High Tech Tools for Water Resources

How smart sensors can help us protect the environment

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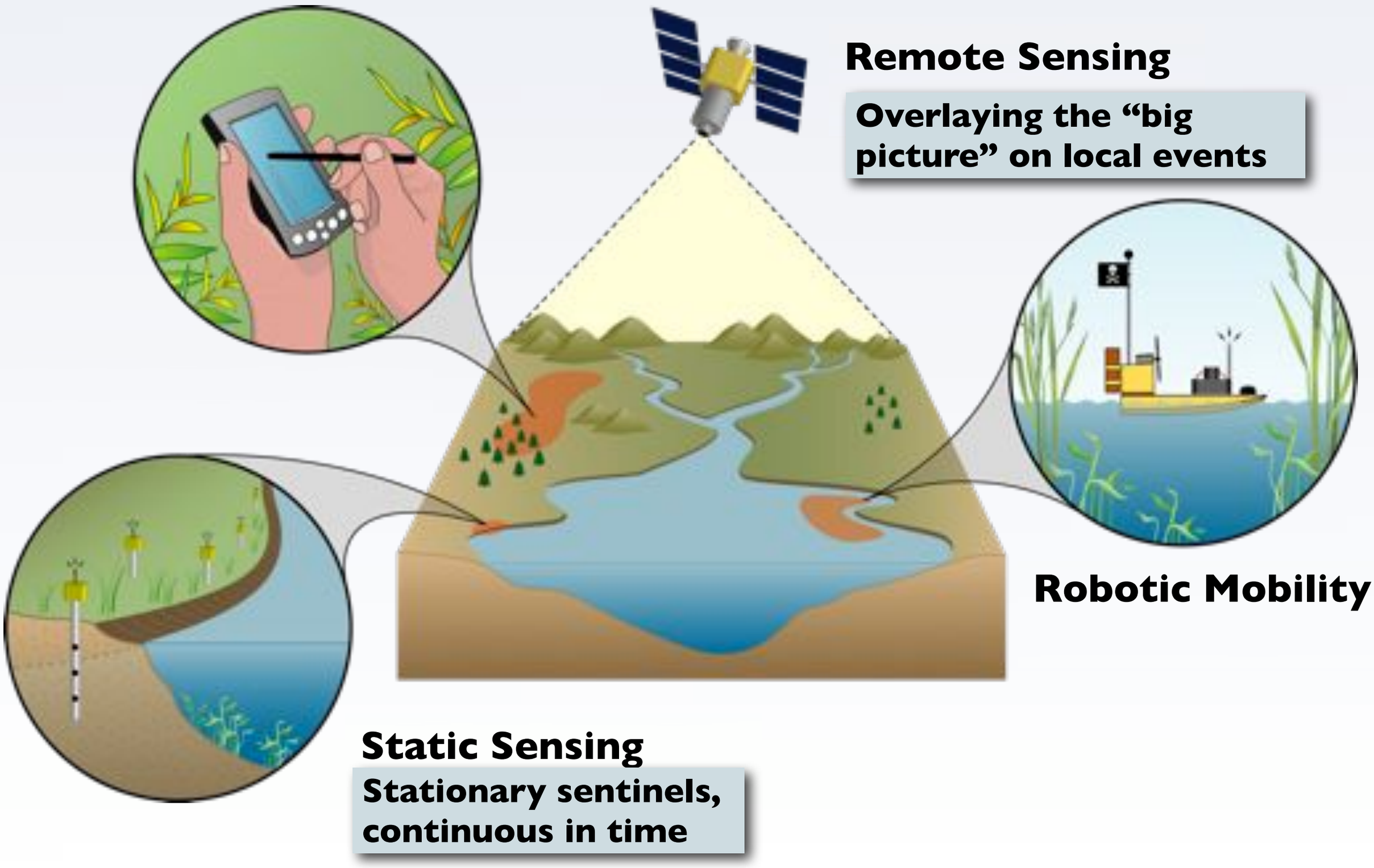
CENS Center for Embedded Networked Sensing

Woodrow Wilson International Center for Scholars
Foresight and Governance Project

...Then to now

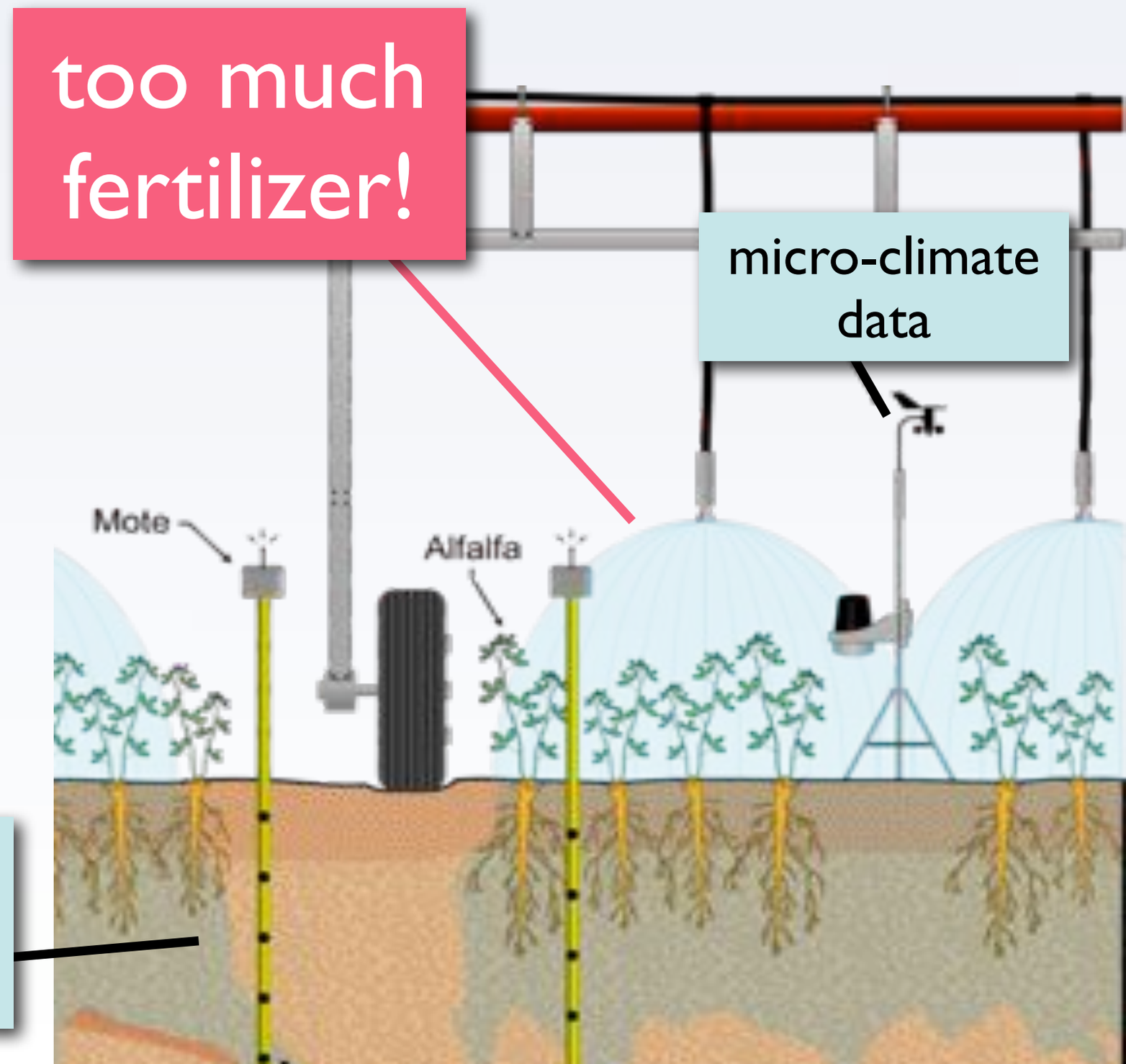
- Sensor Systems defined
- Where sensor technology is ready, what can we do?
- Where sensor technology is not there yet, what should we do?

Sensor Systems: What are they? Multiple observation scales perspective



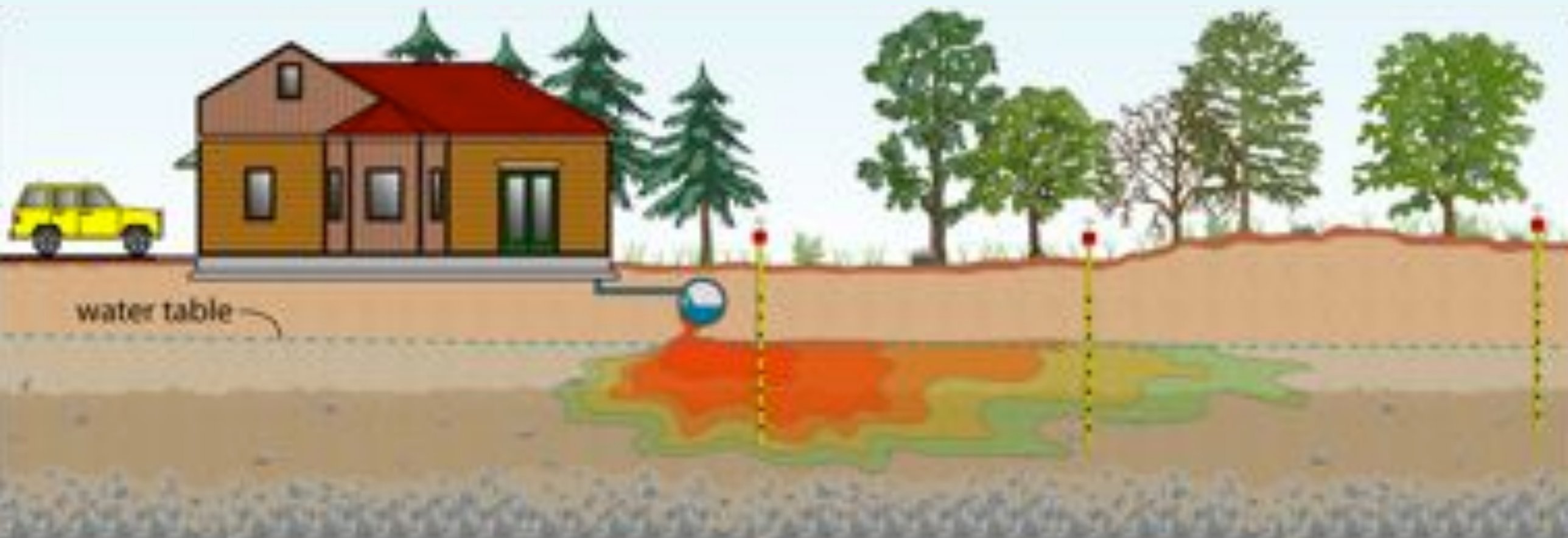
Sensor Systems: What are they? Multiple observation scales perspective

- Sensors measure environmental properties
- Communications devices bring data to the Internet
- On the Internet, users (or automated algorithms) analyze, visualize, model the data, producing a more sophisticated outcome than "a bunch of data"



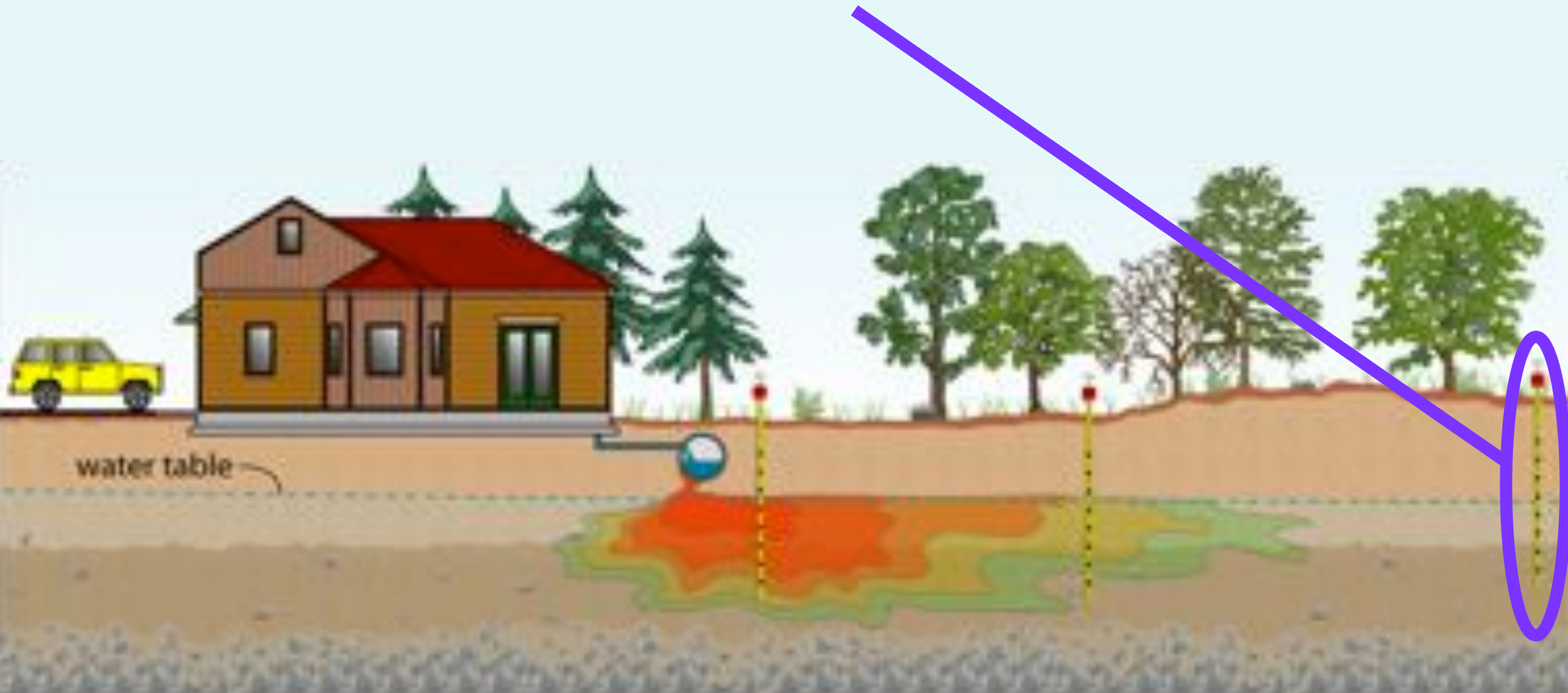
Some sensors are ready to go…

- **Septic systems** are a potentially big problem
- Poor placement of leachfields, badly constructed systems, system failure, high density of tanks…
- Sensors systems could be created for **monitoring and preventative maintenance**



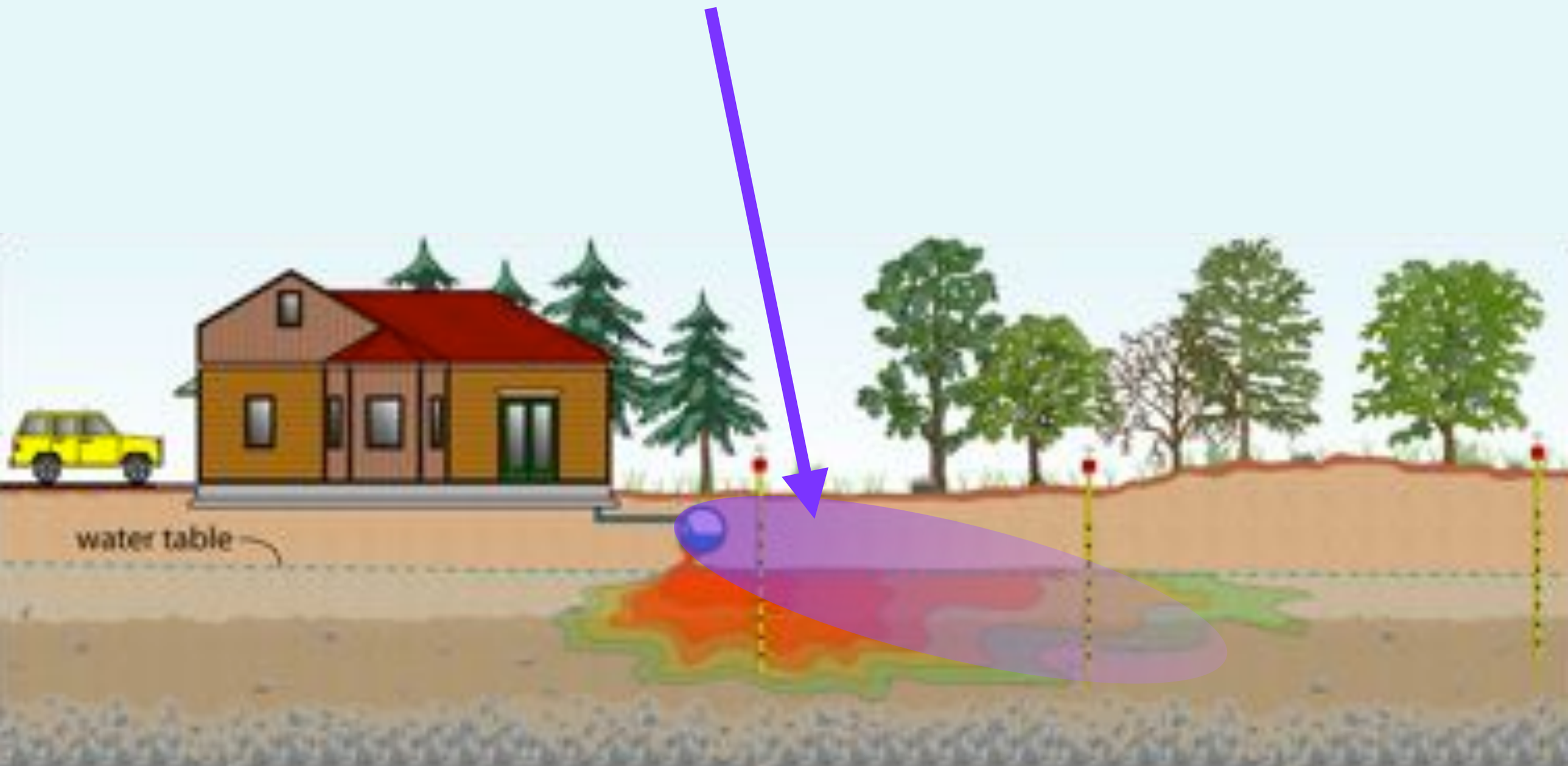
Septic tank scenario 1

Passive: sentinel sensor system…if an indicator (e.g., salinity or temperature changes) appears beyond a certain location, then trigger alarm



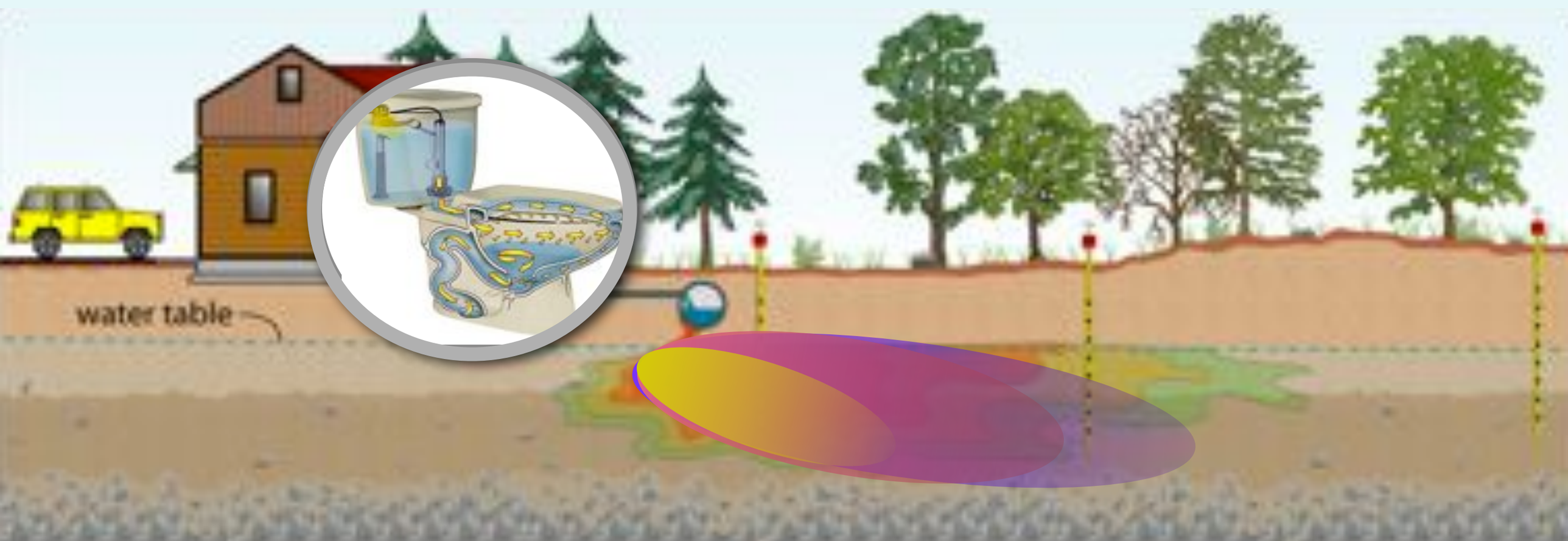
Septic tank scenario 2

Active: map, model, and report diagnostics if "good" patterns begin to change to "bad"



Septic tank scenario 3

Proactive: homeowner perturbs the system and observes whether it reacts in a "healthy" manner



Some sensors are ready to go…

- Non-point source pollution is huge national problem
- Where AND when are pollutants in runoff most problematic?
- Sensors systems can be created to better observe distributed sources, even manage distributed treatment

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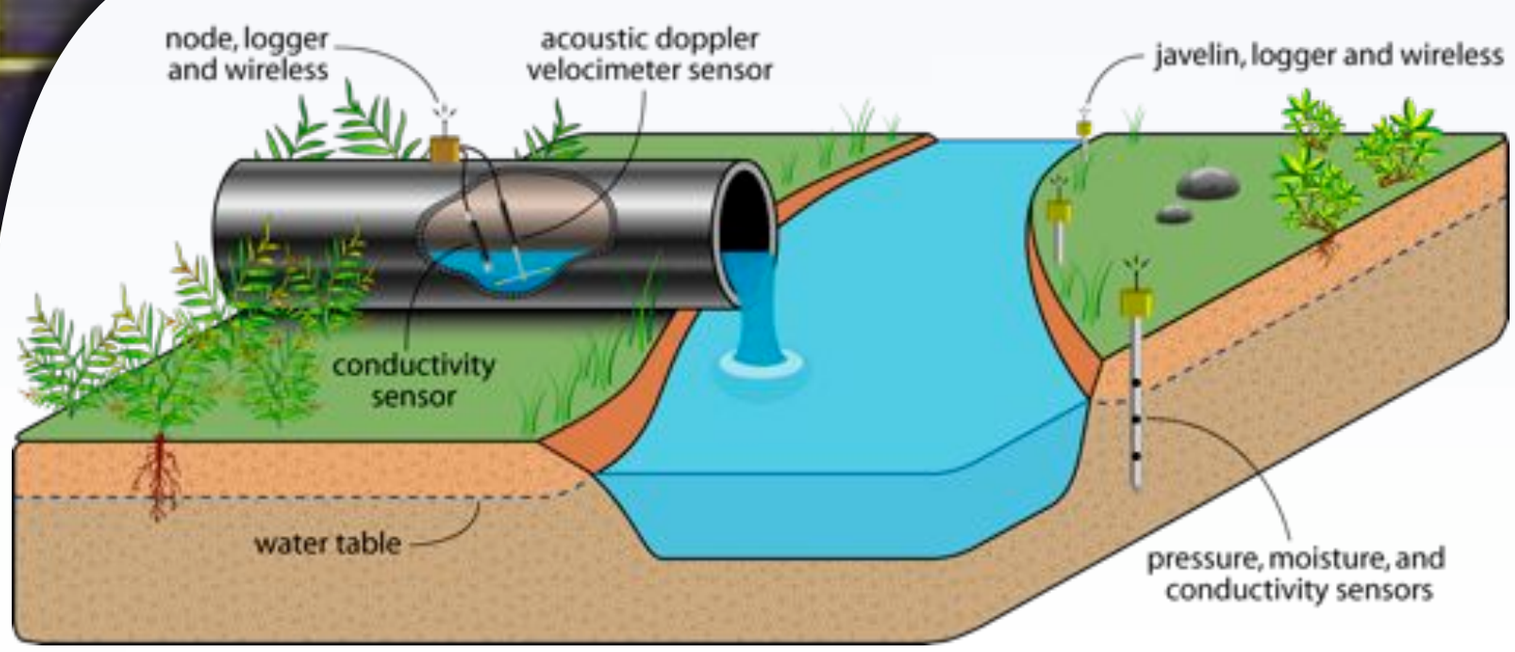


When the sensors are not ready

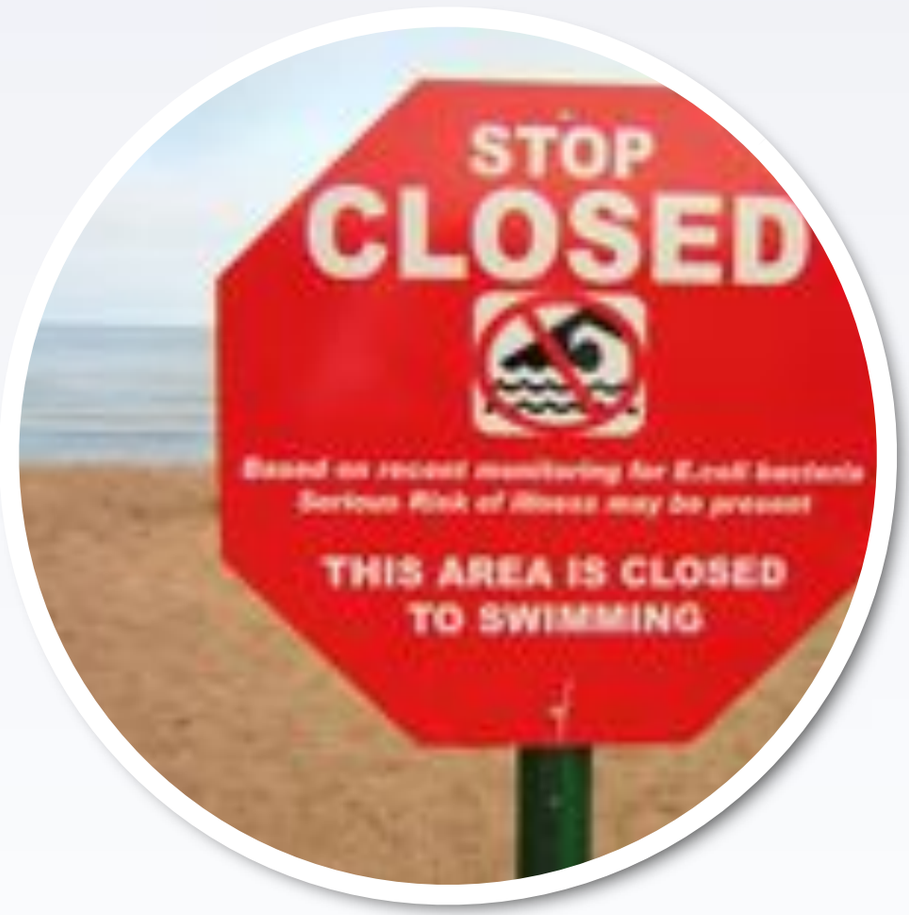


Photo: G. Kleinheinz, UW-Oshkosh

- **Beach closures** due to pollution
- **Pathogens** cannot be directly sensed, so what can we do?
- Sense **surrogates** (biomarkers: some complex, some sensable!)
- Direct approach is always better: research for pathogen sensors

Beach closure scenario

- Another powerful strategy is **actuated sample collection**
- Technology enables automatic, reproducible sampling in **difficult locations** (how does a human sample a turbulent surf zone the same way twice?)
- Key this to surrogate sensors (event-triggered sampling)
- This strategy will always **bridge sensor technology gaps**

Photo: Yosemite Assoc.

Univ.of Heidelberg

Sensor systems with actuators & valves

- **Combined sewer overflows**
- Storms, flows, and timing
- The spatially distributed properties are known here
- **“do something about it”**

Combined sewer overflows

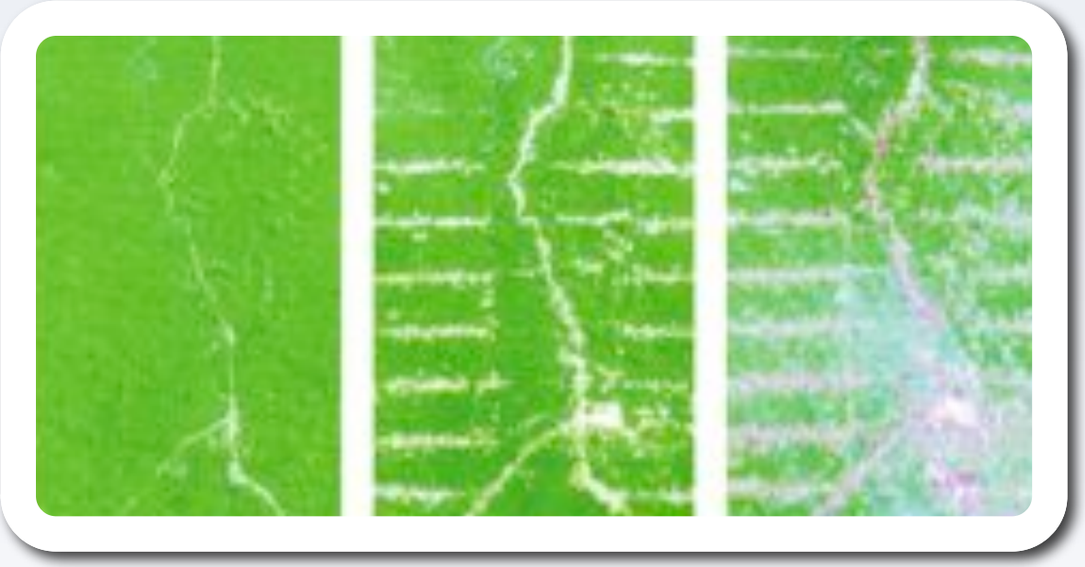
- **Forecast** storm runoff
- Monitor flow throughout the pipe network
- **Actuate** gates, valves to channel combined flow to storage until storm subsides
- **Experience and simulations** can identify critical junctions

Now to the future...

- **Multiple observational scales** (septic tank to city sewer network)
- **Numerous** applications even with limited sensor types
- **Actuated** sampling bridges the gap between now and the future
- Many sensor systems ready for testing **today**
- What sorts of **sensing technologies** are currently being tested?

Environmental Monitoring Applications

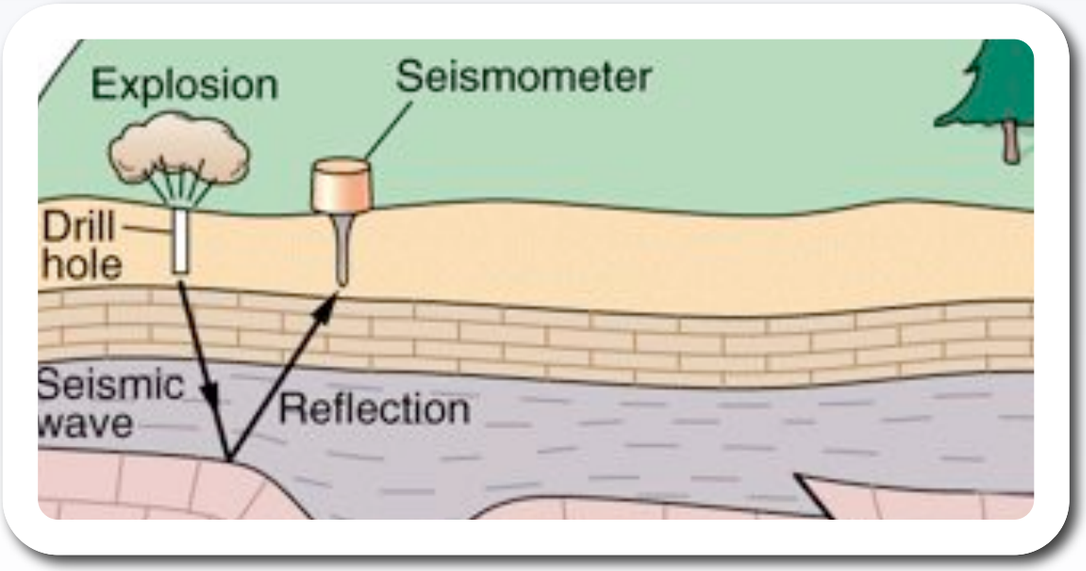
Spatial variations and heterogeneity



Impact of fragmentation on species diversity

Precision agriculture, water quality management

Algal growth as part of eutrophication



Earth structure inhomogeneities

Embedded Networked Sensing

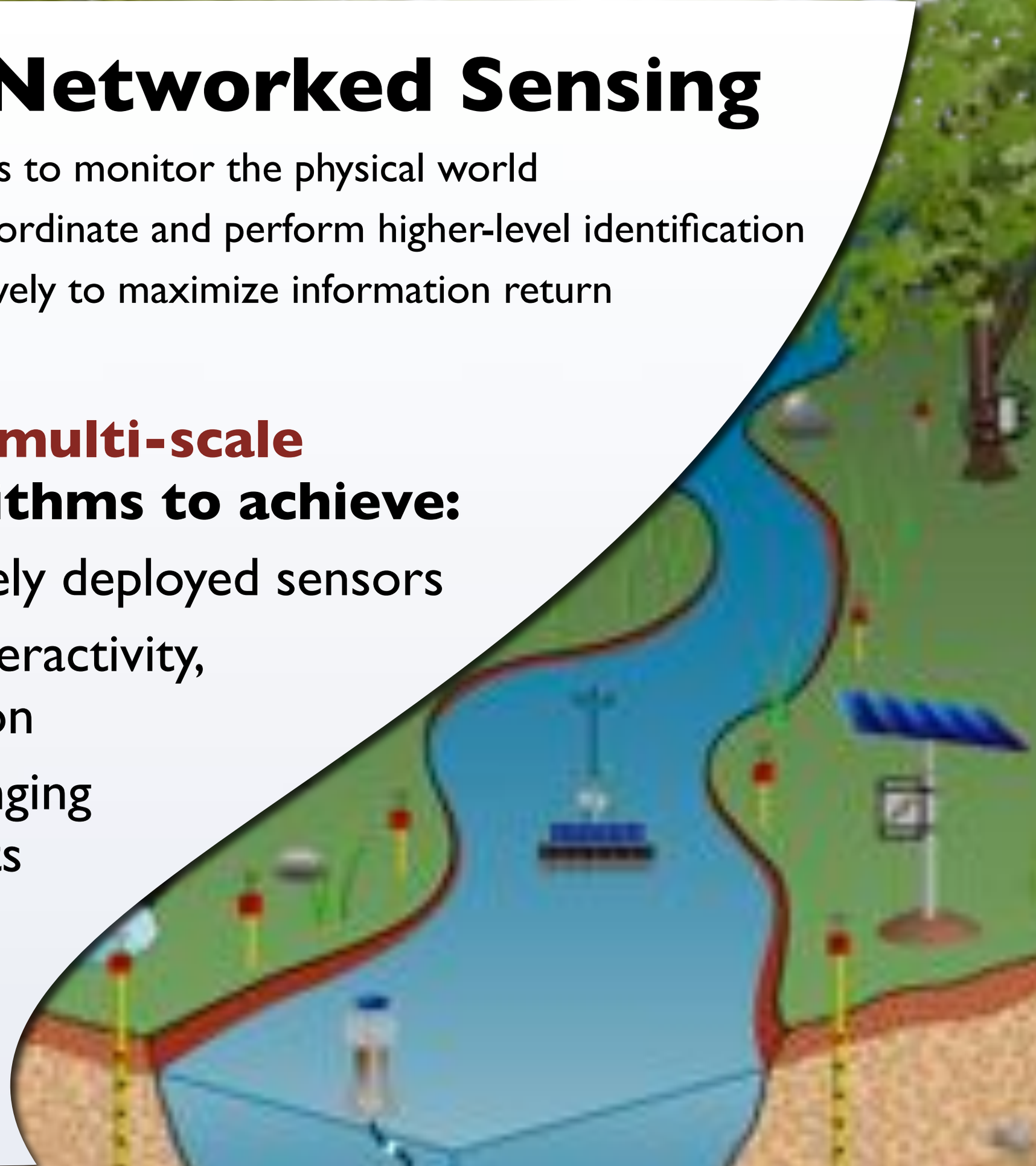
Embed numerous devices to monitor the physical world

Network to monitor, coordinate and perform higher-level identification

Sense and actuate adaptively to maximize information return

In-network and multi-scale processing algorithms to achieve:

- Scalability for densely deployed sensors
- Low-latency for interactivity, triggering, adaptation
- Integrity for challenging system deployments



Technology Challenges

Objectives

- Embeddable, low-cost sensor devices
- Robust, portable, interactive systems
- Data integrity, system dependability
- Programmable, transparent systems
- Multiscale sensing and actuation

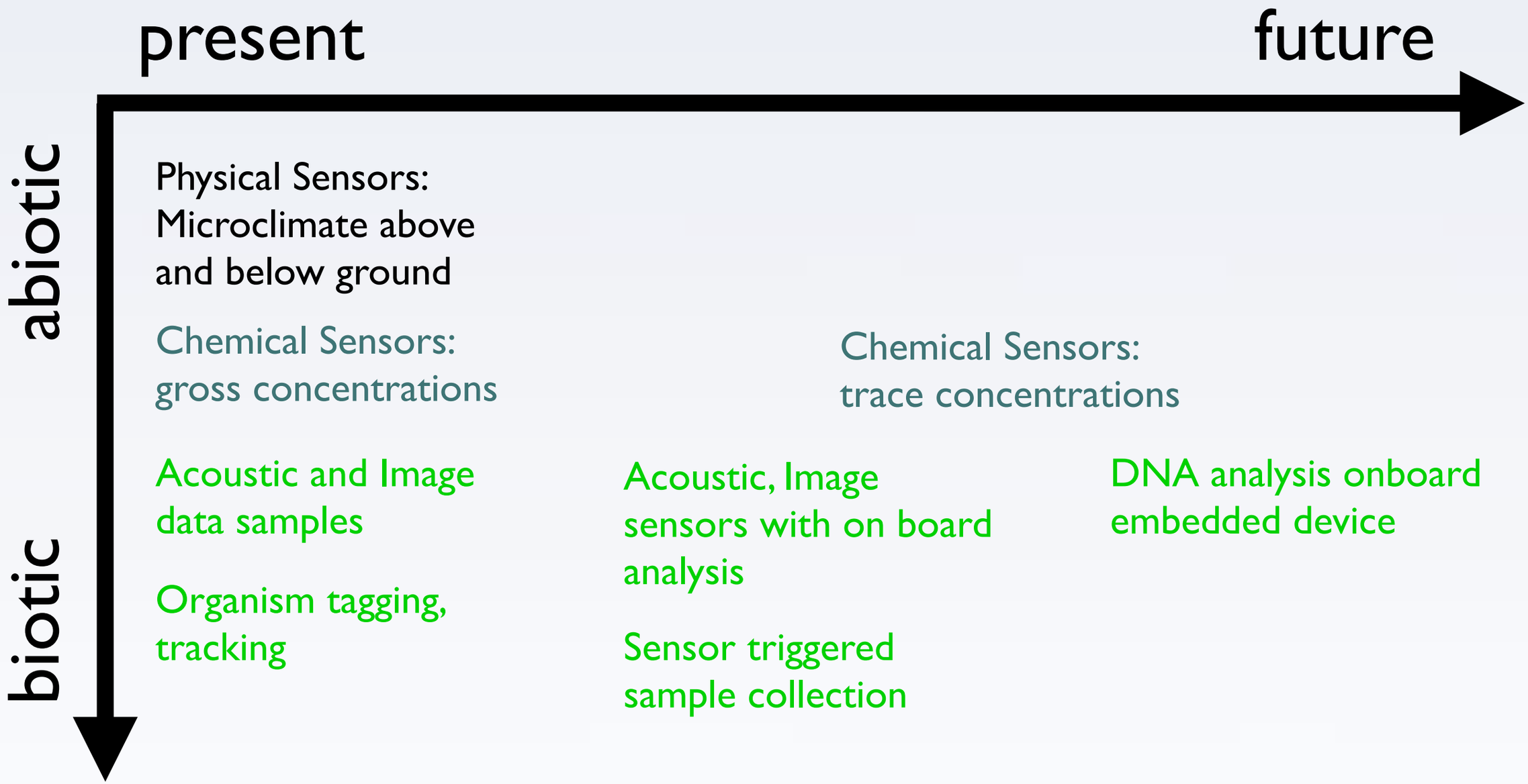
Constraints

- Sensing channel uncertainties Environmentally compatible deployment
- Limited resources: node, infrastructure Complexity of distributed systems No ground truth

Drivers

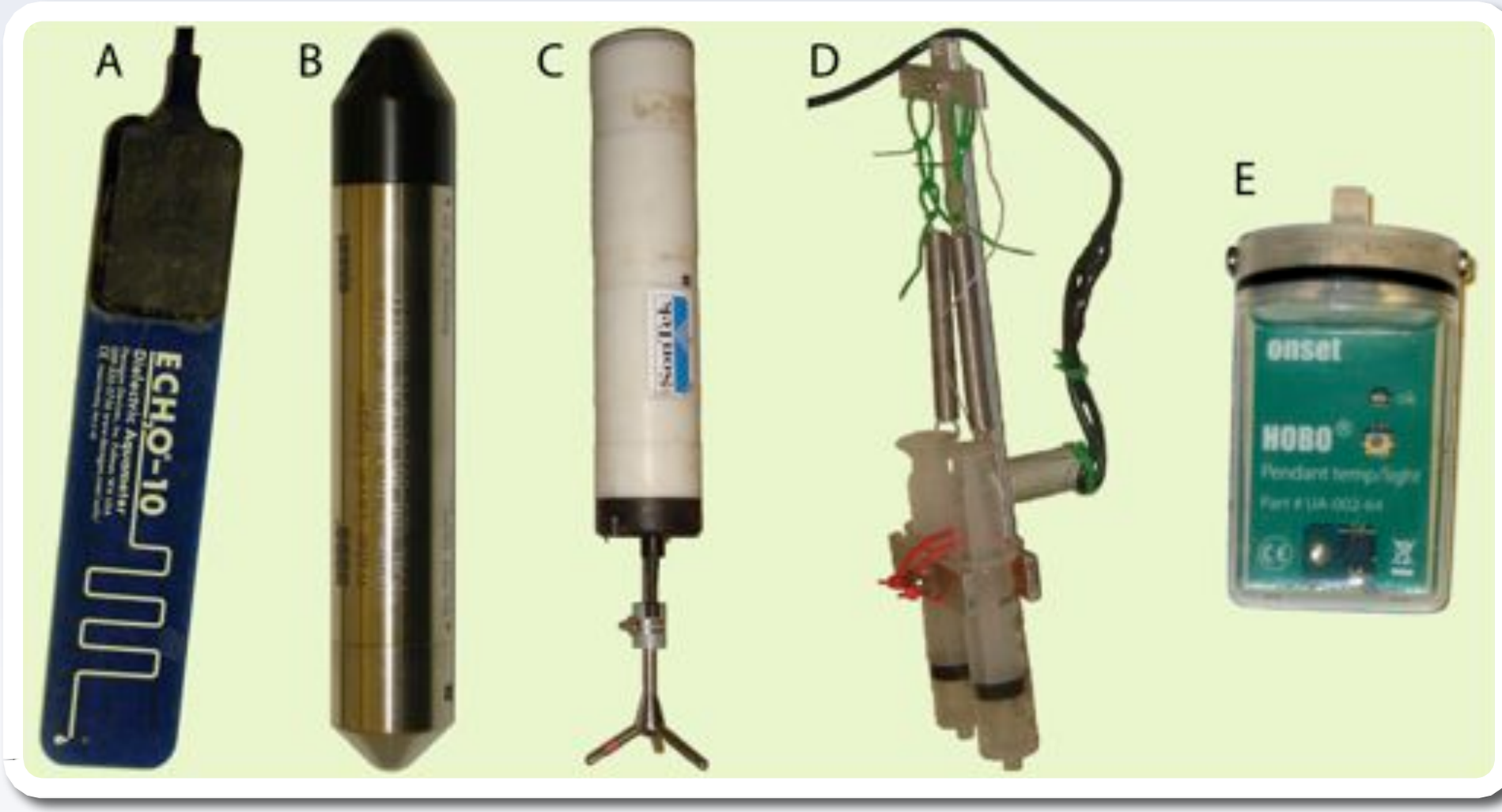
- Comm vs. storage vs. processing
- The power vs. energy efficiency vs. performance choice
- Achieving sustained operation
- High cost of sensor sampling

Expanding Sensor Suite



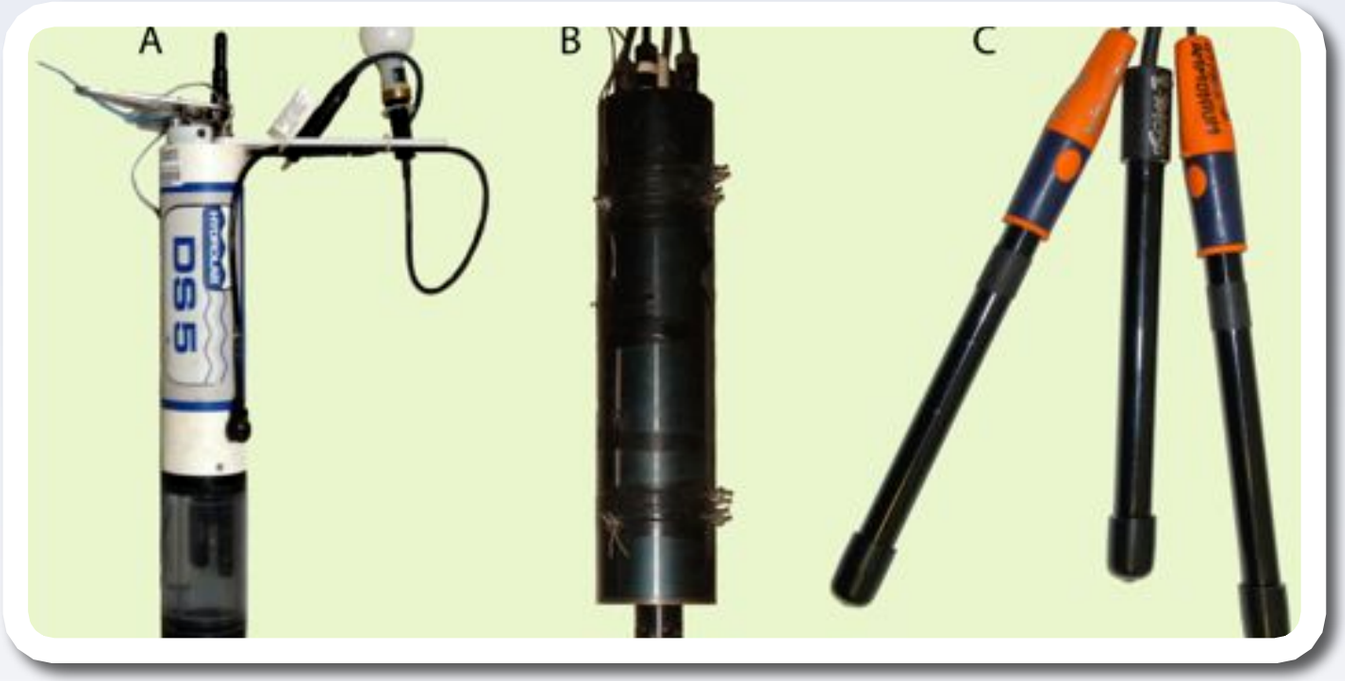
- Commercially available devices available for many physical and chemical measures
- Advancements in sensor technologies will further transform wireless sensing systems as new capabilities broaden physical, chemical, and biological *in situ*, autonomous, observations

Physical Sensors



Parameter	Field-Readiness	Scalability	Cost
Temperature	High	High	50–100
Moisture Content	High	High	100–500
Flow rate, Flow velocity	High	Medium–High	1,000–10,000
Pressure	High	High	500–1,000
Light Transmission (Turbidity)	High	High	800–2,000

Chemical Sensors

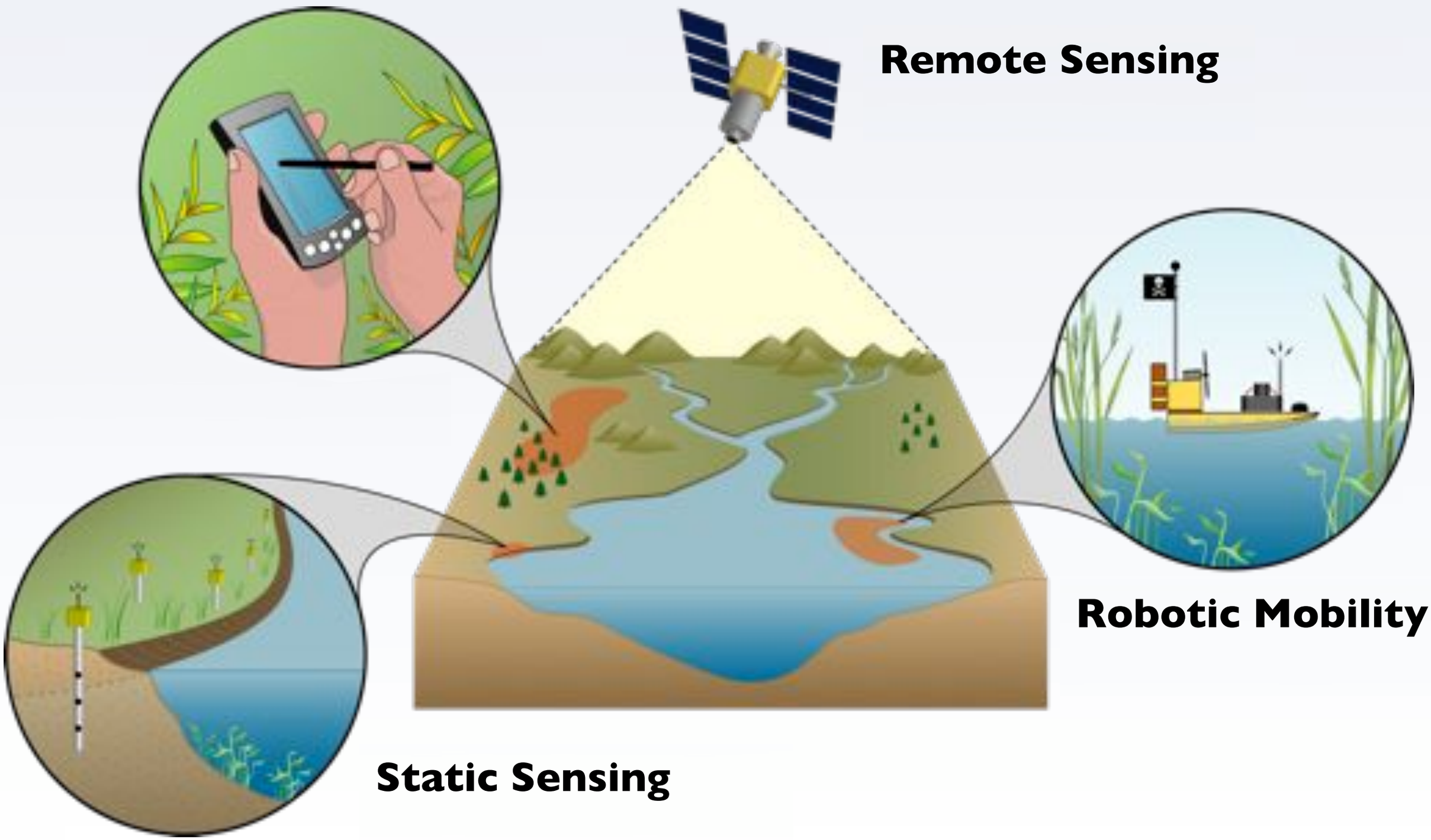


Parameter	Field-Readiness	Scalability	Cost ($)
Dissolved Oxygen	High	High	800–2,000
Electrical Conductivity	High	High	800–2,000
pH	High	High	300–500
Oxidation Reduction Potential	Medium	High	300–500
Major Ionic Species (Cl-, Na+)	Low–Medium	High	500–800
Nutrients (Nitrate, Ammonium)	Low–Medium	Low–High	500–35,000
Heavy metals	Low	Low	NA
Small Organic Compounds	Low	Low	NA
Large Organic Compounds	Low	Low	NA

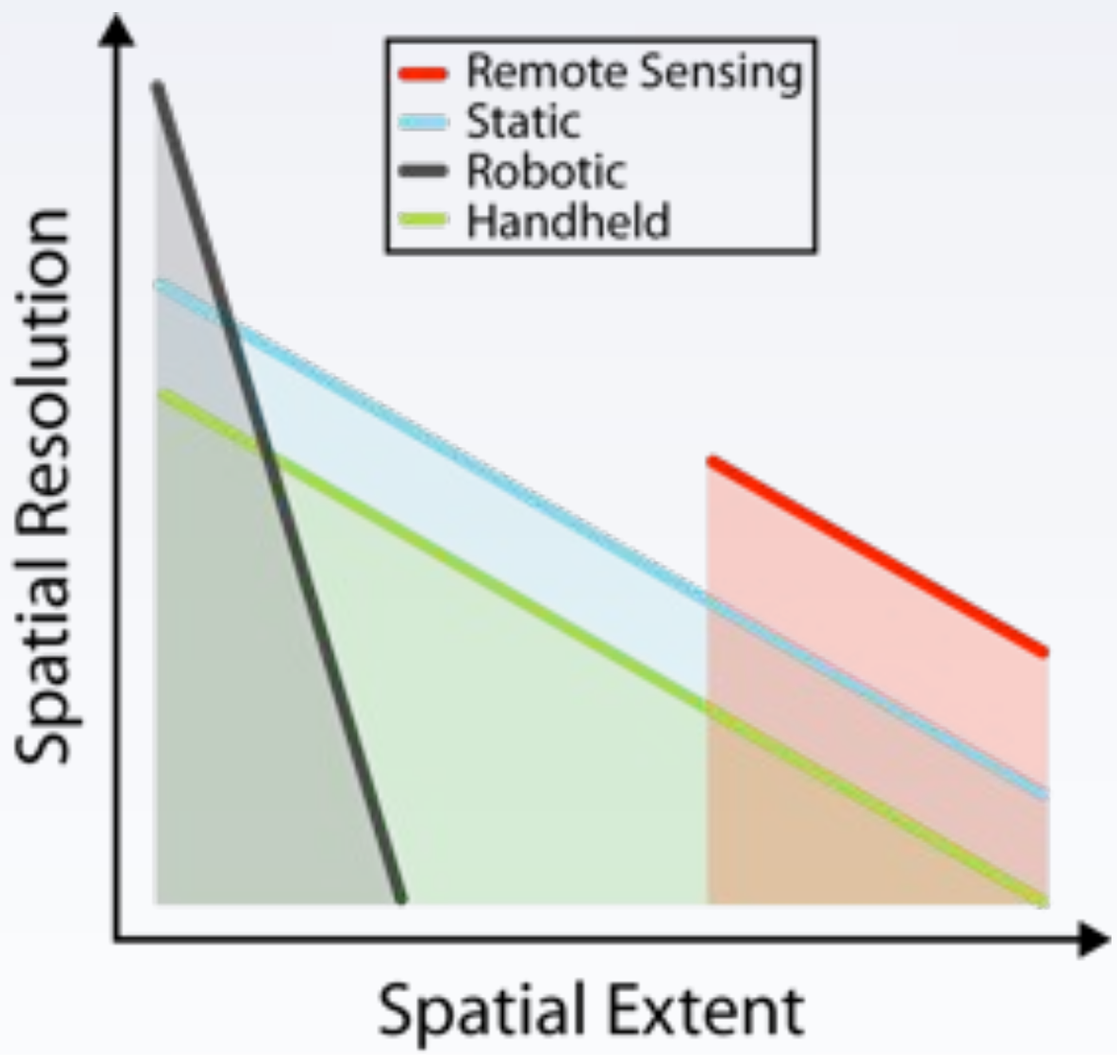
Biological Sensors

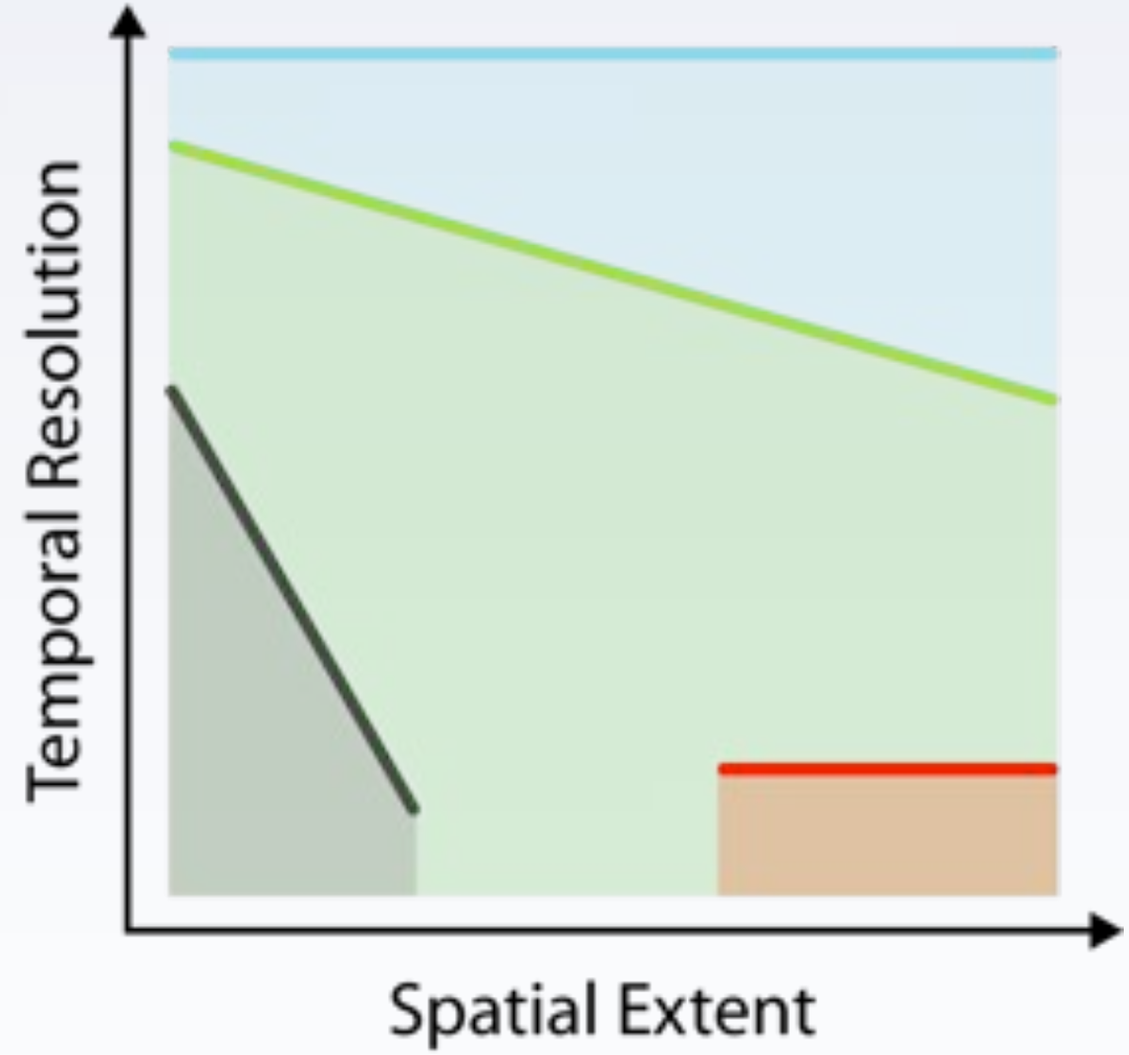
Parameter	Field-Readiness	Scalability	Cost
Microorganisms	Low	Low	NA
Biologically active contaminants	Low	Low	NA

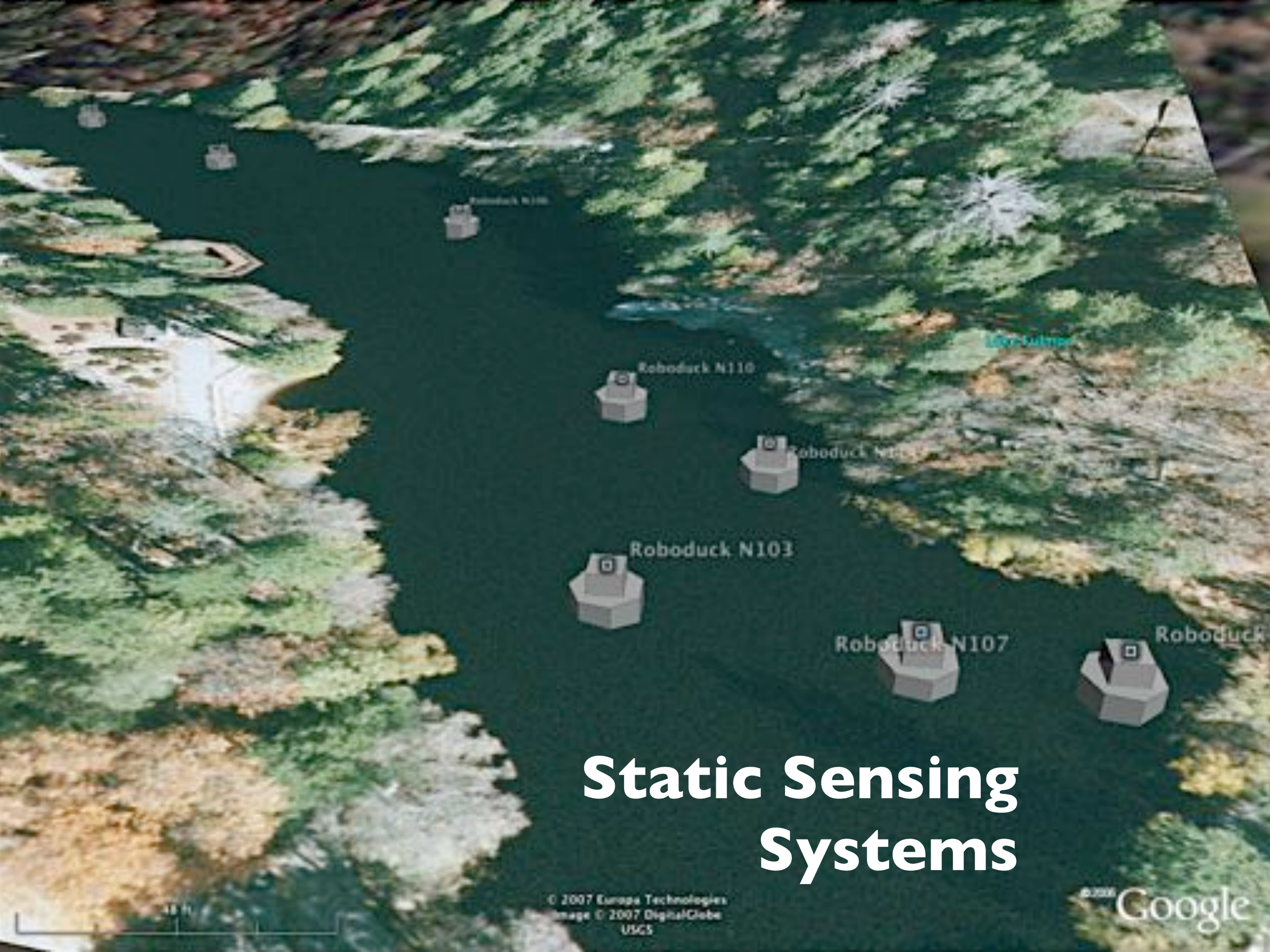
The power of multi-scale and multi-modal sensing



Deployment modes offer different information return & tradeoffs







Static Sensing Systems

Mobility & actuation help deal with heterogeneity

While ENS is a revolutionary technology for dense sensing

- The likelihood of under-sampling phenomena is surprisingly high
- Meeting sampling objectives is sometimes impractical with static nodes

Mobility is a critical amplifier of system coverage

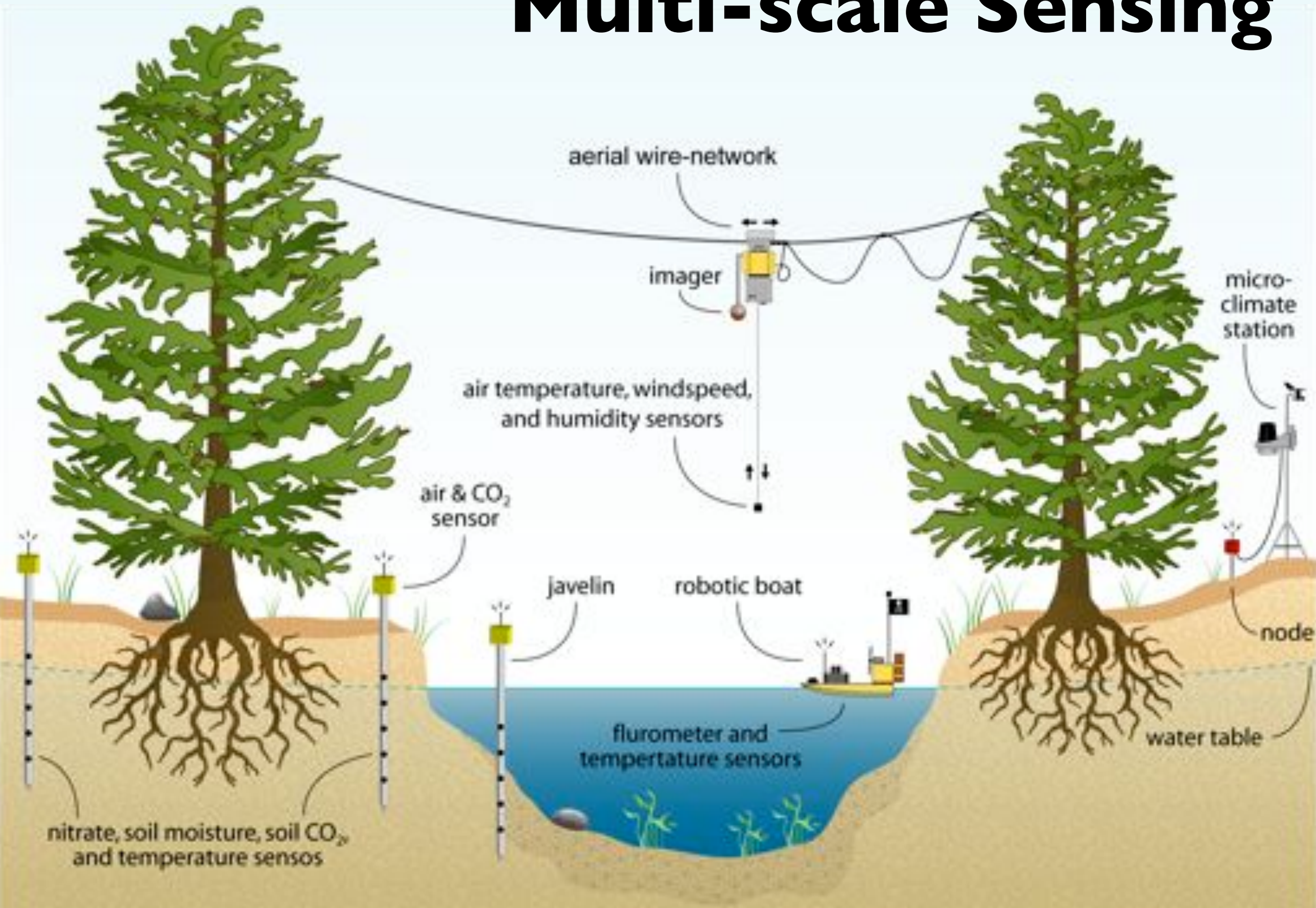
- From highly constrained articulation to long range spatial traversals
- Articulation magnifies effective sensor range and spatial diversity
- Infrastructure-supported mobility (NIMS) enables sensor diversity
- Enables adaptive, fidelity-driven, 3-D sampling

Mobile Sensing System

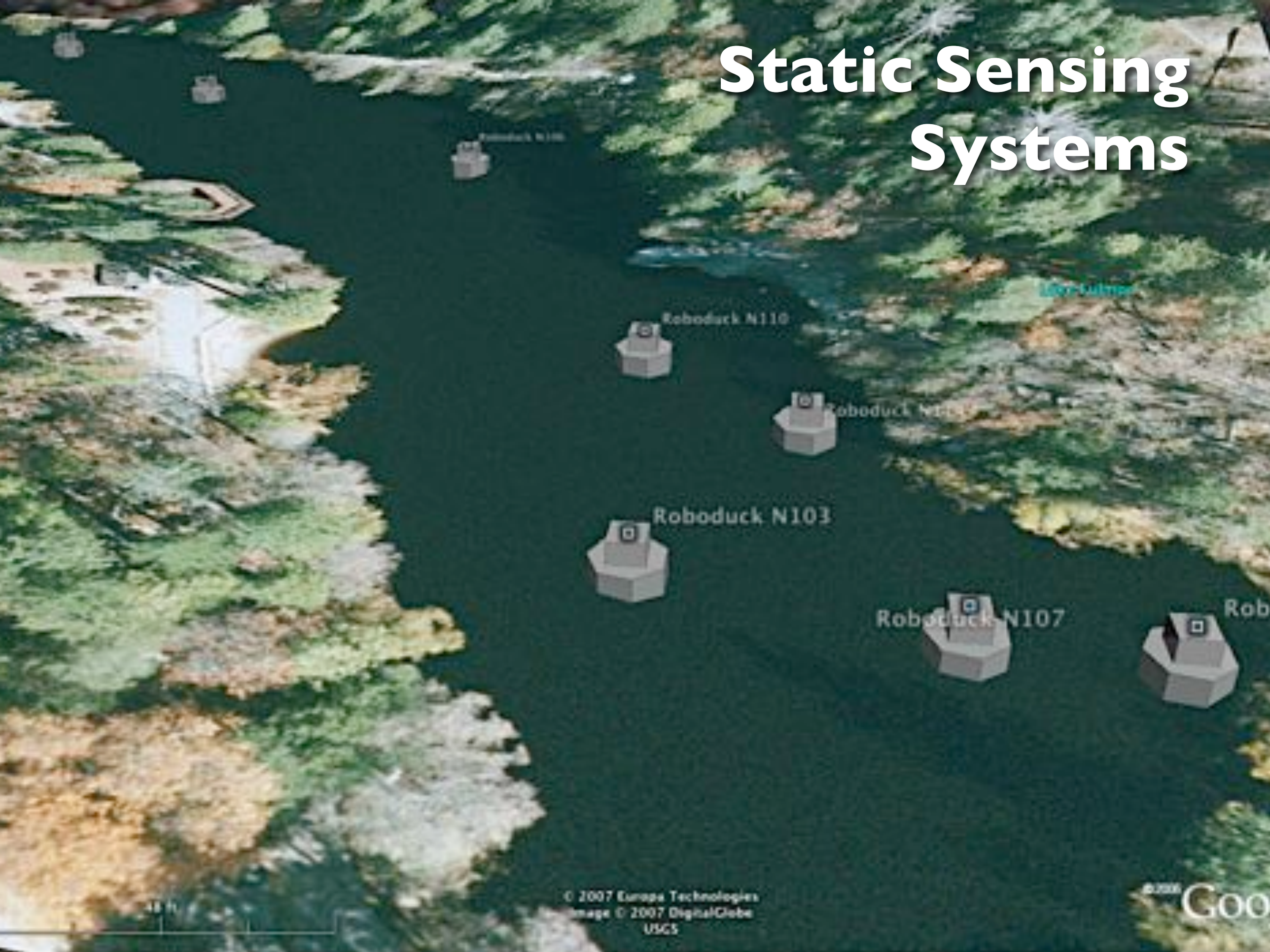
Handheld Sensing

- From data entry to imagers to connected sensors (bluetooth, usb)
- Automatic geocoding
- Automatic upload
- Real-time sanity-checking of data on handheld or on server end
- Access to maps, models, reference images or data

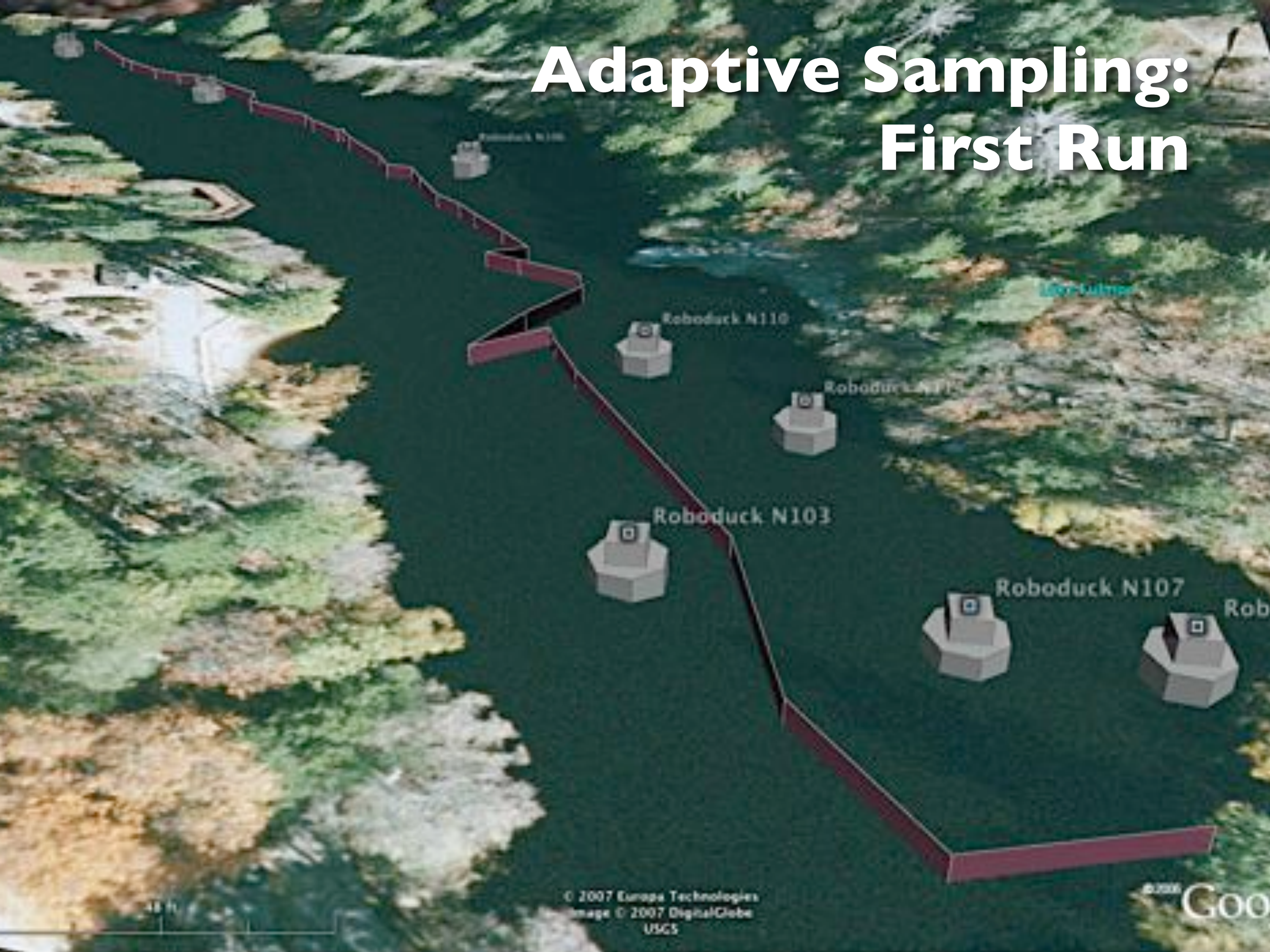
Multi-scale Sensing



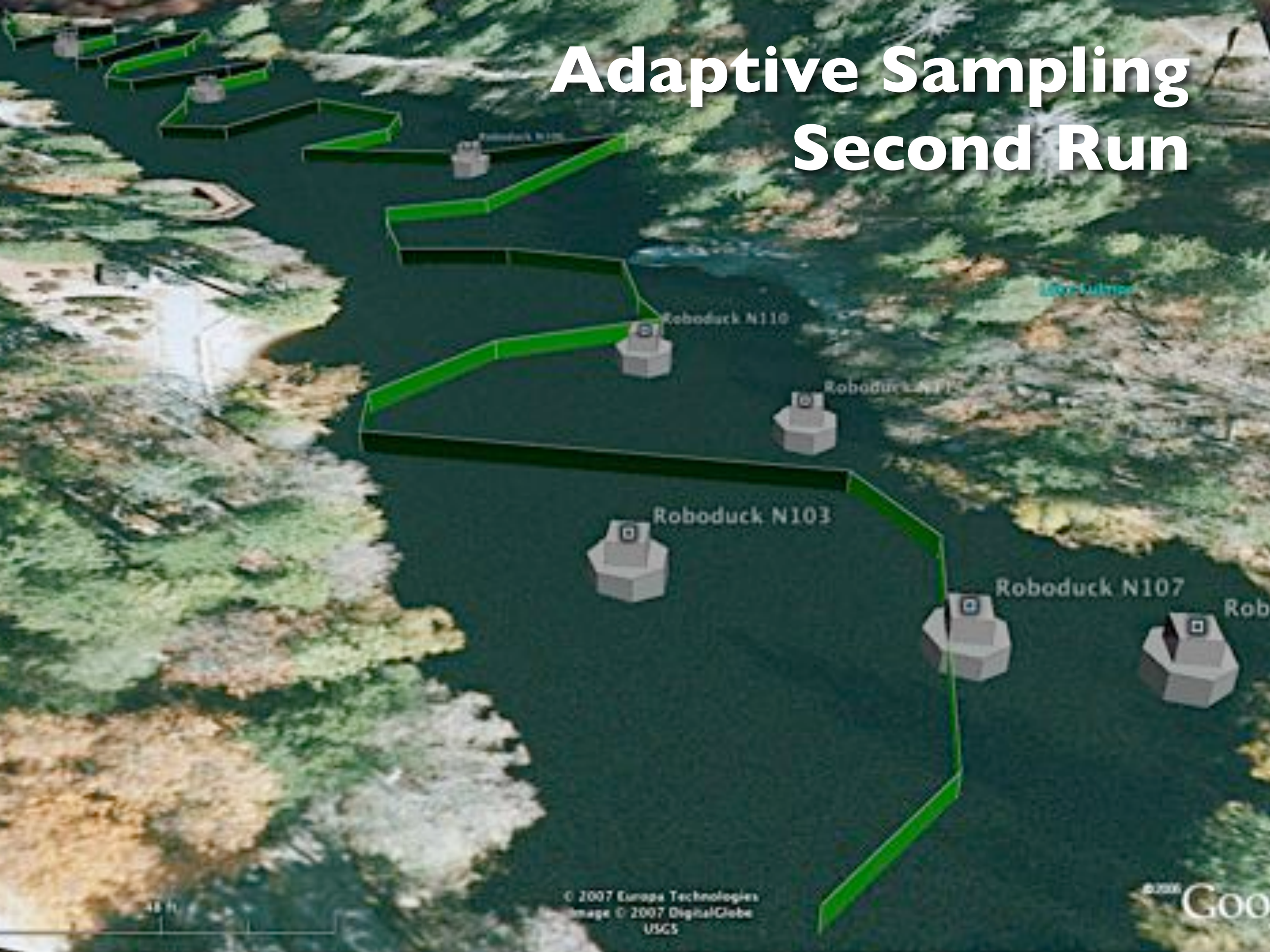
Static Sensing Systems



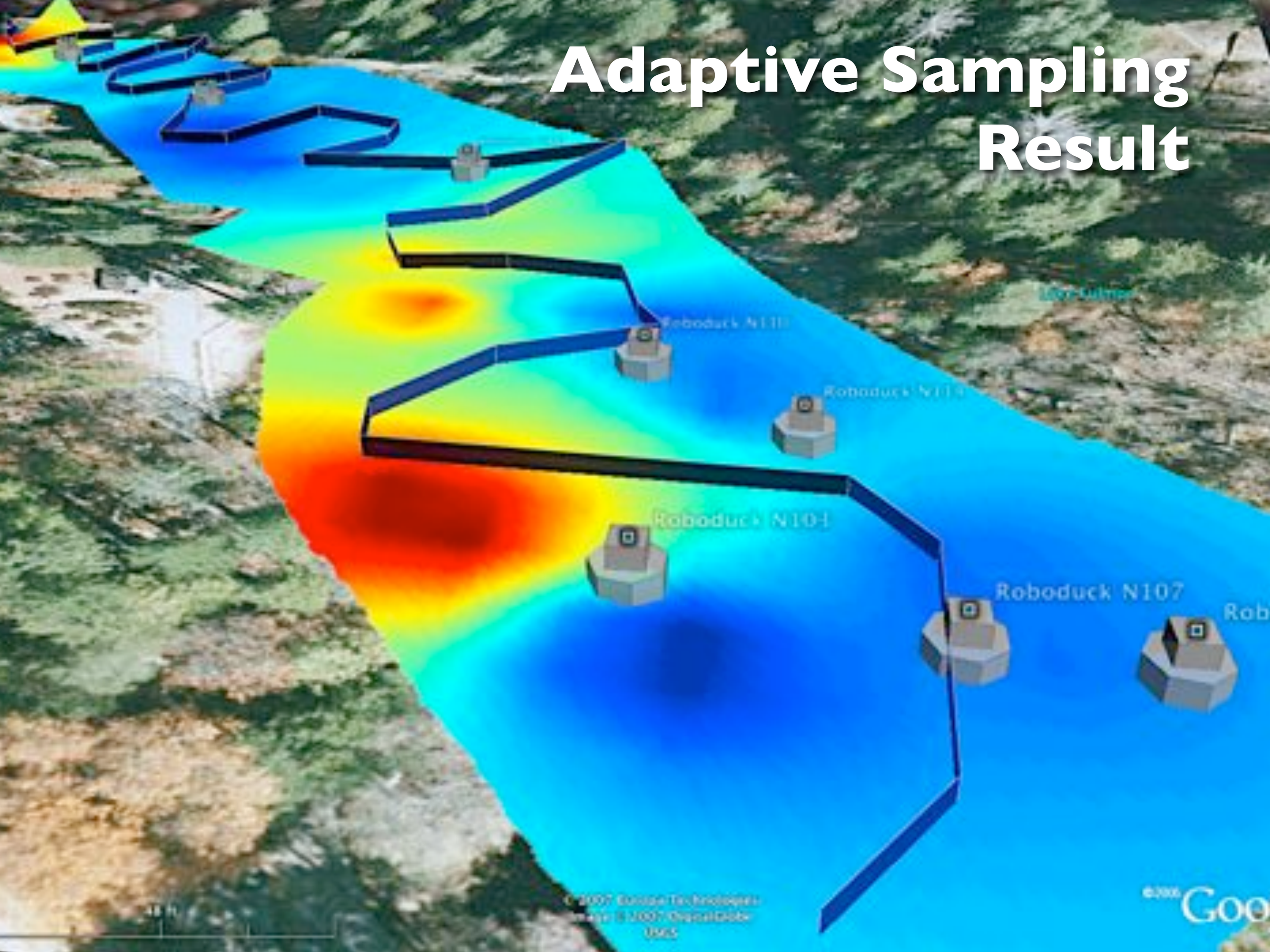
Adaptive Sampling: First Run



Adaptive Sampling Second Run



Adaptive Sampling Result



Rapid Deployments

Systems deployed many times for short durations

Powerful usage model for environmental assessment

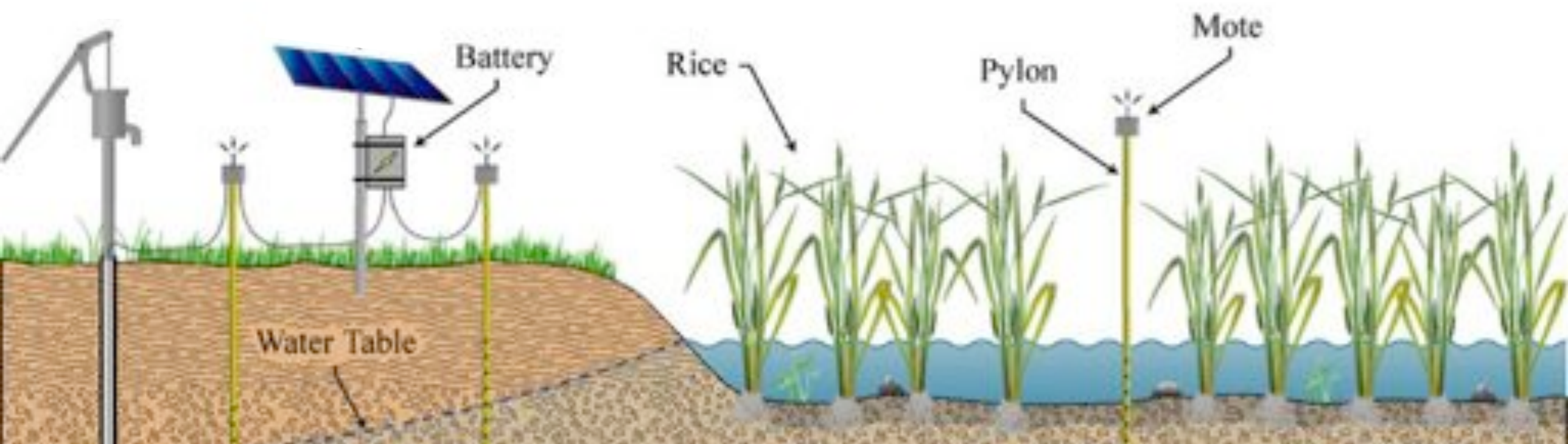
- trade temporal for spatial density and coverage

Short duration enables

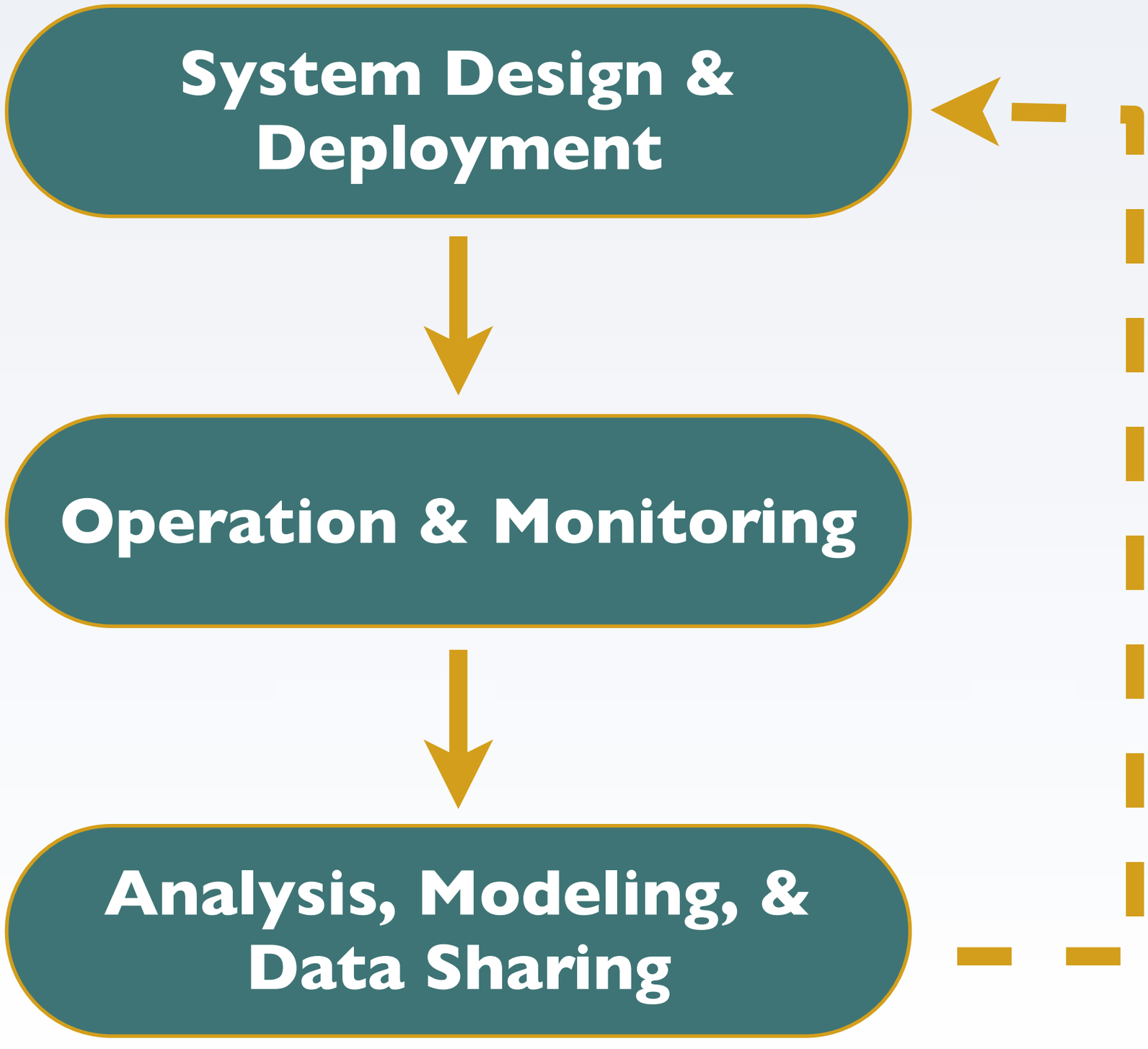
- Frequent calibration and maintenance
- User presence with increased functionality, data quality

Research challenges

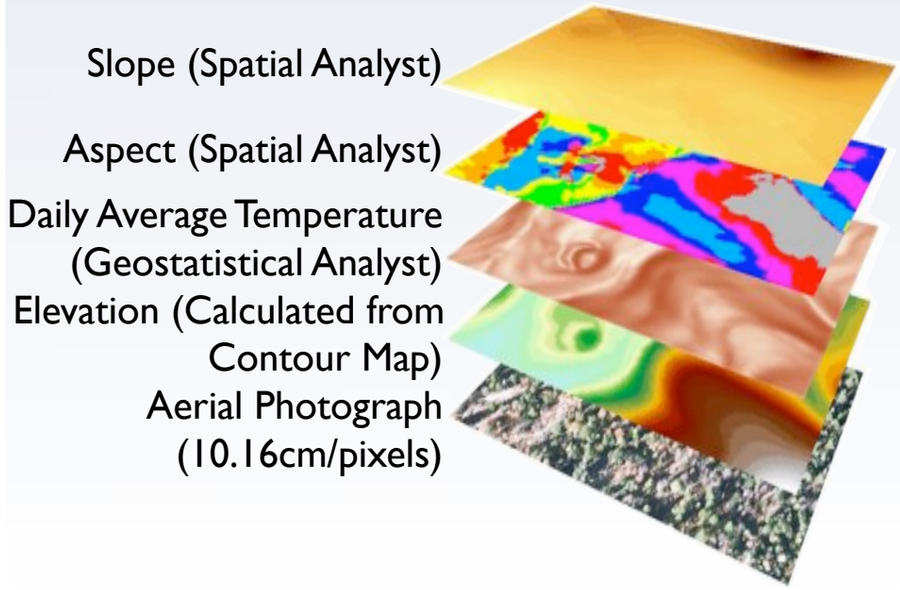
- Rapid setup, data return
- System visibility mechanisms tools
- Models to inform deployment adjustments as deployment unfolds
- In-field calibration, data integrity tools



Data Life Cycle



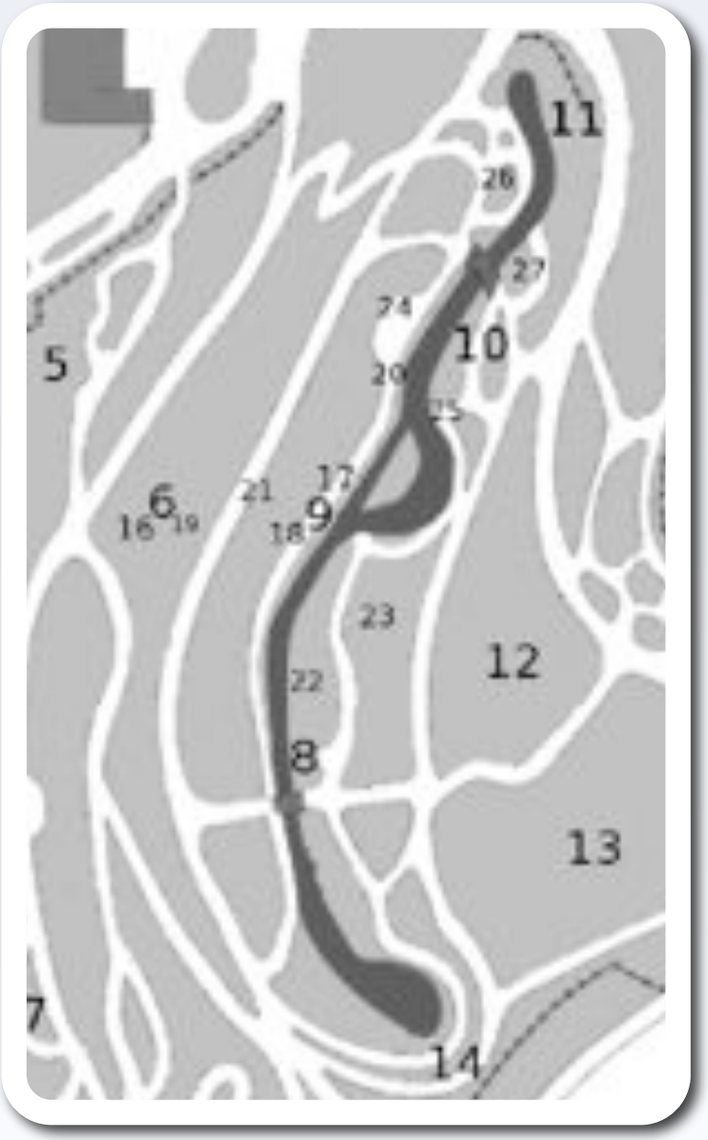
Coupled Human-Observational Systems



Transform physical observations from batch to interactive process

- Whereas we focused initially on very long lived, autonomous systems design, interactive and rapid deployments are high value.
- Interactive systems take advantage of human observer, actuator
- Addresses critical issues such as adaptive sampling, topology adjustment and faulty sensor detection
- Requires real time data access, model based analysis, and visualization in the field

Increasing role of statistical models & methods I

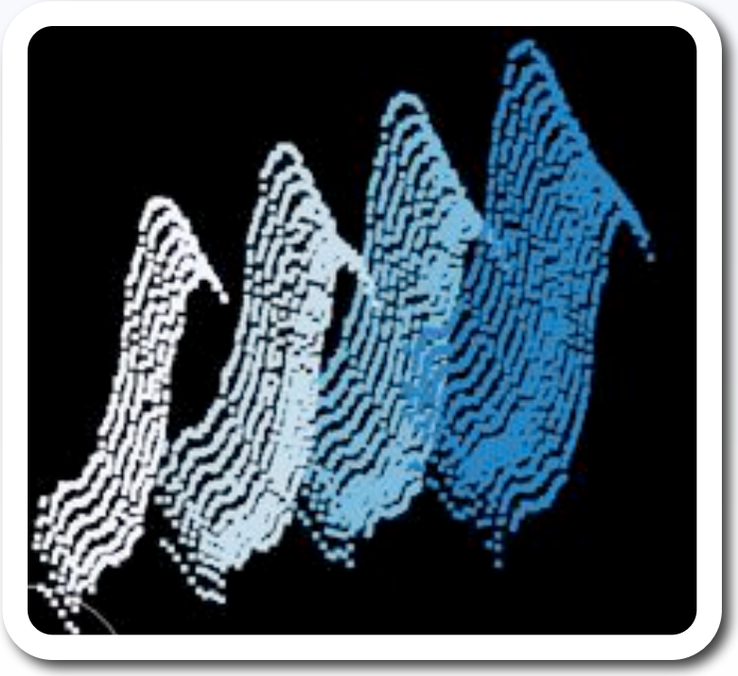


Experimental design and sensor layout: adaptive, iterative schemes for deployment

- Botanical gardens microclimate system design: Source of variability via PCA, Optimization via ILP
- Palmdale soil observation network design: Geospatial statistical methods for optimal sensor placement

Spatio-temporal models: flexible or "nonparametric" descriptions of signals

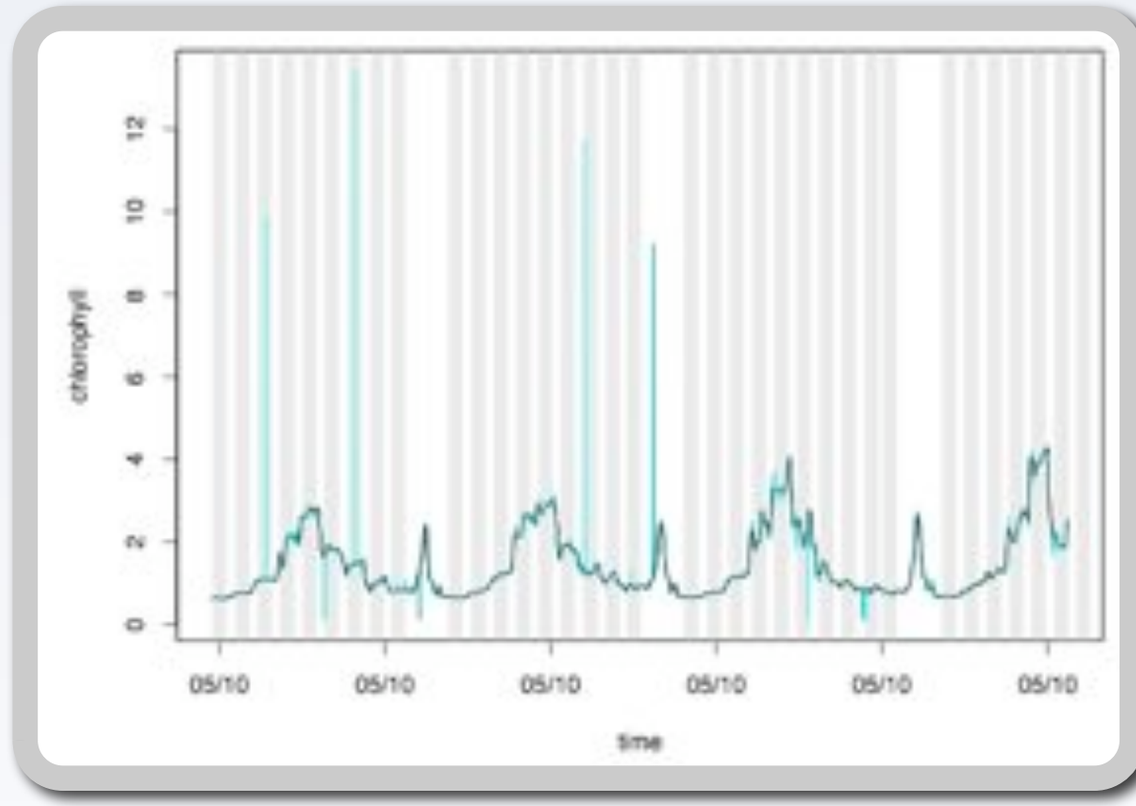
- Media creek nitrate studies: spline based estimators

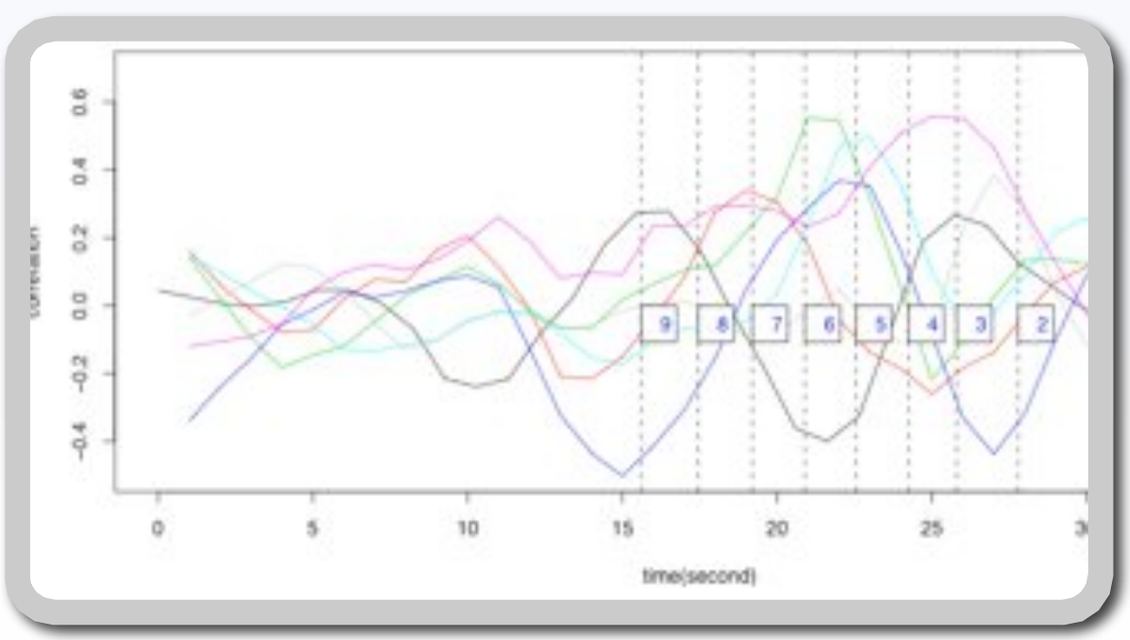


Increasing role of statistical models & methods 2

Data integrity: robust procedures for aggregation and analysis

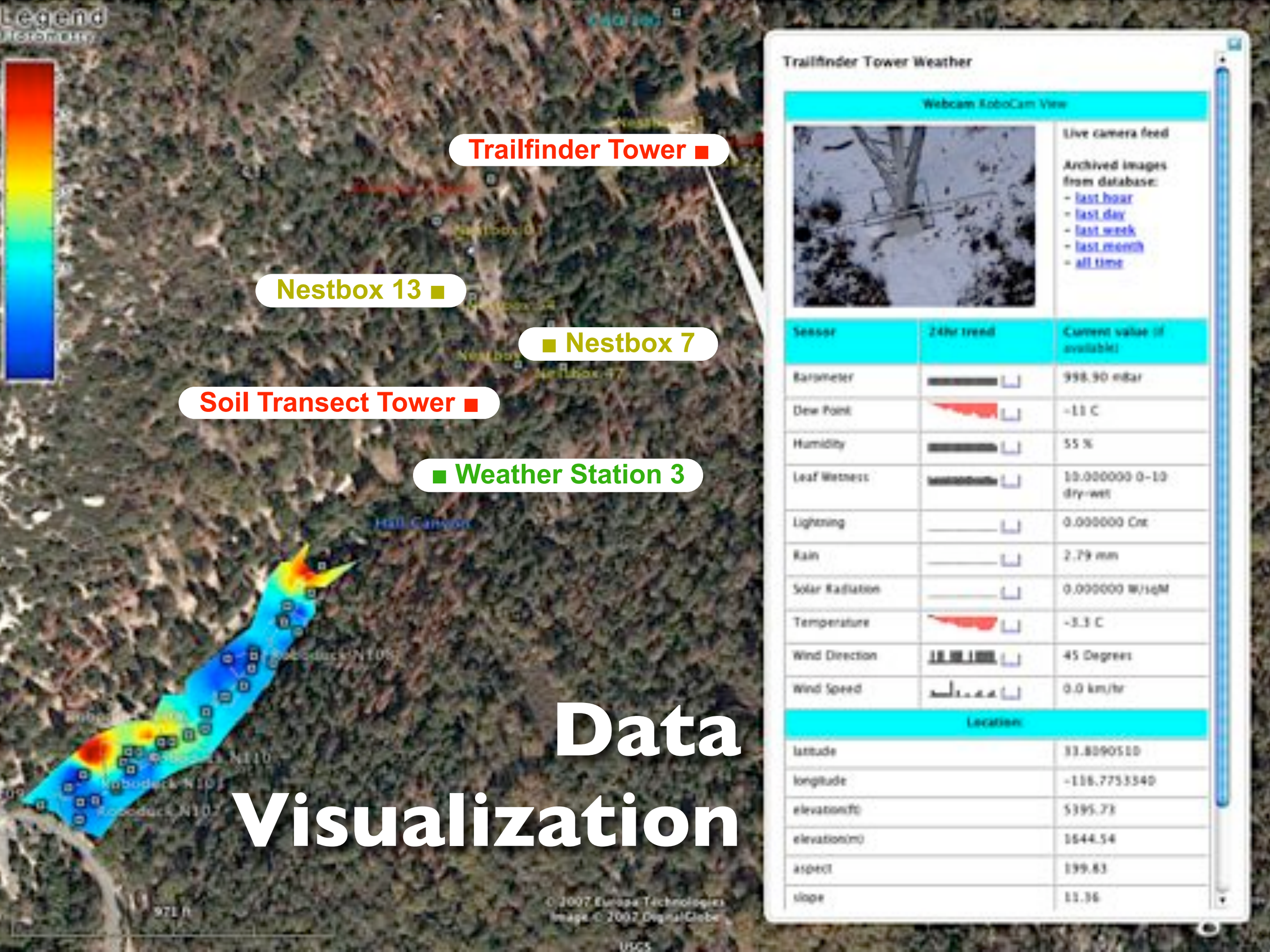
- Fluorometer measurements at lake Fulmor: Running medians





Opportunistic measures: identifying and integrating existing sources of data from other engineered systems

- Elevator tracking for structural health monitoring: wavelet coherence



Data Visualization

New themes will drive next 5-10 years of wireless sensing systems

- Mobile, Multi-scale, Multi-modal
- Integrity, sensing, participatory and interactive
- Participatory sensing: public health, social, personal
- Publishing and sharing sensor data:
- New advanced integrated-sensor development will take time and investment

Technology development model

- "Early-to-application" to leverage deployments and resulting data: provides feedback to system innovation, from theory to algorithm

Getting from

here

to

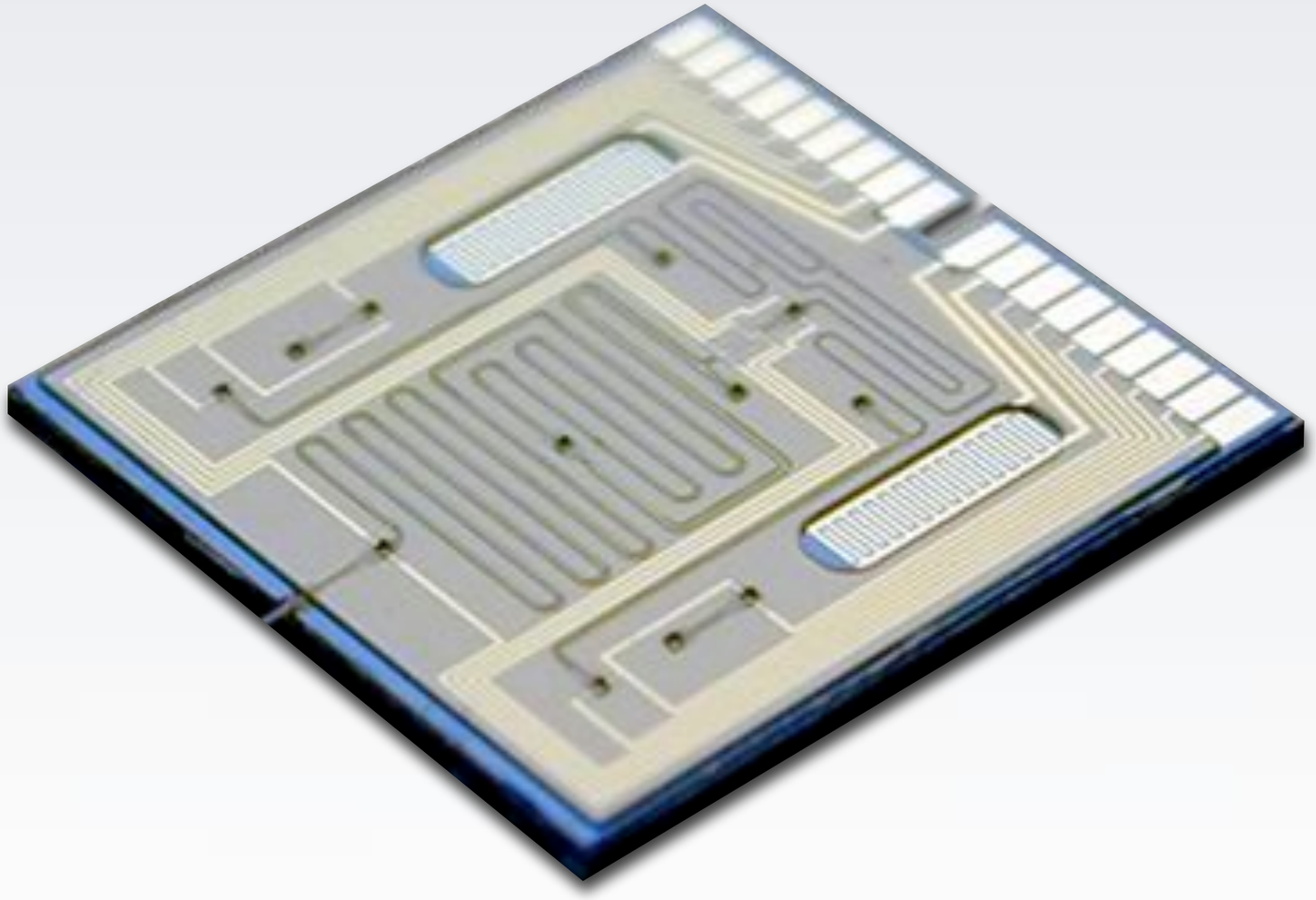
there

I. Sensors

II. Systems & Data

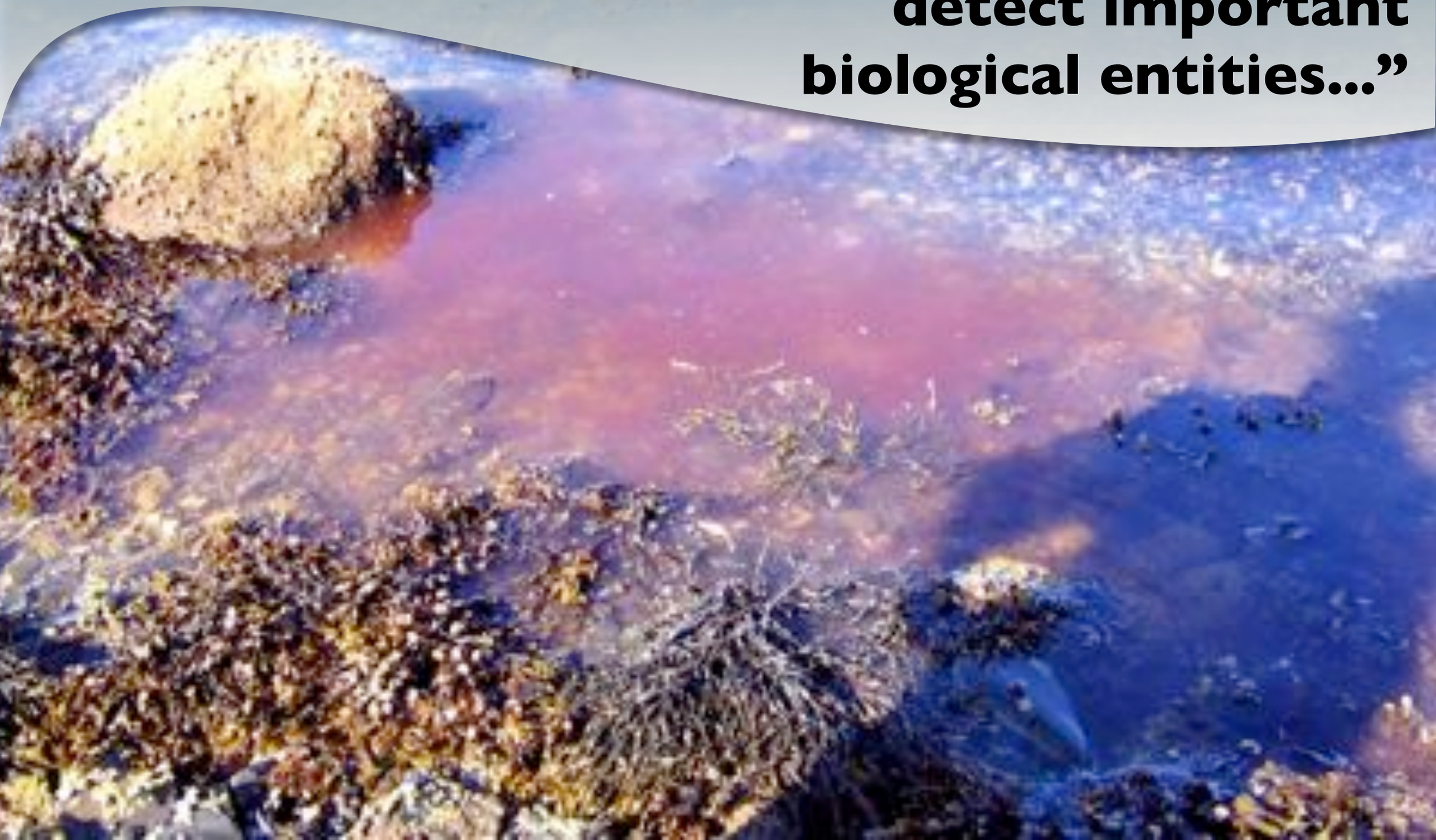
III. Education & Training

1.
Sensors



Long-term research...

"Currently few field-ready sensors can detect important biological entities..."



Short-term development...

existing sensors for harsh field environments

Case Study

A tale of two soil nitrate sensors

	commercial model	research prototype
size	pencil	pencil-lead
cost	$500	??? ($10)
life-span (lab)	months	months
life-span (field)	months	hours
performance	good	good

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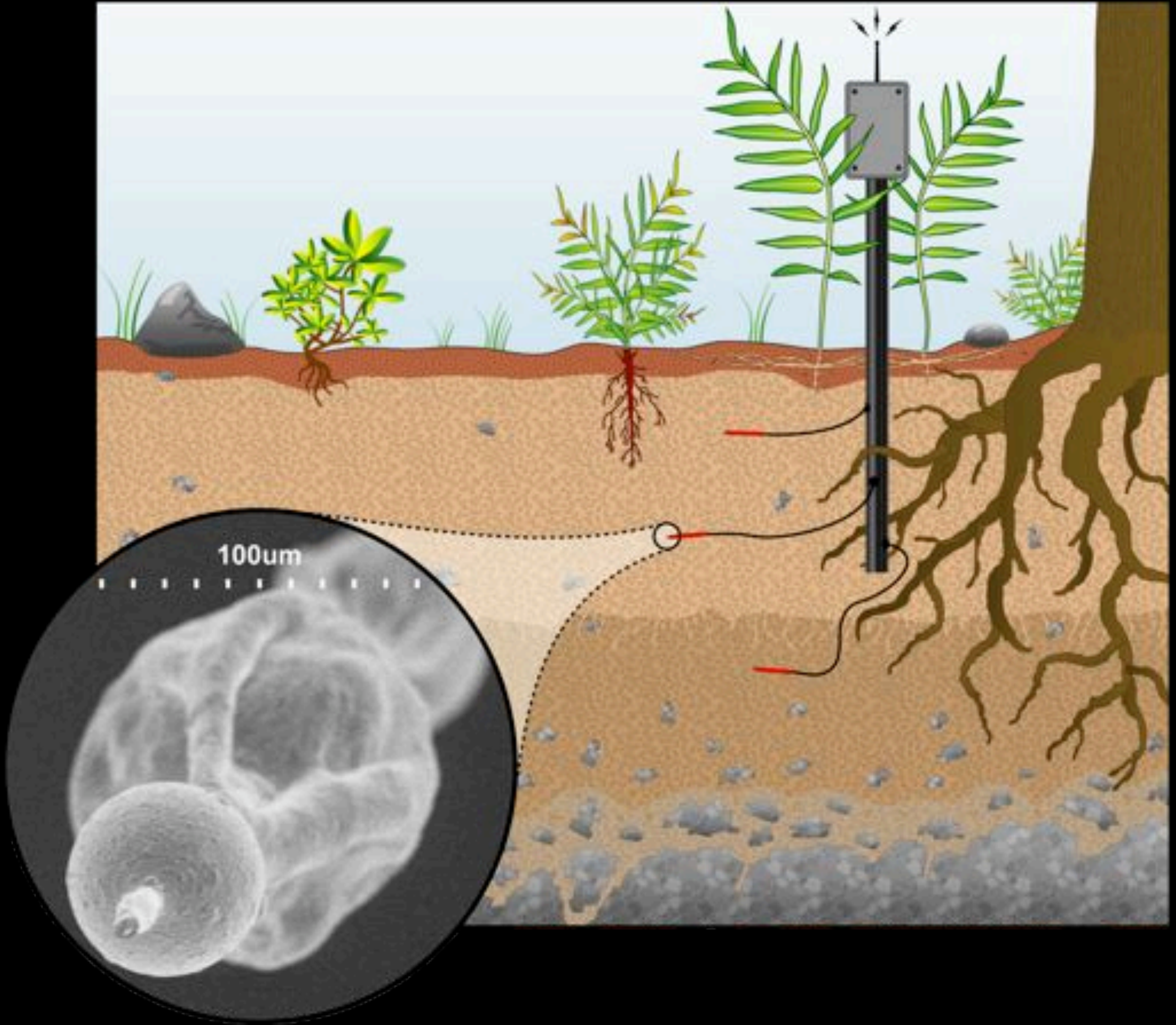
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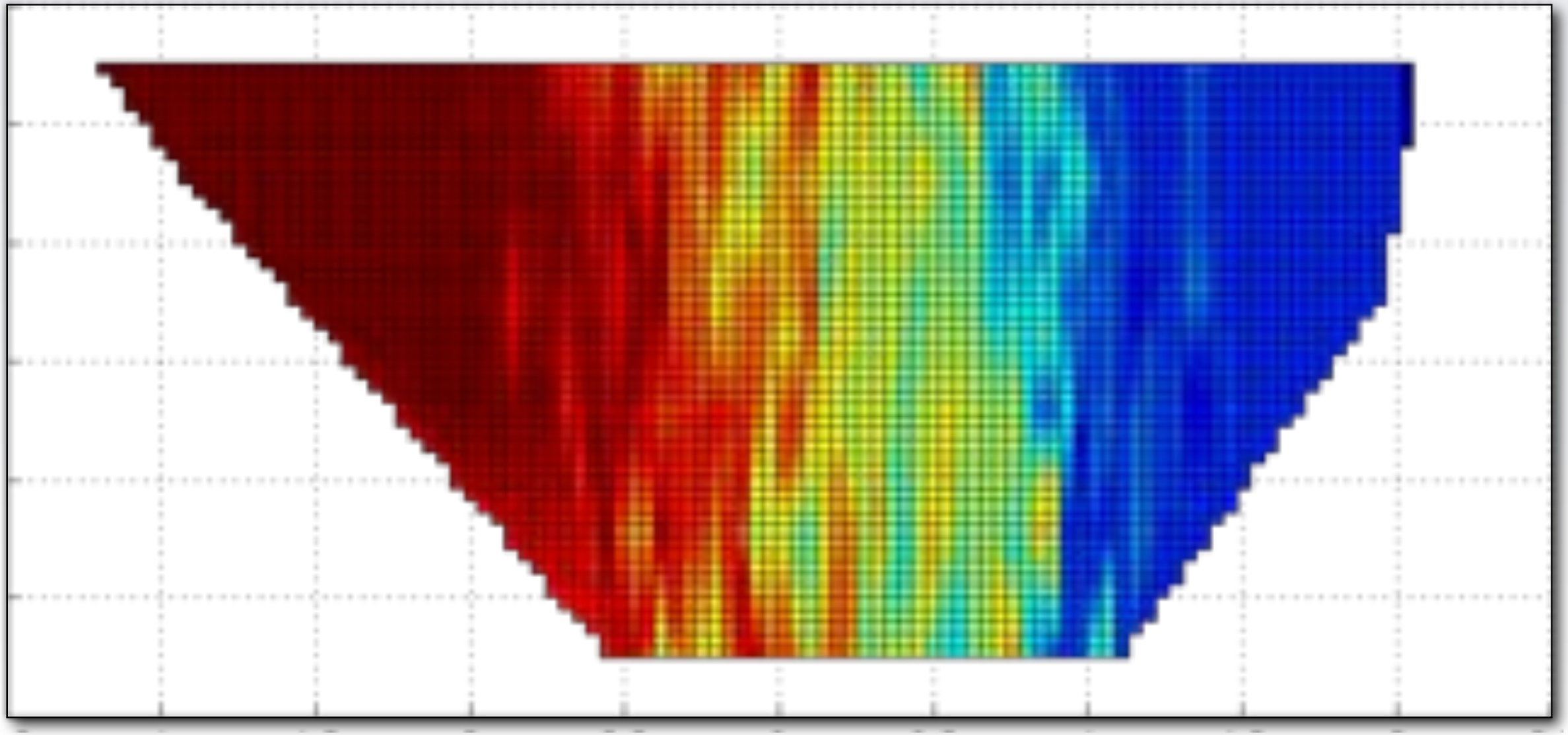
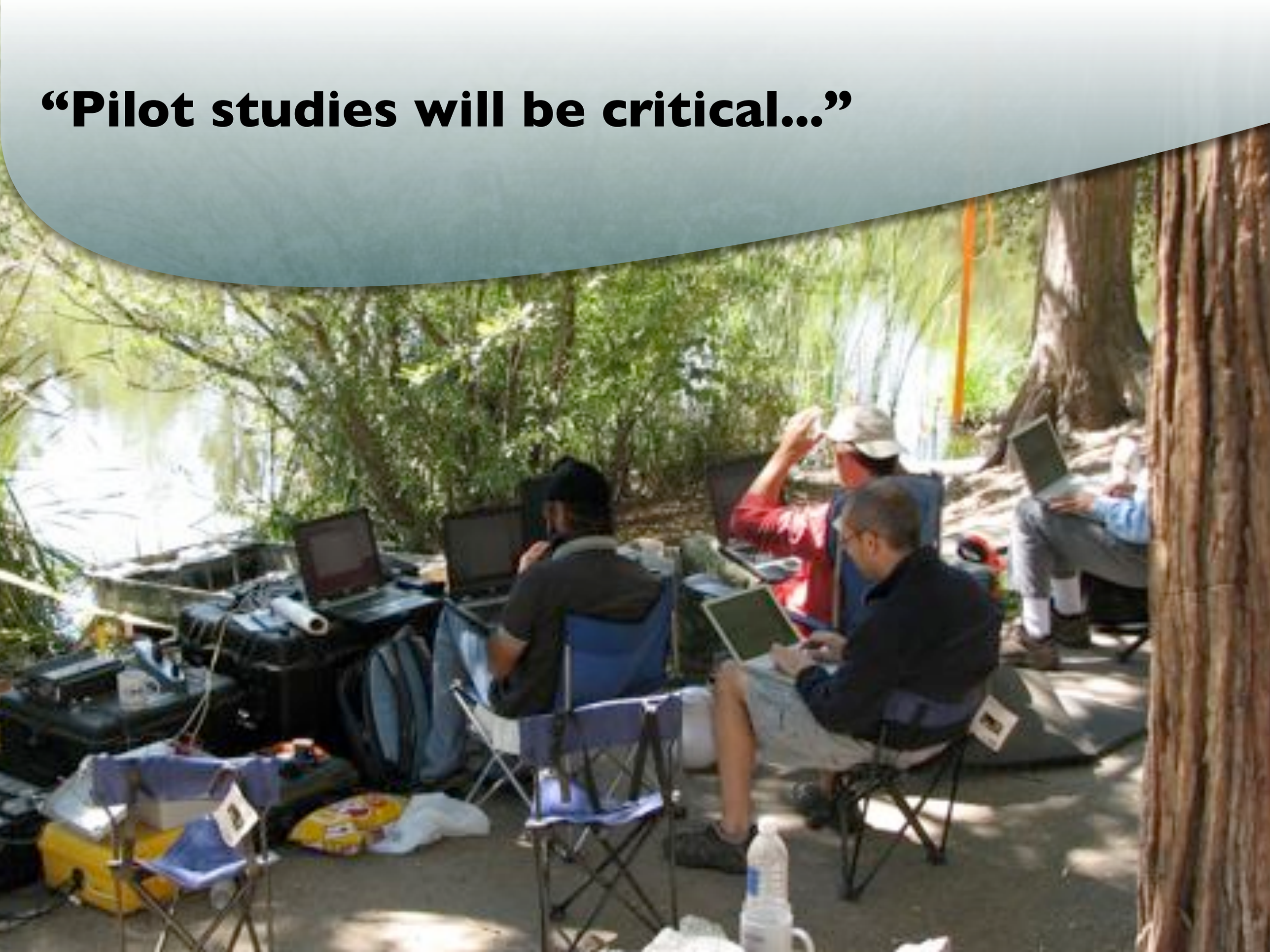
II.
Systems & Data

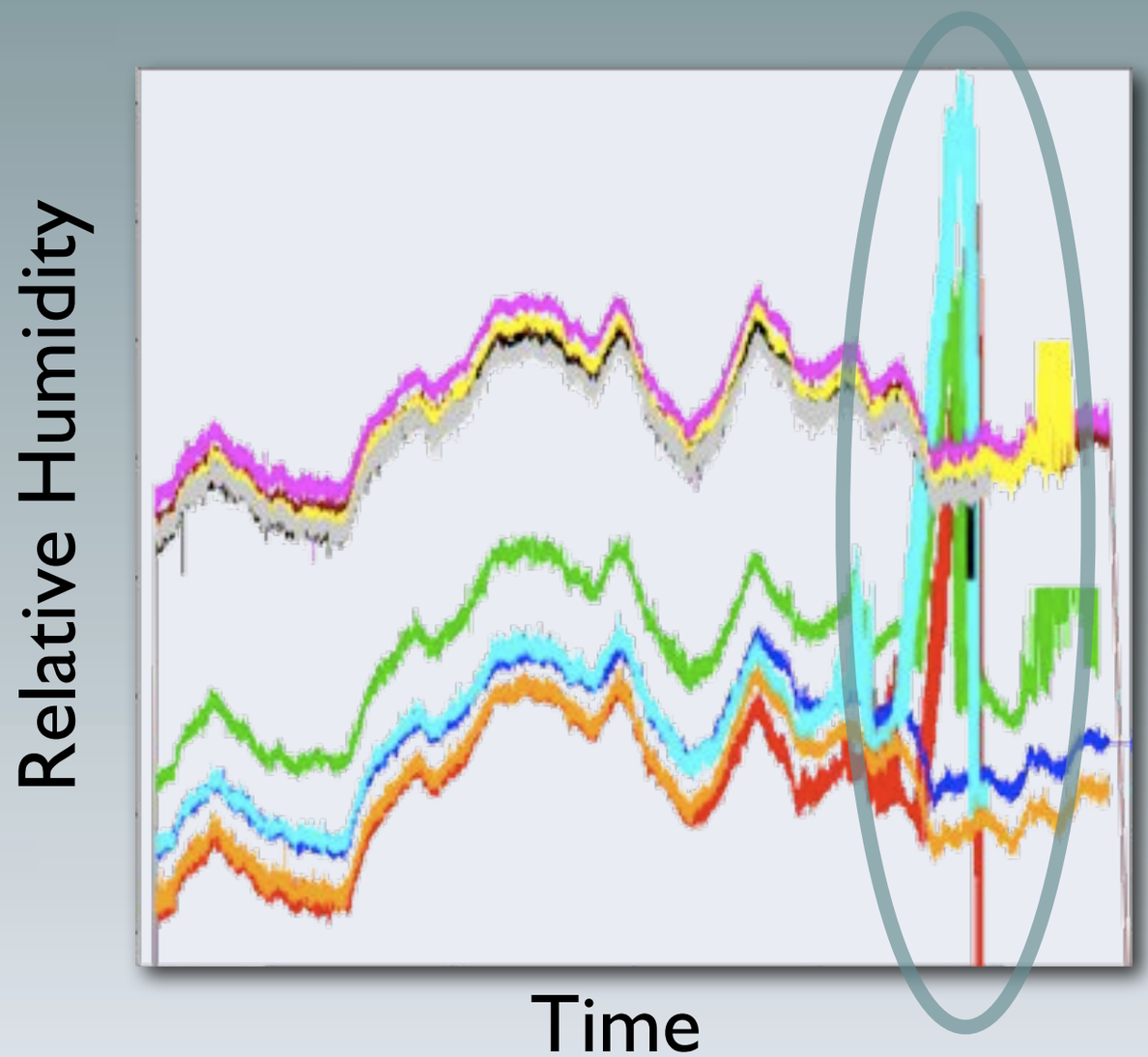


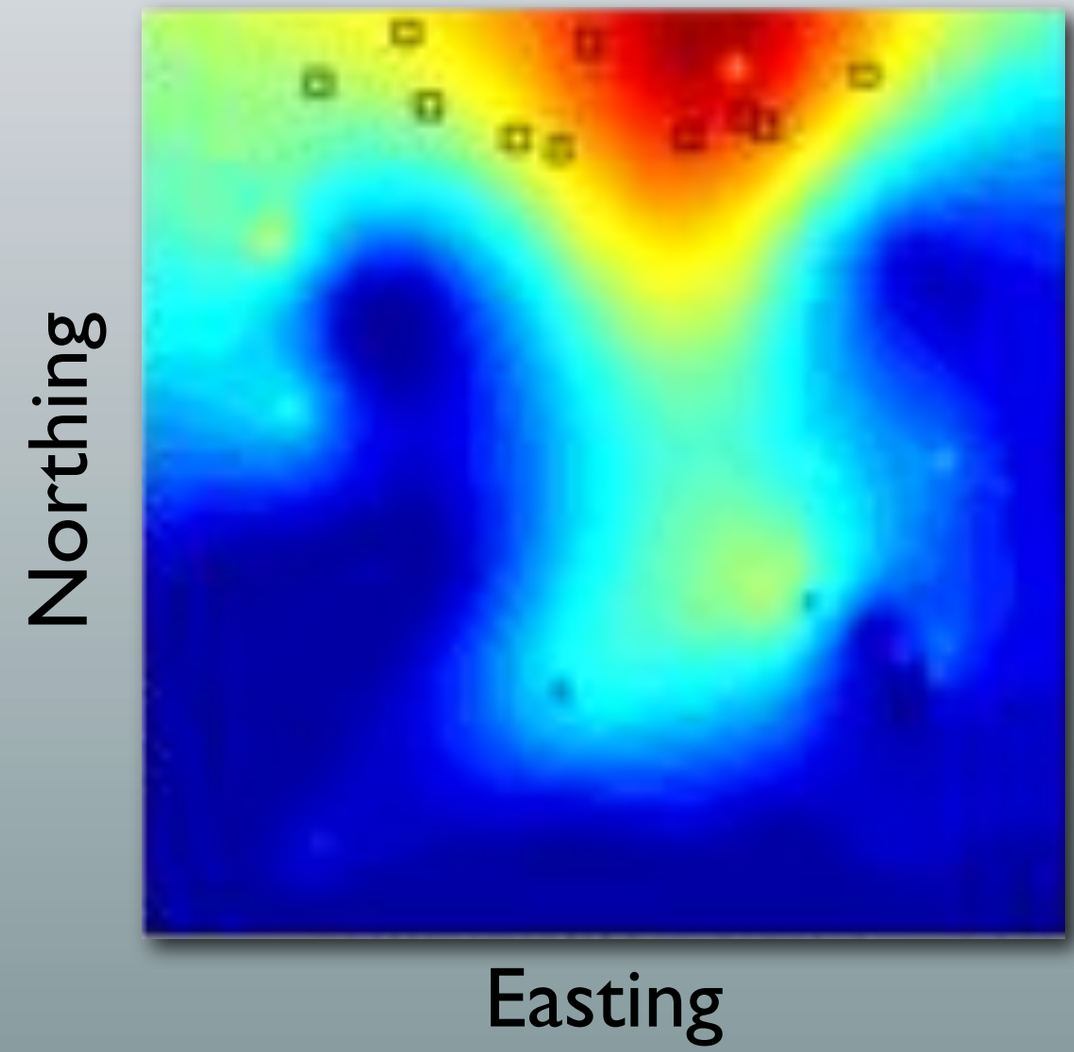
“Pilot studies will be critical...”



challenge

data integrity



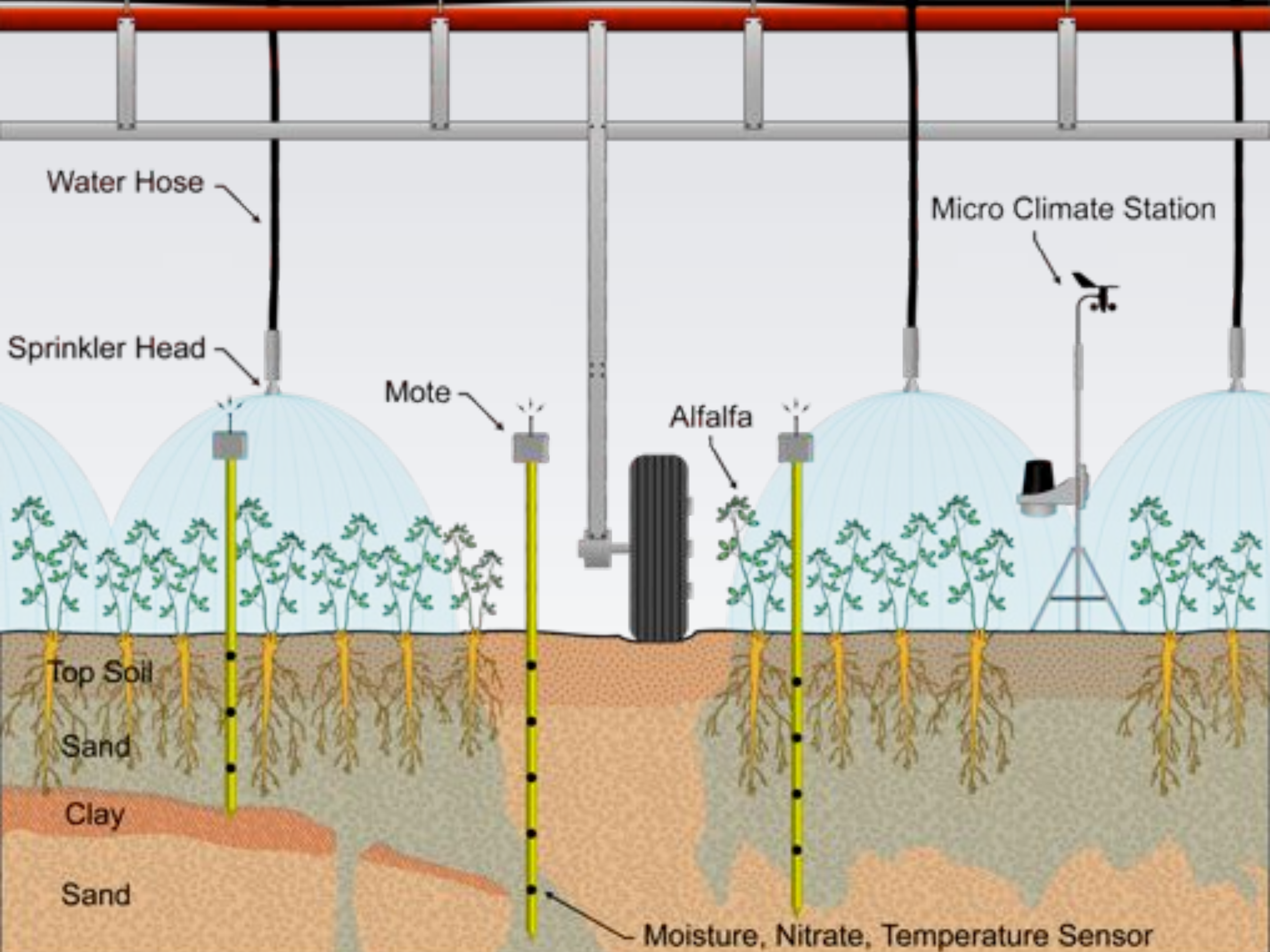


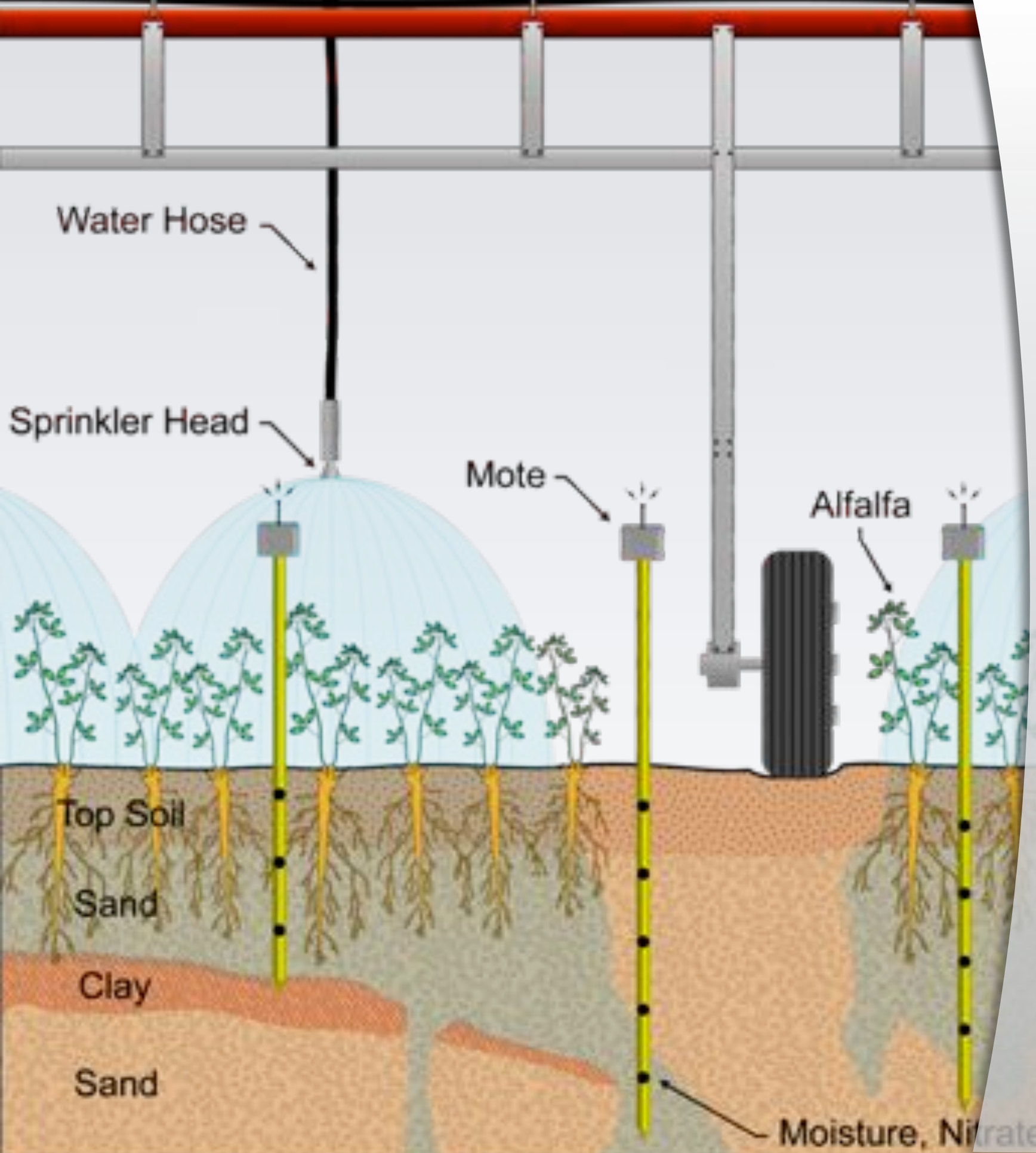
opportunity

modeling & simulation

Case Study

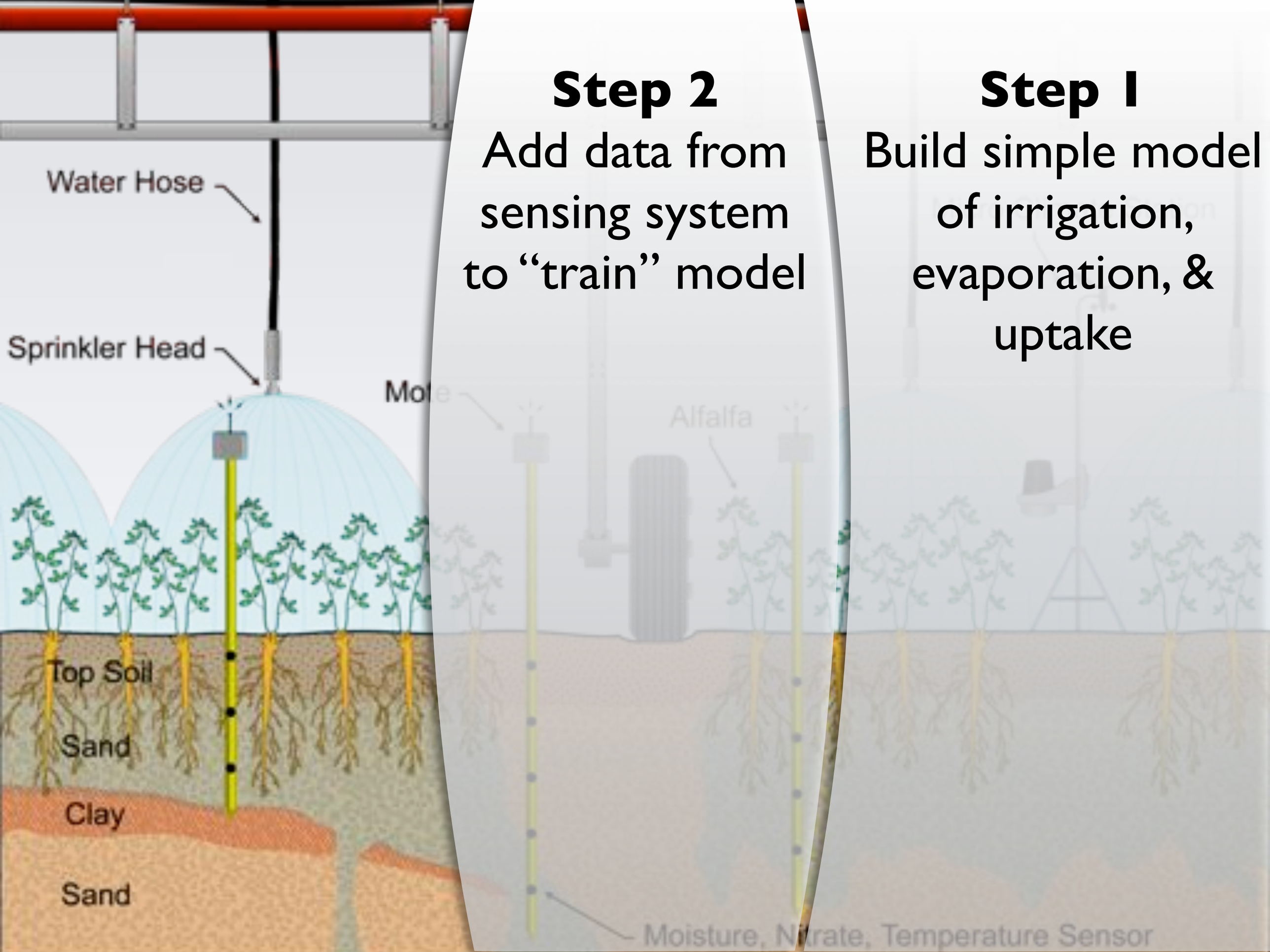
Managing reclaimed wastewater irrigation


Water Hose
Micro Climate Station
Sprinkler Head
Mote
Alfalfa
Top Soil
Sand
Clay
Sand
Moisture, Nitrate, Temperature Sensor



Step 1

Build simple model of irrigation, evaporation, & uptake



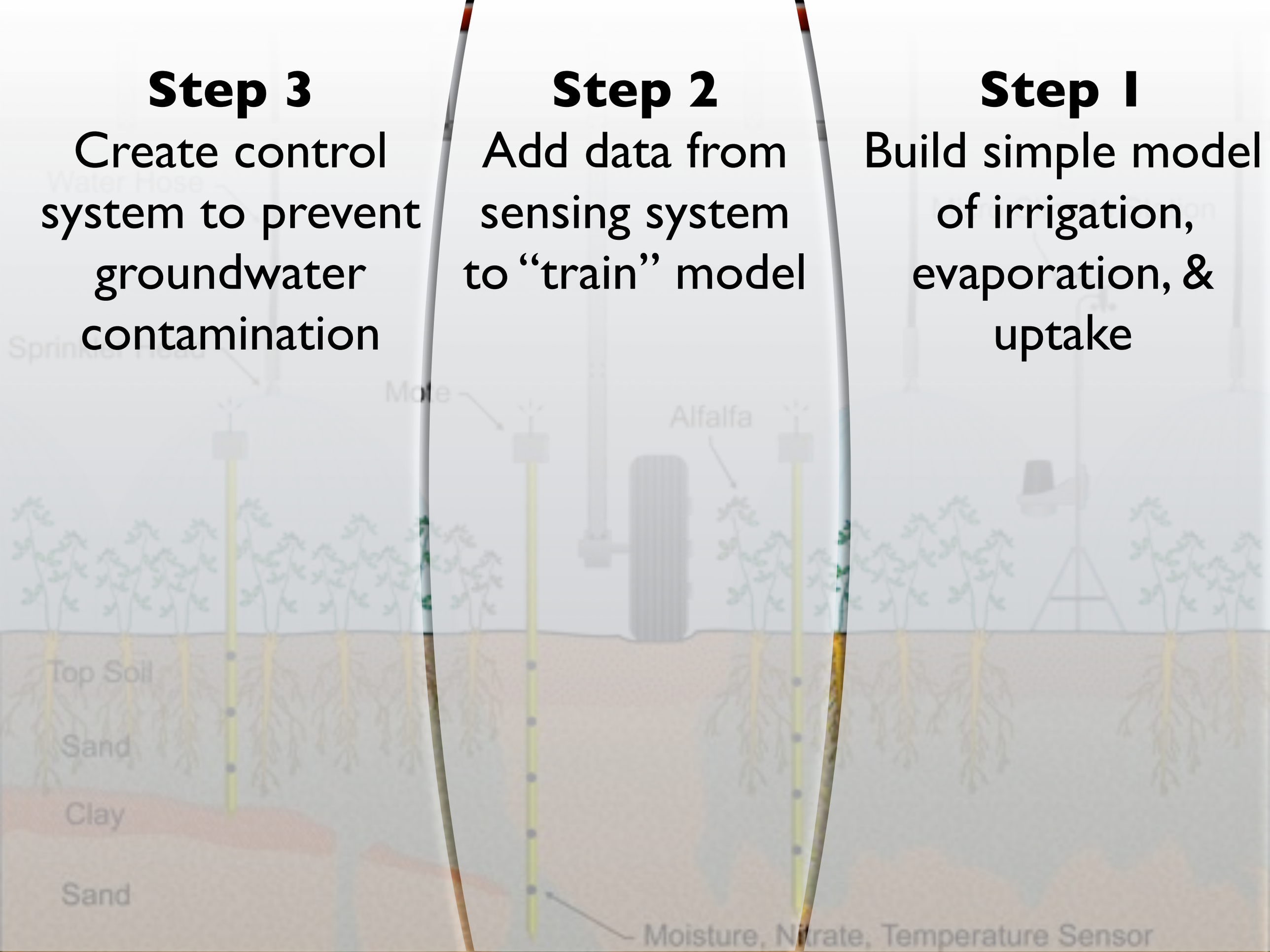
Step 2
Add data from sensing system to "train" model

Step 1
Build simple model of irrigation, evaporation, & uptake

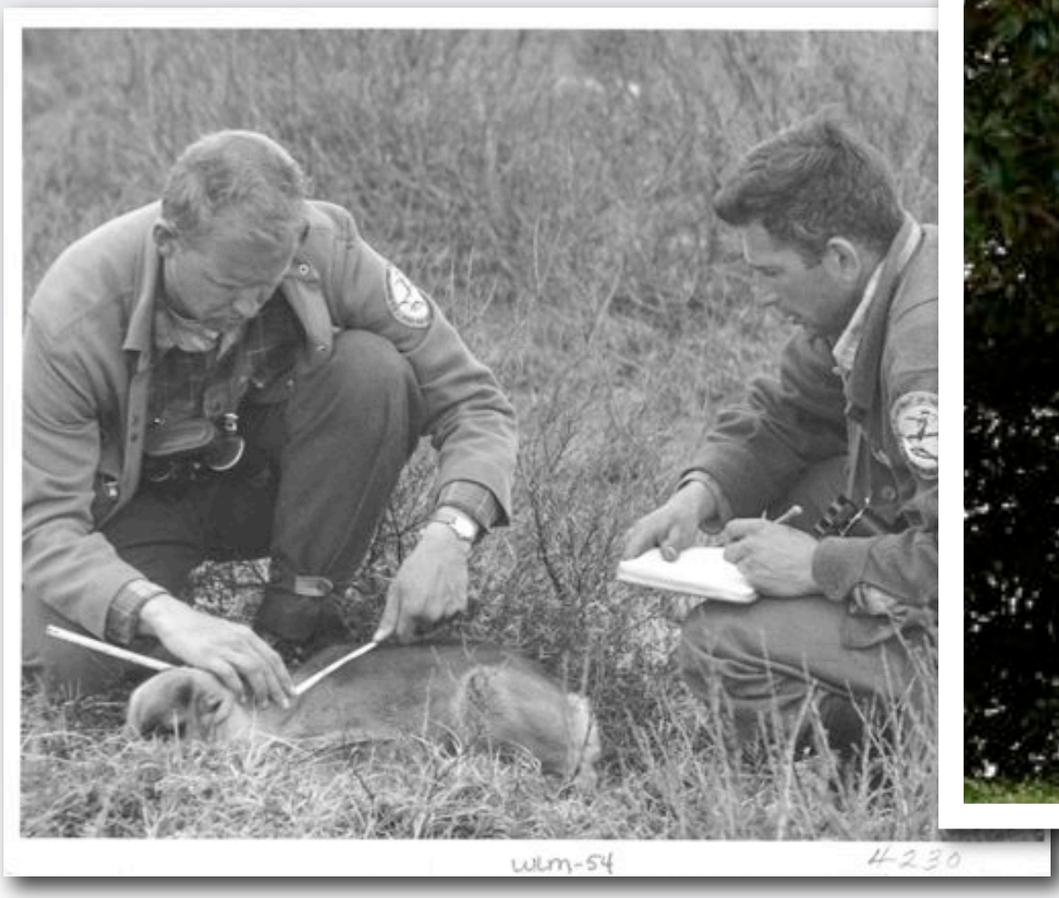
Step 3
Create control system to prevent groundwater contamination

Step 2
Add data from sensing system to "train" model

Step 1
Build simple model of irrigation, evaporation, & uptake

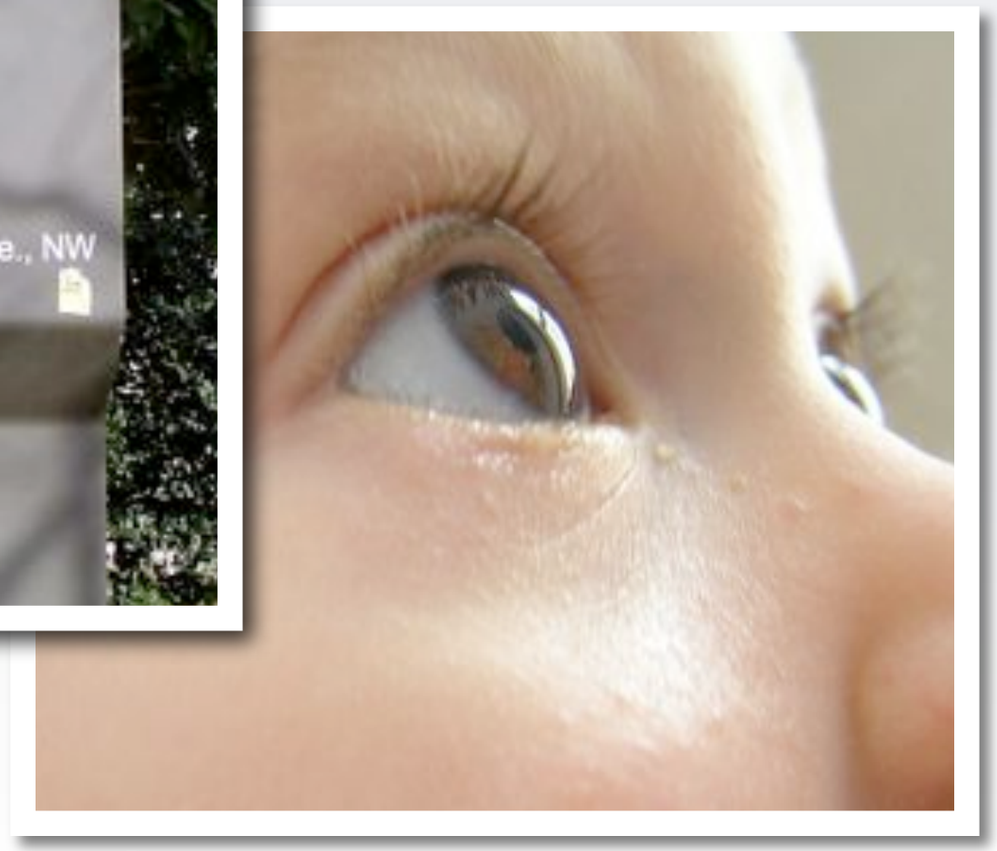


III.
Education & Training



...in the field

...environmental decisionmakers



...the next generation

Review

I. Sensors

- Long term research on detection methods
- Short term development and commercialization of currently viable prototypes

II. Systems & Data

- Real pilot deployments
- Continued research on data quality & incorporation of models

III. Education & Training

- encourage awareness and use of sensing technology at all levels