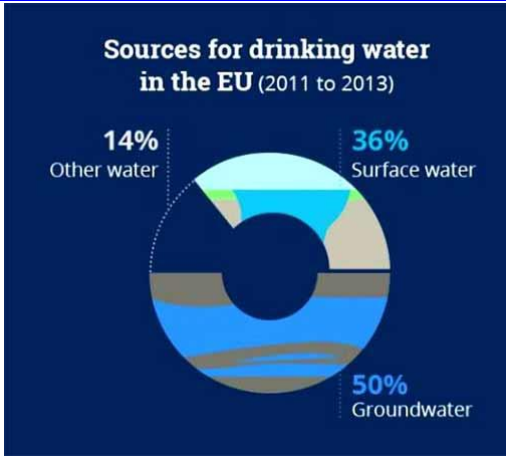
- 130 million (~50%) of US population uses groundwater
- ~43 million people (15% of population) use unregulated drinking water sources – mostly private wells
- Private wells located in agricultural areas, suburban/rural northeast

US Geological Survey
https://www.sciencebase.gov/

E.U. Drinking Water Regulations

- European Union Drinking Water Directive (1998)
  - Regulates supplies serving 50+ people or >10 m^3/day
  - ~50% of population uses groundwater

- Small scale water supplies (SSWS) including private wells:
  - <5000 population, 22% of EU (~109 million)
  - ~7% served by private wells
  - Range from 0 (Netherlands) to >1 million (Romania)
  - Mostly located in rural/agricultural areas
  - Monitoring data are sparse

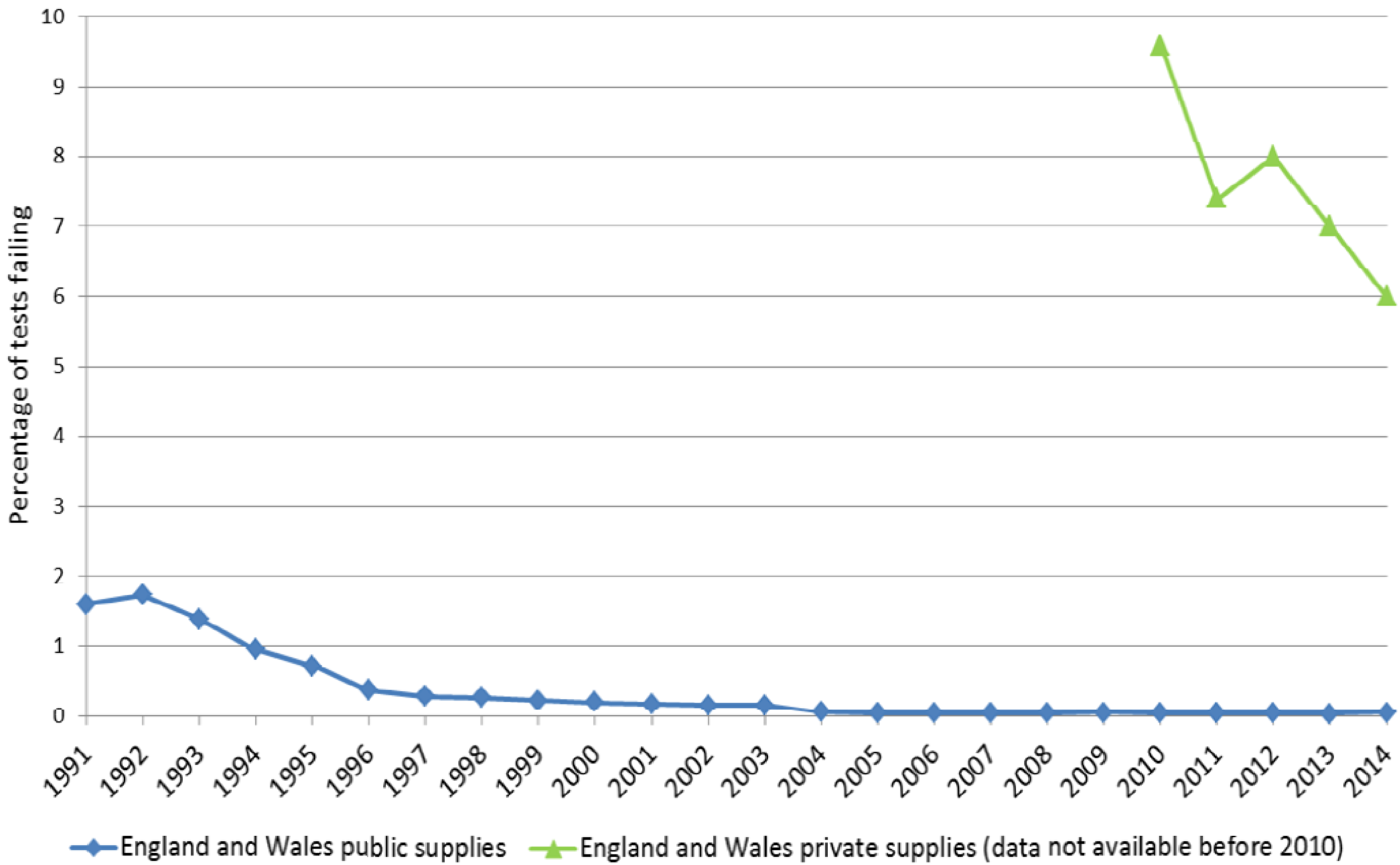


Well house of a rural, public water supply, Lithuania
© UBA, Dessau-Roßlau (Germany)/ Oliver Schmoll

Gunnarsdottir et al. IJERPH 2017; WHO report on SSWS, 2011

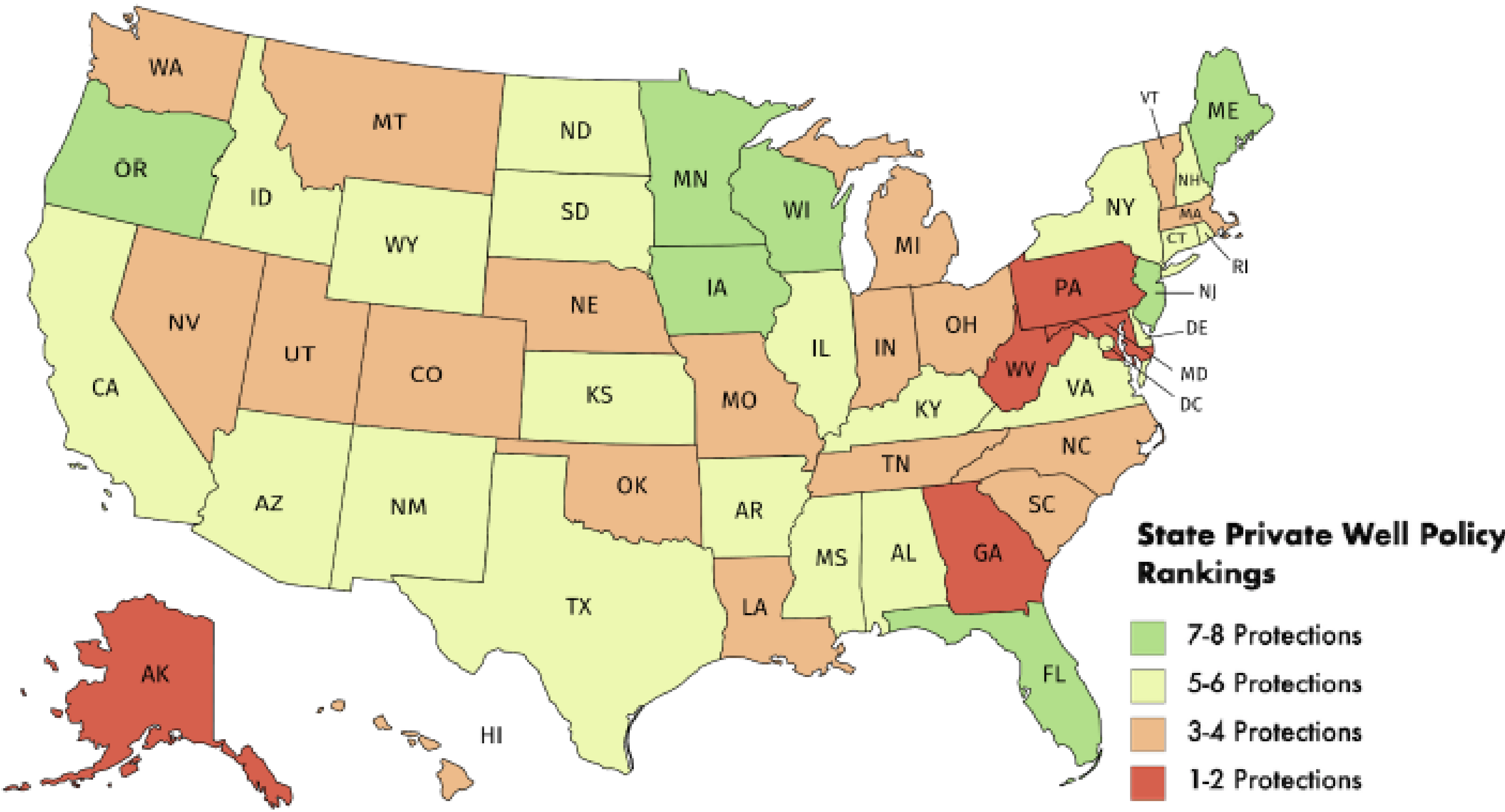
U.K. private vs. public water supplies – water quality

Fig. 11.1. Tests failing drinking-water standards in public and private supplies



WHO report on SSWS, 2018

Figure 6. Private Well Protection Rankings By State

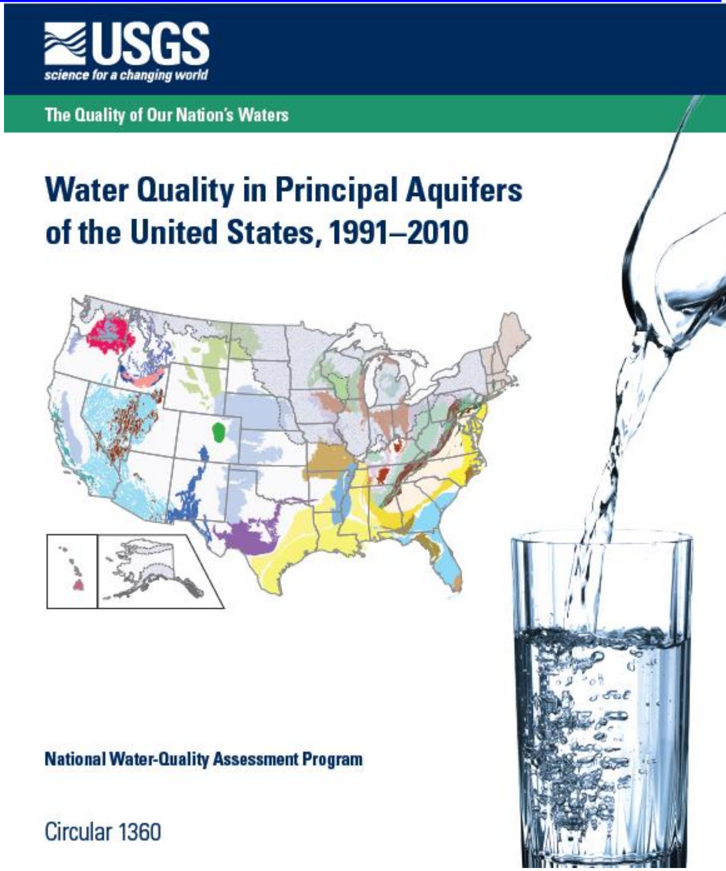


WHO report on SSWS, 2011

Center for Progressive Reform 2021. Tainted Tap

Water quality in U.S. groundwater

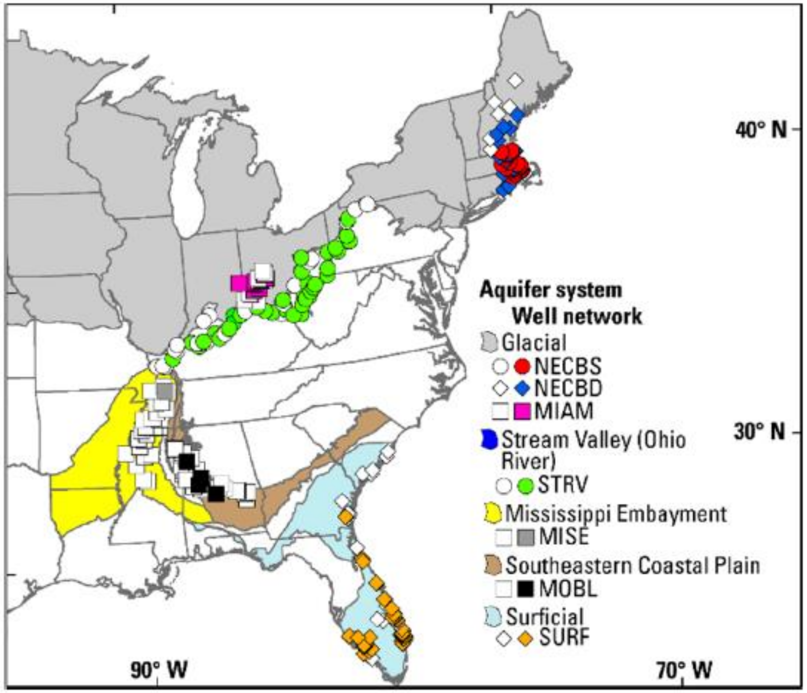
- 62 principal aquifers in 50 states (1991-2010)
  - Private wells in 30 aquifers
  - Measured inorganics, nutrients, pesticides, VOCs, microbes
- 22% of wells had 1+ contaminants above maximum contaminant level (MCL) or human-health benchmarks
  - Most were inorganics (As, Mn, U, Ra)
  - Nitrate >10 mg/L NO_3-N: 4 percent of wells
- Organics in ~60% of private wells
- Microbial contaminants ~33% of private wells
- ***Contaminants usually co-occurred with other contaminants as mixtures***



DeSimone et al. 2009; 2014. USGS Circulars 1332, 1360,

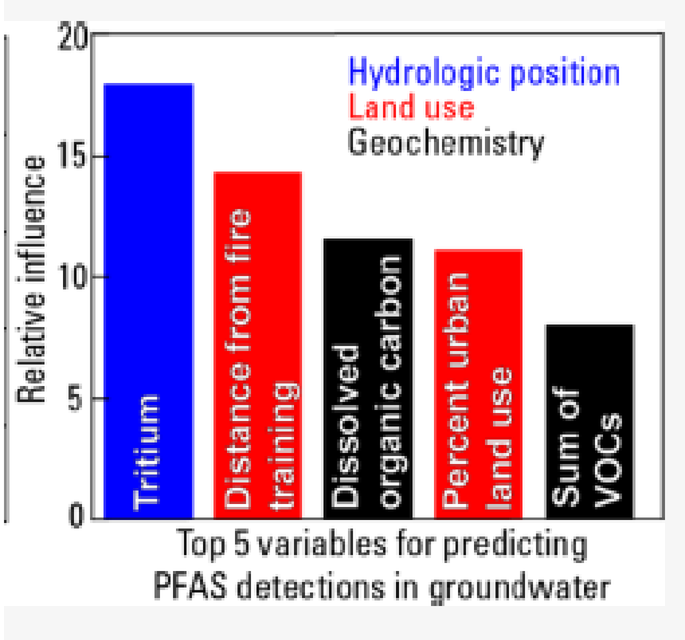
PFAS in groundwater - USA

- 5 principal aquifers in eastern states:
  - Measured 24 PFAS, VOCs nutrients, ions, tritium (groundwater age)
  - 60% of public wells had 1+ PFAS
  - 20% of private wells



- Urban land (<500 m), fire training, VOCs, groundwater age (post-1953) were important predictors

- ***PFAS often occurred with other contaminants as mixtures – VOCs, pharmaceuticals, nitrate***



McMahon et al. ES&T, 2022

Drinking water quality exposure disparities

- US national scale study of 40,000 public water supplies (Schraider et al. Env Health; 2019)
  - 5.6 million exposed 5 mg/L NO_3-N or above
  - 3x higher probability for Hispanic/Latinos
  - Served by smaller public supplies

- Review of disparities in drinking water exposures (Vanderslice AJPH; 2011) – water quality issues:
  - Tribal lands, Alaskan Native villages, colonias US/Mexico border, small communities in agricultural areas
  - High cost of nitrate & As removal exacerbates socioeconomic disparities

- Eastern shore of Maryland (Minovi & Schmitt, Center for Progressive Reform. 2020)
  - Highest nitrate in counties with high poverty, African-Am population

Private drinking water wells and small supplies: Exposure assessment considerations

- Typically pump groundwater from relatively shallow depths vs. public supply wells
- Private wells often have higher contaminant concentrations than public supplies, occurring as mixtures
- Treatment not common
- Contaminant movement to groundwater usually takes years
- Few regulations – limited monitoring data

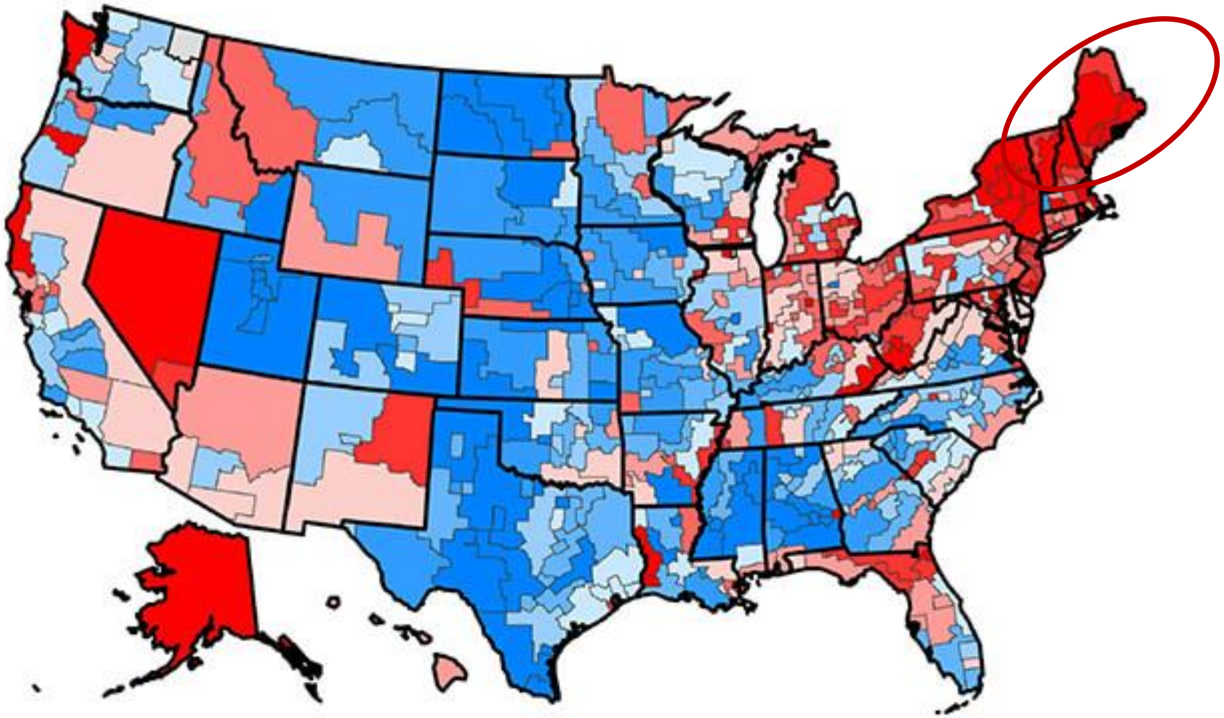
DeSimone et al. USGS Circular 1332; 2009; Center for Progressive Reform, Tainted Tap; 2020

How do we move forward to assess exposure?

- New methods of surveillance and monitoring (Tools and Technologies Session)
- Modeling approaches for private wells in rural and agricultural areas:
  - Two examples from epidemiologic studies of drinking water contaminants and cancer
  - Multi-year, interdisciplinary collaborations of exposure scientists, epidemiologists, hydrogeologists, statisticians

Example 1: Bladder cancer in Northern New England

Mortality rates among white women
1980-2004

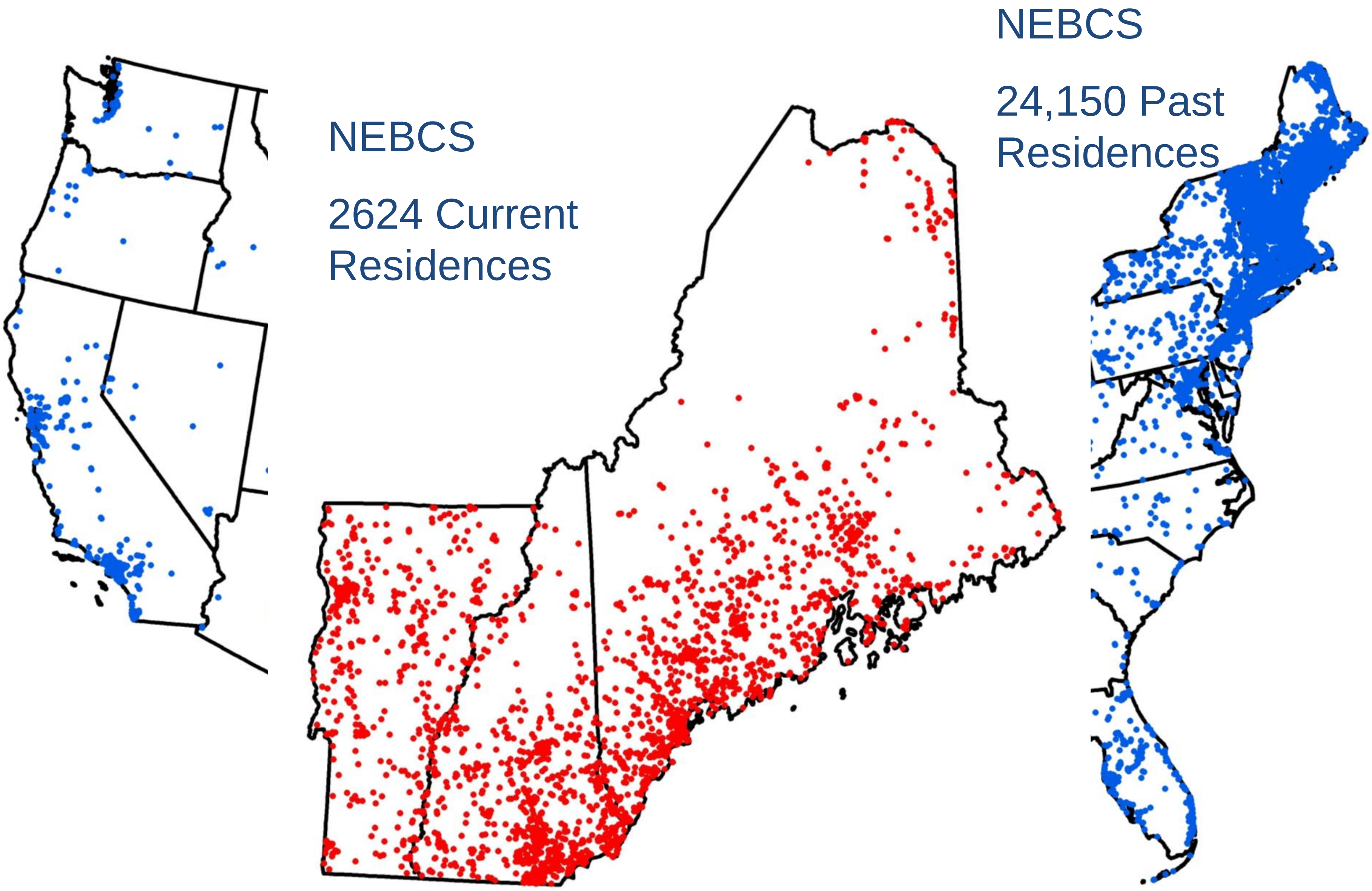


Red=high rates, Blue=low

New England Bladder Cancer Study

- Popn-based case-control study (1213 cases, 1418 controls) Maine, New Hampshire, Vermont
  - Newly diagnosed cases 2001-2004, ages 30-79
- Home interviews
  - Residence and workplace water source histories
  - Private well depth, type of well (drilled, dug)
  - Tap water intake
  - GPS of current home, geocoded past addresses
- Water samples for private wells (46%), some past homes on private wells
- Measured & modeled known or suspected bladder carcinogens in water:
  - Arsenic
  - DBPs
  - Nitrate

Baris et al JNCI; 2016; Nuckols et al. EHP; 2001

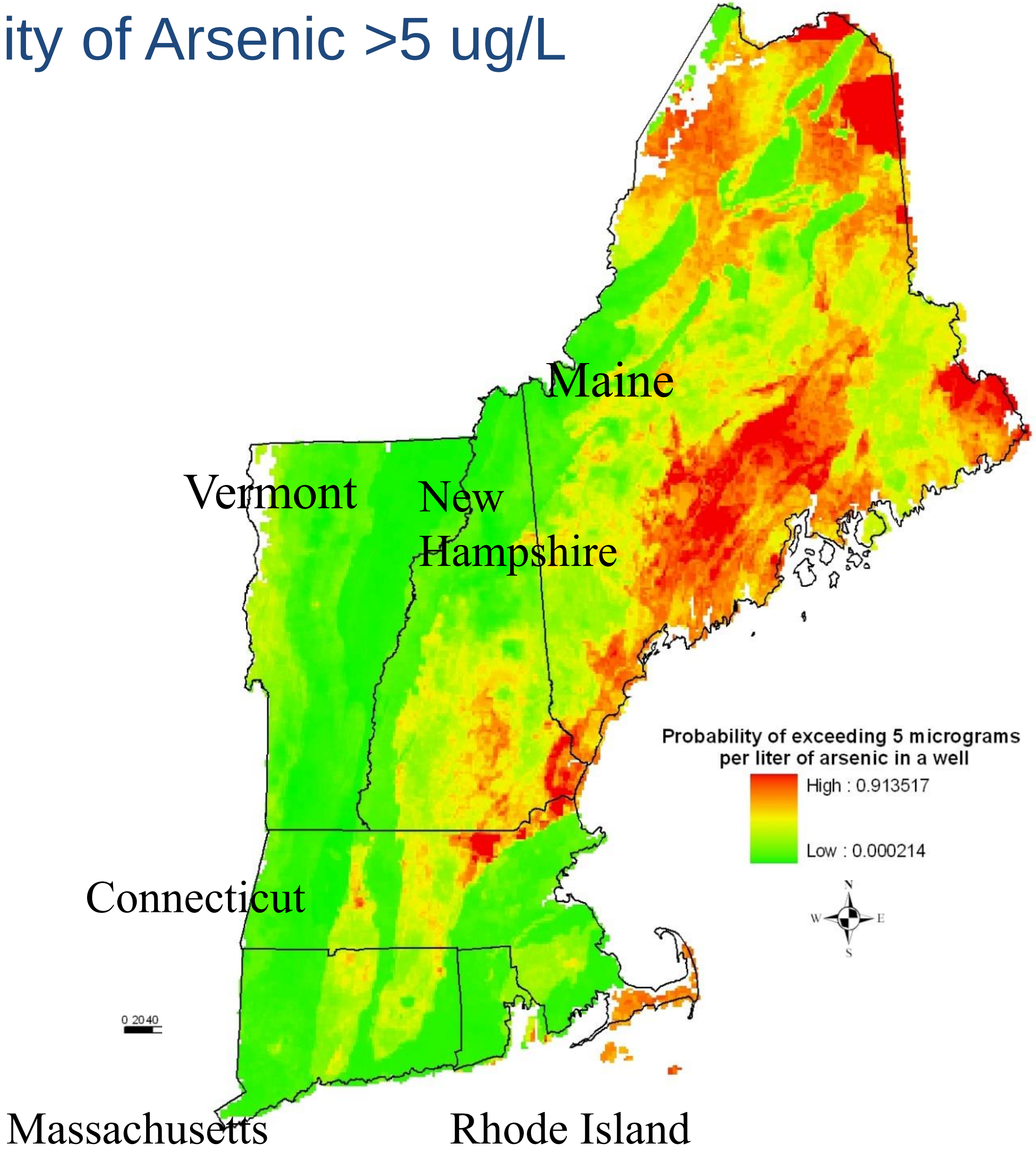

NEBCS
2624 Current
Residences
NEBCS
24,150 Past
Residences

GIS-based prediction Models for Assigning Arsenic Concentrations for Residences and Workplaces on Private Wells

Model Categories	Description of Measurements	Model Description
	Private Water Supply (6-State Region) [7]	
Wells - Bedrock Aquifer Source	N = 3,527	Model: $\ln(As) = \beta x + \varepsilon$ Model includes 12 geographic-based variables (x) based on geologic provinces, litho chemistry and surficial geology of bedrock units (Table 2).
Wells - Unconsolidated Materials Aquifer Source	N = 1,557	Model: $\ln(As) = \beta x + \varepsilon$ Model includes 13 geographic-based variables (x) based on geologic provinces, litho chemistry and surficial geology of bedrock units (Table 2).
	Private Water Supply (outside 6-State Region)	
USGS Hydroregion Subbasin (Watermolen, 2005) modeling unit	N =18,651; H = 934 subbasins where residences/workplaces located	Model: $\ln(As) = \sum_h \beta_h x_h + \varepsilon$ h=1,...,H, where x_h zero/one indicator variables for hydroregion h, β_h is the parameter estimate (mean measurement data for h), and ε is the error, derived from normally distributed measurements N, mean 0 and variance σ^2
Principal Aquifer Modeling Unit	N =15,687, P = 64 Principal Aquifer boundaries (USGS 2008) where hydroregion subbasins with residences/workplaces located	Model: $\ln(As) = \sum_p \beta_p x_p + \varepsilon$ USGS Principal Aquifer-specific model using measurements from all study hydroregion subbasin wells located within each aquifer boundary

Nuckols et al; EHP; 2011

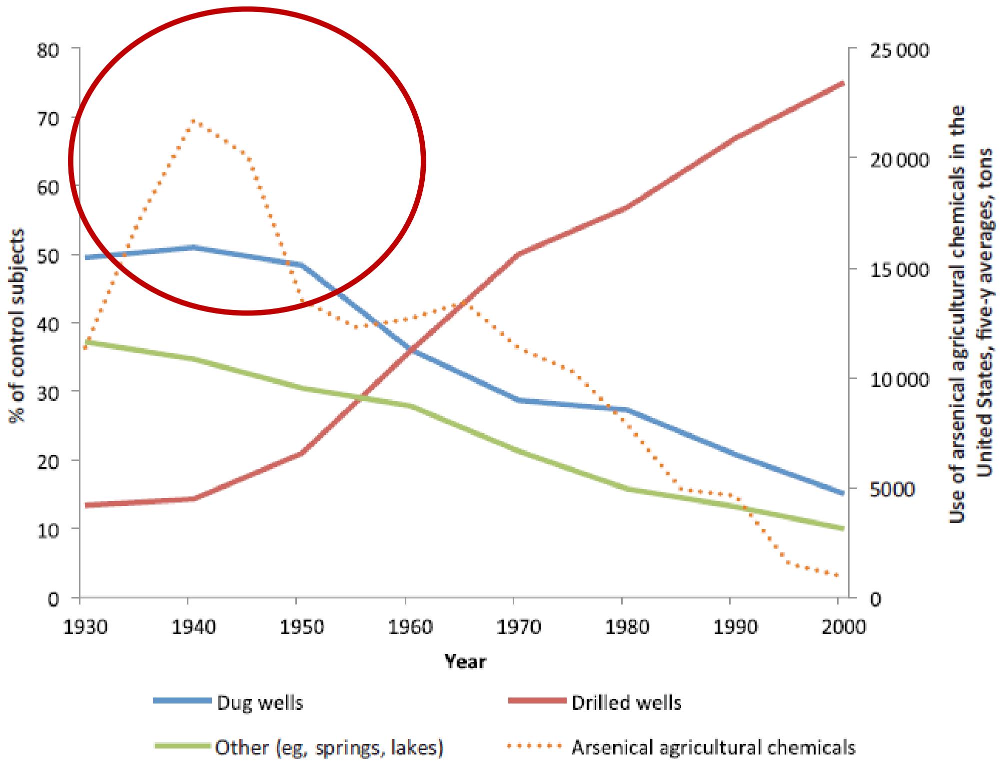
Modeled Probability of Arsenic >5 ug/L in Bedrock Wells



Nuckols et al. EHP; 2011

Results

- Significant exposure-response for bladder cancer risk with cumulative arsenic, elevated risk for high average concentrations lagged 40 years
- Consumption of water from dug wells during period of arsenical pesticide use (<1960) associated with 2.3x bladder cancer risk



Baris et al, J Natl Cancer Inst; 2016

Conclusions and challenges

- Regulatory limit 10 µg/L (as of 2001, previously 50 µg/L)
  - Public supplies were mostly in compliance
  - Levels were higher in private wells
- Cancer (especially of internal organs) has a long latency requiring lifetime water source histories
- Exposures mostly low, required large study with good exposure assessment
- Models required accurate geocodes, well depth, type, measurement data from study area and other US states

Example 2: Nitrate in private wells

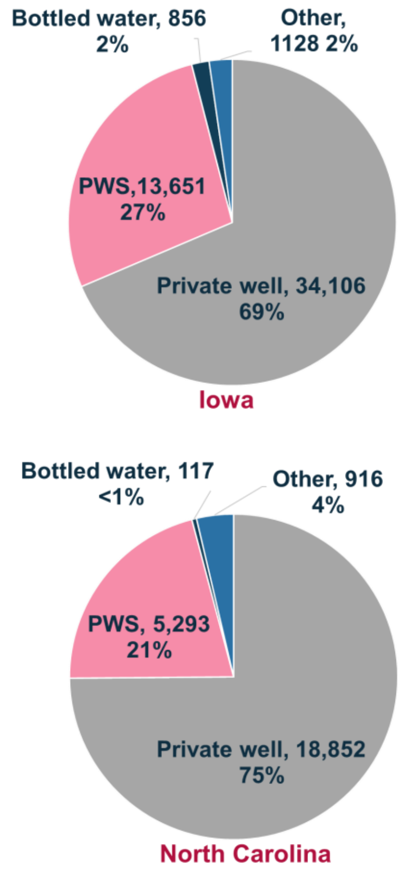
- Regulatory limit (Maximum Contaminant Level [MCL]):
  - 10 mg/L as **NO_3-N** (USA)
  - 50 mg/L as **NO_3** (EU)

- Highest exposures:
  - Residents on private wells in agricultural areas
  - N fertilizers, animal feeding operations

Agricultural Health Study

- Cohort study of pesticide applicators and spouses in Iowa and North Carolina (58,563 from Iowa; 31,092 from North Carolina)
- Residence histories, drinking water source at enrollment (1993-97) & follow-up interviews
- Developed separate random forest models for Iowa and North Carolina (Wheeler/Nolan et al. STOTEN; 2015; Messier/Wheeler et al. STOTEN; 2018)

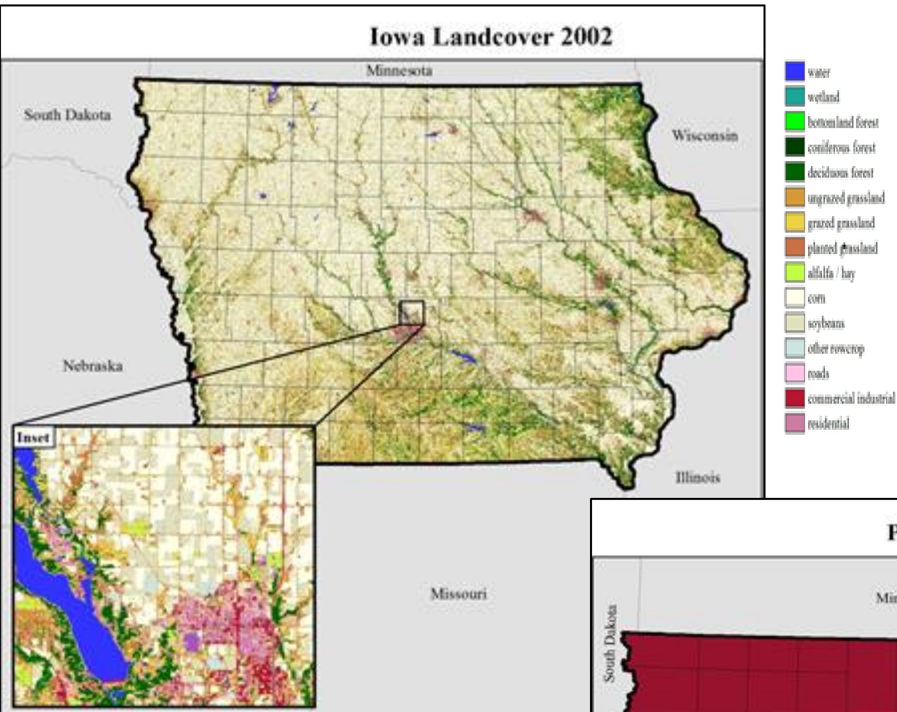
Drinking water source by state

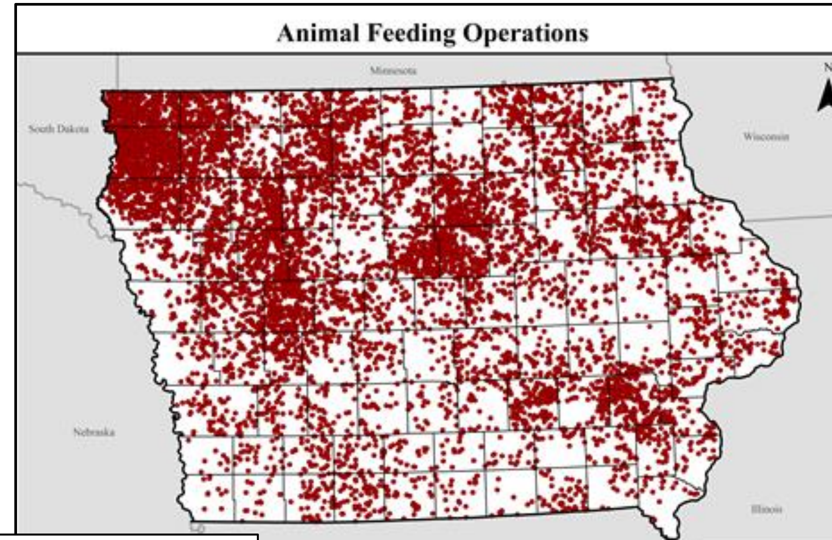


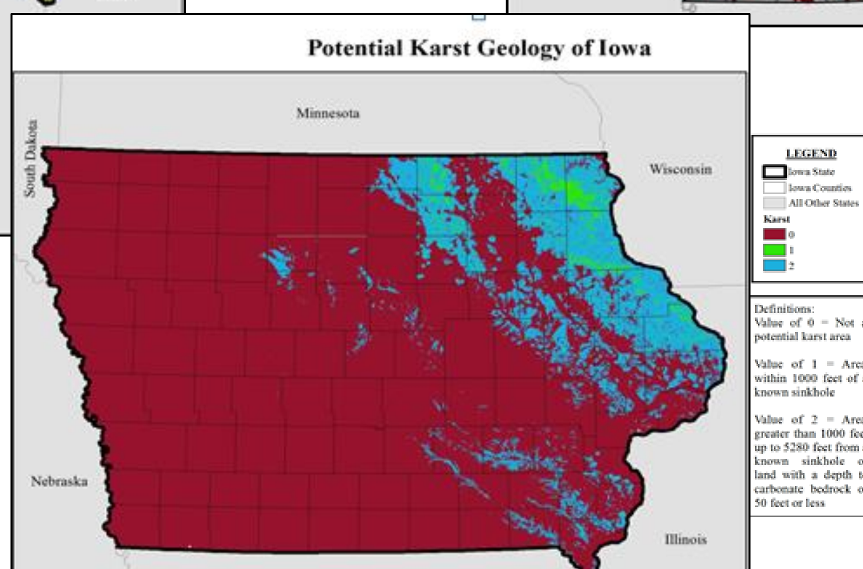
Manley et al. Env Epidemiol. 2021

GIS-based model of nitrate in Iowa private wells

- ~34,000 nitrate measurements (1980-2000s)
- Evaluated >150 variables (e.g., land use, animal feeding operations geology, soils, slope, precipitation)







Wheeler/Nolan et al.
STOTEN; 2015

Nitrate model results

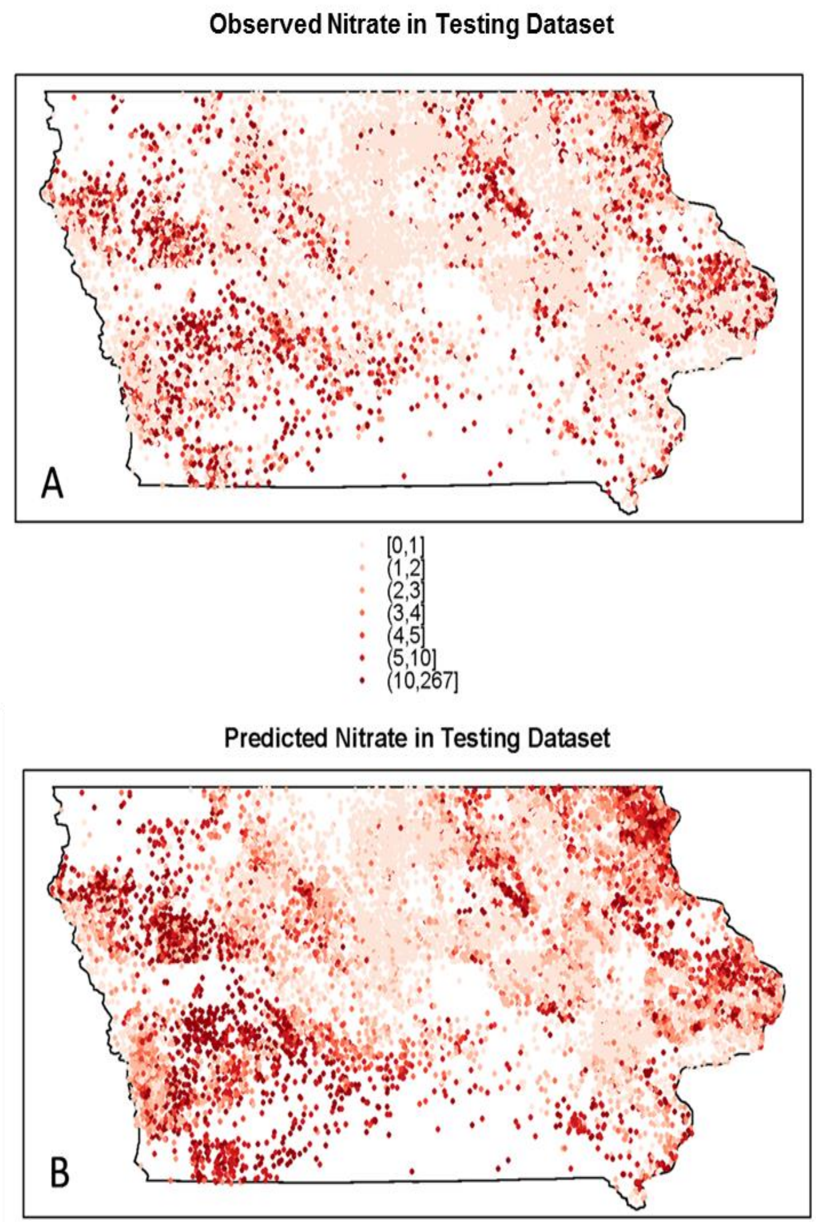
-66 variables explained 77% of variation in training dataset:

- Well depth
- Geologic features – karst geology, sinkholes
- Slope, elevation
- Animal feeding operations
- Agricultural land (1990)
- Precipitation
- Soil characteristics at well screen
- Year

Wheeler/Nolan et al. STOTEN; 2015

Observed and predicted nitrate
Sensitivity and Specificity (5 mg/L)

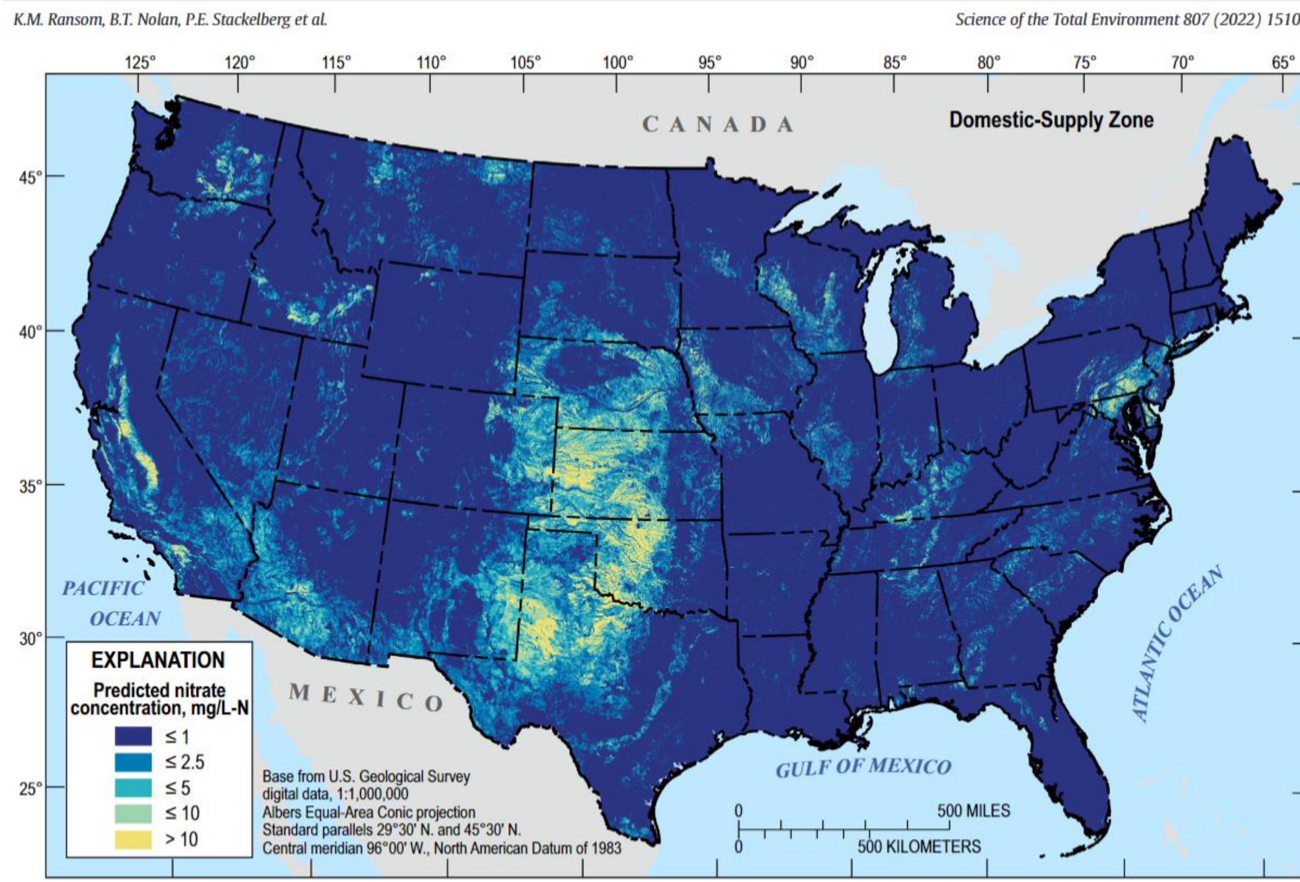
		NO_3-N *Observed*	
		≥5 mg/L	<5 mg/L
NO_3-N *Predicted*	≥5 mg/L	**Sensitivity** 2615 **(67%)**	2598 (14%)
	<5 mg/L	1280 (33%)	**Specificity** 15660 **(86%)**



Wheeler/Nolan et al. STOTEN; 2015

USGS National Models of Nitrate in Groundwater

- Domestic & public supply well depths
- Machine learning methods: 3D extreme gradient boosting
- 76 variables: well depth, soils, land use, climate were most important
- Fertilizer & manure inputs in ag areas



- Utility for exposure assessment?
  - 1 km scale
  - Compare with regional/state models

Ransom et al. STOTEN; 2022

Exposure Assessment Challenges

- Lack of publicly available measurement data for private wells and small water systems

- Modeling is feasible:
  - Representative measurement data
  - Accurate location
  - Well depth, type
  - GIS-based variables for study area (e.g. land use, pollutant sources, soils, aquifer characteristics, slope, meterologic data)

- Challenges for modeling exposure:
  - Hydrogeology and geochemistry may not be well understood
  - Multidisciplinary effort
  - Can be expensive especially if monitoring required
  - Modeling contaminant mixtures

Exposure Assessment Challenges

- Health risks likely from low level exposures over lifetime
  - Lifetime history including water treatment, well depth
  - Historical recall is challenging
- Route of exposure
  - Ingestion: Tap water intake may vary over time, likely misclassification
  - Dermal, inhalation for DBPs, volatile organic contaminants (e.g. trichloroethylene)
- Susceptible subgroups - pregnant women, infants, children
  - Many contaminants cross the placenta

Collaborators on AHS and NEBCS

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Virginia Commonweath University
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Colorado State University
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