ZERT Controlled Release Experiment

Lee H. Spangler
Director, ZERT and The Energy Research Institute
Montana State University

Zero Emissions Research & Technology

A collaborative involving Universities and
DOE National Labs

- **Montana State University - Lead Institution**
- **Los Alamos National Laboratory**
- **Pacific Northwest National Laboratory**
- **West Virginia University**
- **Lawrence Berkeley National Laboratory**
- **National Energy Technology Laboratory**
- **Lawrence Livermore National Laboratory**

Montana - A Brief Comparison

Japan

Area: 377,930 km^2

Population **127,078,680**

Germany

Area: 357,021 km^2

Population **82,282,988**

0.7% of world's coal reserves

Norway

Area: 384,802 km^2

Population **4,660,539**

3rd largest oil exporter

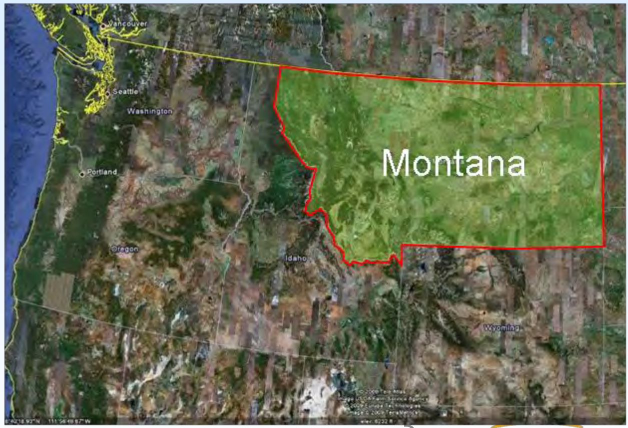
Montana

Area: 380,837 km^2

Population **967, 440**

6% of world's coal reserves

Significant Oil & Gas



Near – Surface Monitoring Zones

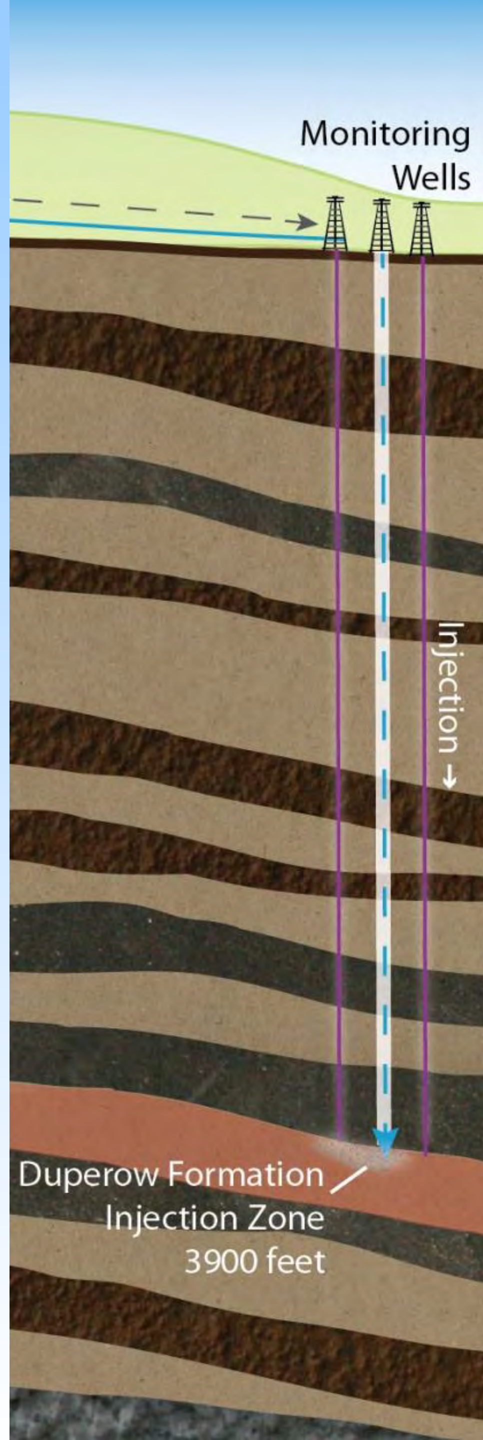
Atmosphere

Biosphere

Soil
(Vadose & Shallow
Saturated Zones)

Caprock &
Deep Overburden

Injection Zone



- **Atmosphere**
  - Ultimate Integrator
  - Dynamic
  - Monitoring & Modeling
- **Biosphere**
  - dynamic
  - requires protection
  - opportunity for wide area monitoring but indirect methods
- **Soil**
  - Integrates
  - dynamic
- **Aquifers**
  - Integrates
  - Requires protection

Motivation (2006)

The situation in 2006 when we started planning the work:

- **Near-surface detectors were considered highly desirable for public assurance**
- **They had been deployed at sequestration pilot sites**
- **These pilot sites were well chosen and do not leak**
- **Thus, the near-surface detection techniques had not been adequately tested under realistic conditions**
- **The primary initial purpose was detection verification**

Facility Goals

- Develop a site with known injection rates for testing near surface monitoring techniques
- Use this site to establish detection limits for monitoring technologies
- Use this site to improve models for groundwater – vadose zone – atmospheric dispersion models
- Develop a site that is accessible and available for multiple seasons / years

Scaling

Imagine a realistic feature that might result in leakage

We chose to mimic a fault which might be on the order of 1 km long with a surface expression of 10m – 100m in width.

A 100m horizontal well would be 10% of the first case and 1% of the second case.

Scaling by a factor of 10 – 100 is a reasonable extrapolation

Sally Benson Lee Spangler

What Are Relevant Release Rates?

- 4 Mt/year injection from 500 MW power plant
- 50 years injection - Total of 200 Mt Injected
- Consider maximum leakage rates discussed to mitigate climate change
  - 1% over 100 years = 0.01% / year = 0.0001
  - 1% over 1000 years = 0.001% / year = 0.00001
- 200,000,000 x 0.00001 = 2,000 Tonnes / yr
- 5.5 Tonnes / Day
- This is the equivalent of about 85 idling cars

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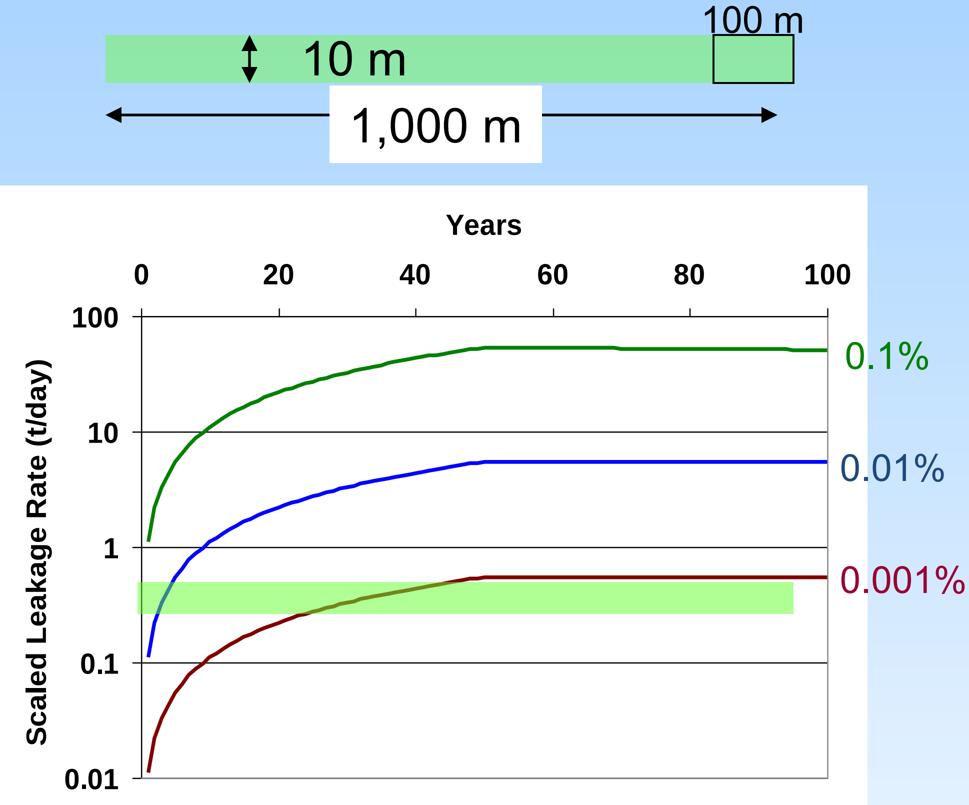
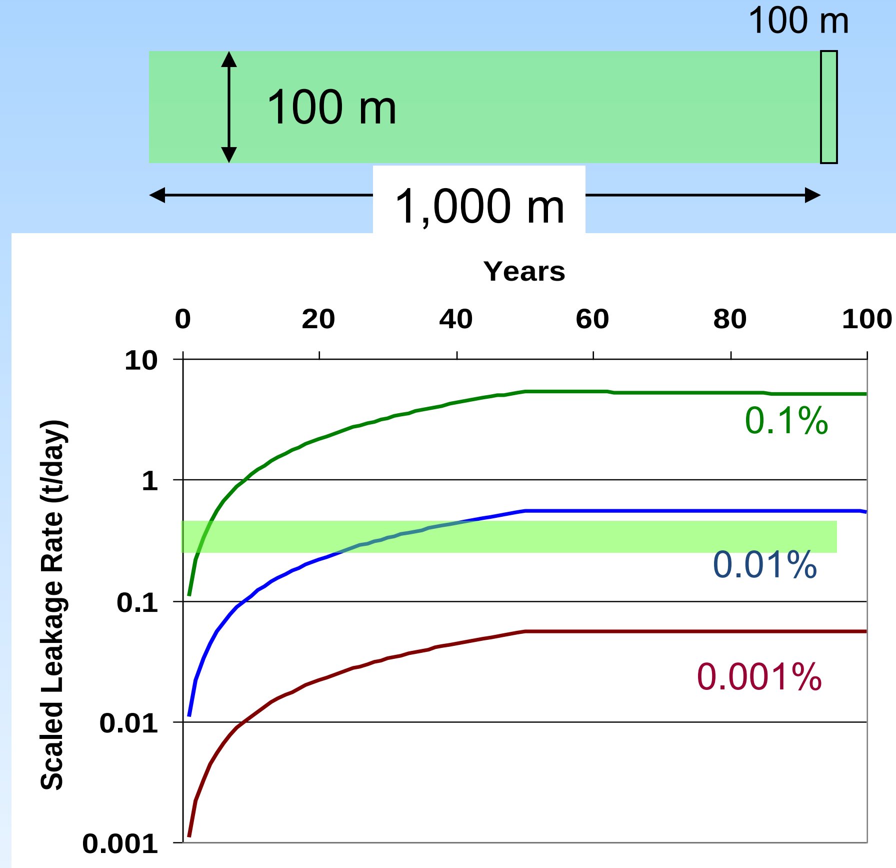
Injection Rate

Sally Benson Lee Spangler



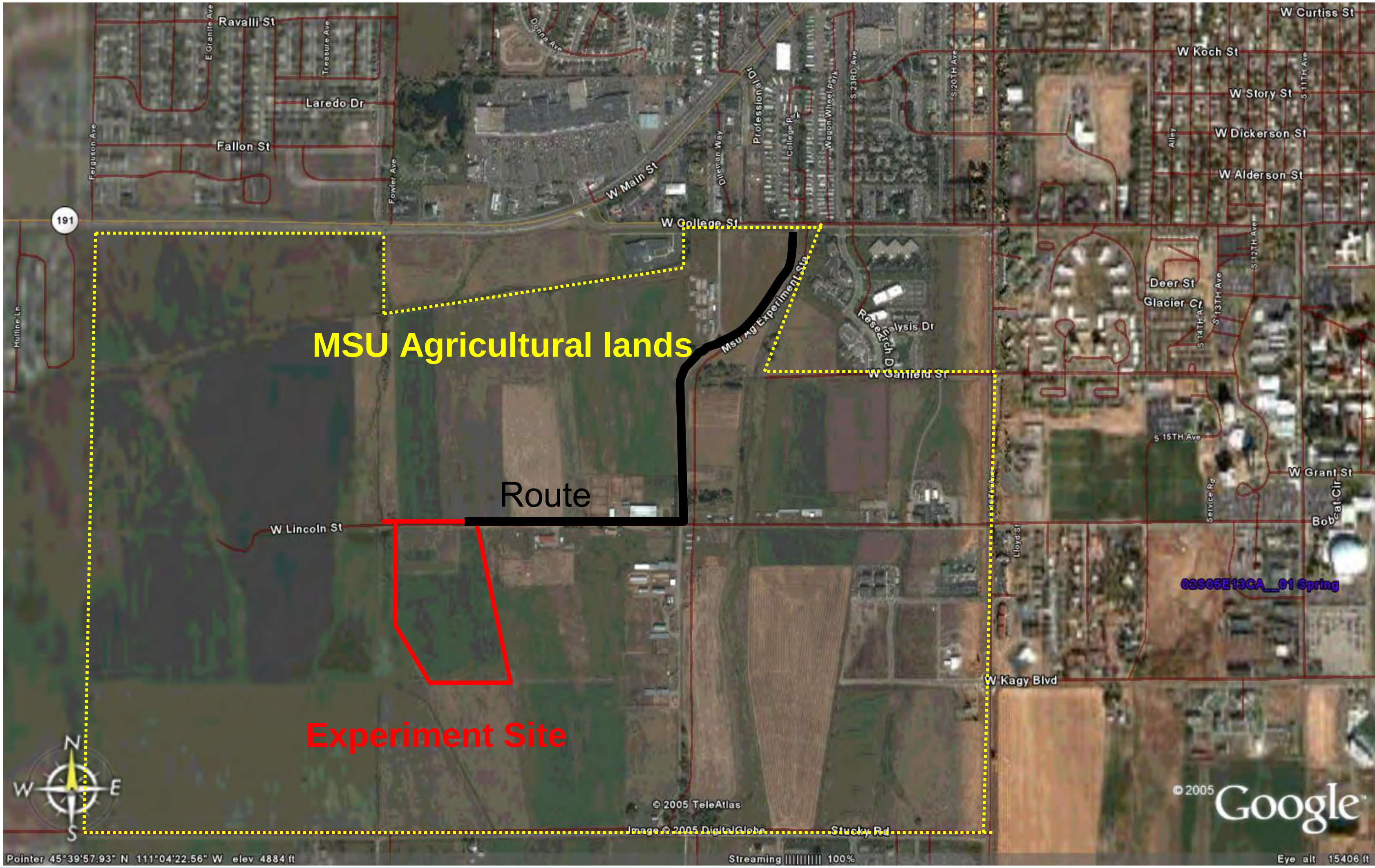
Scale to 1000 m leak
1,000 kg/day: 1 tonne/day



We used a 0.15 Tonne / Day rate

An idling car generates about 0.04545 kg CO_2 / min or 64.5 kg CO_2 / day. **Our injection rate is about equal to 2.3 idling cars**

Field Test Facility



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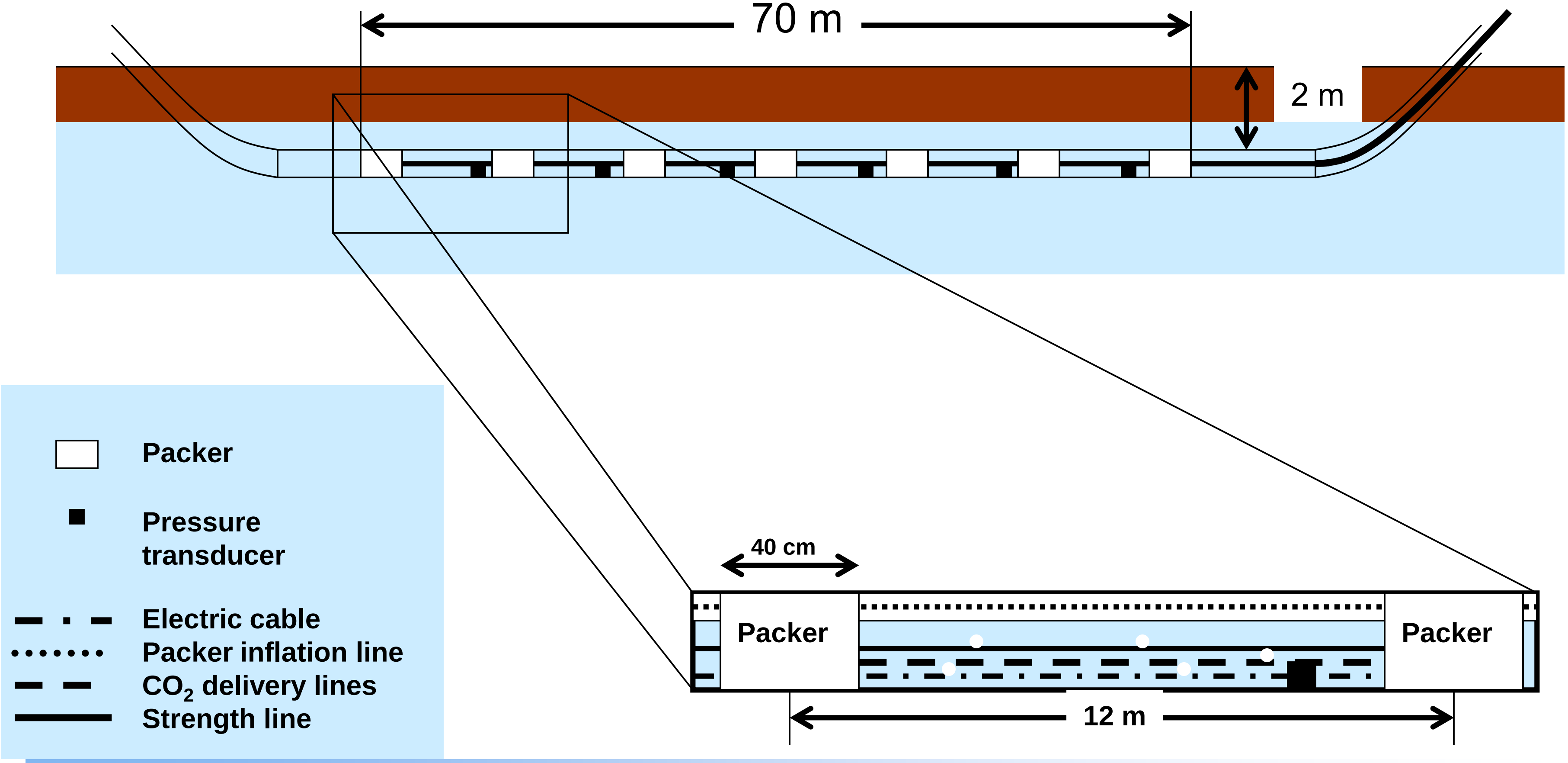
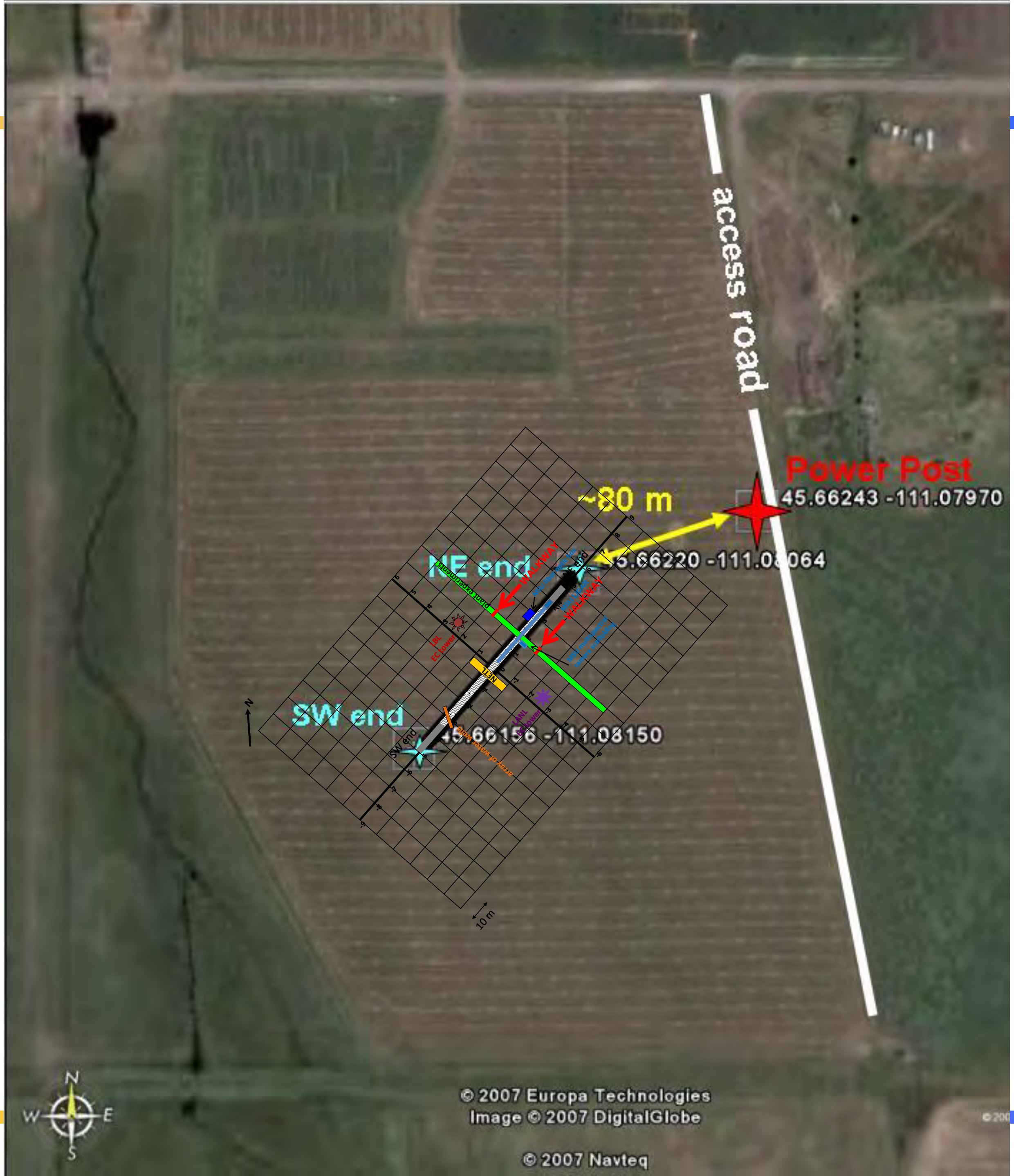
MONTANA STATE UNIVERSITY · Los Alamos NATIONAL LABORATORY EST. 1943 · Pacific Northwest National Laboratory Celebrating 40 Years of Science & Discovery 1965-2005 · West Virginia University · NETL · BERKELEY LAB

Horizontal Well Installation

Ray Solbau, Sally Benson

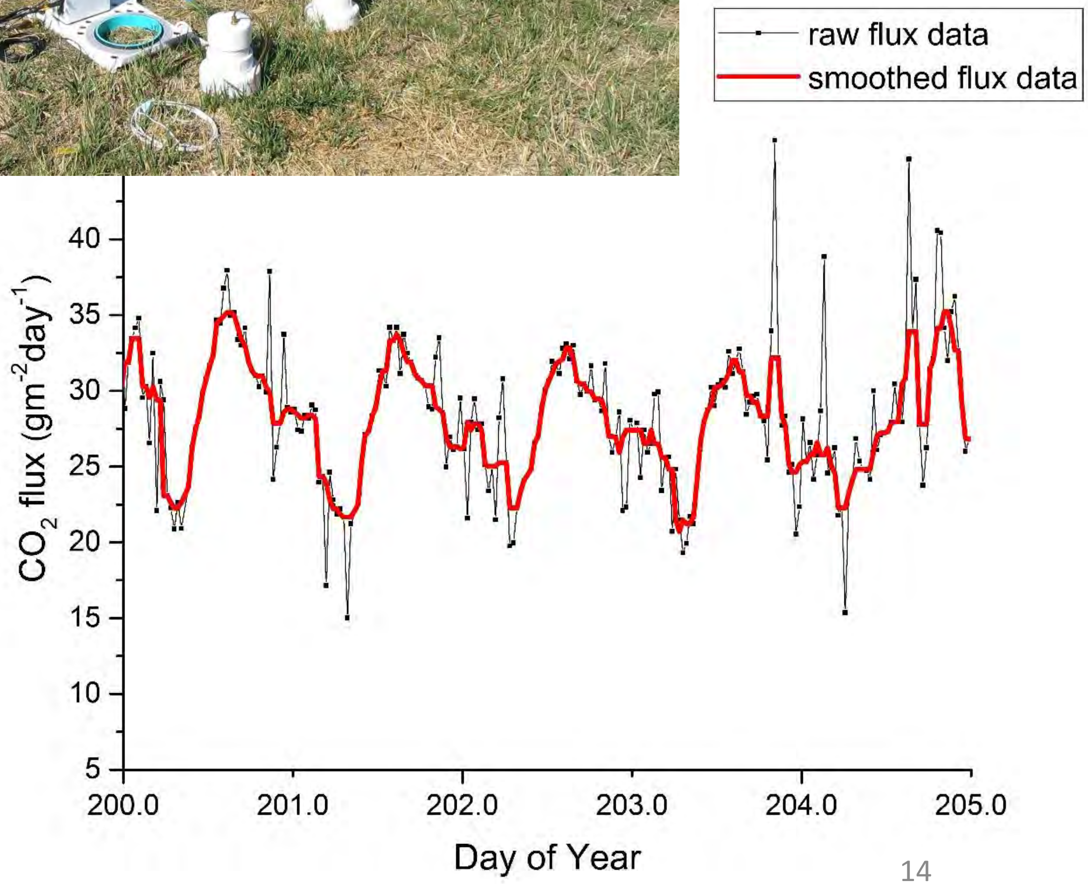



access road
Power Post
45.66243 -111.07970
~80 m
NE end
45.66220 -111.08064
SW end
45.66156 -111.08150
10 m
N
W
E
S
© 2007 Europa Technologies
Image © 2007 DigitalGlobe
© 2007 Navteq

Methods

- Soil Gas Monitoring
- In-situ soil gas probes
- Eddy Covarience
- Soil Flux chambers
- Differential Absorption LIDAR
- Cavity ring-down, other isotopic measurements
- Water chemistry
- Tracers
- Hyperspectral / mutispectral imaging
- Many more

CO_2 Background is Highly Variable

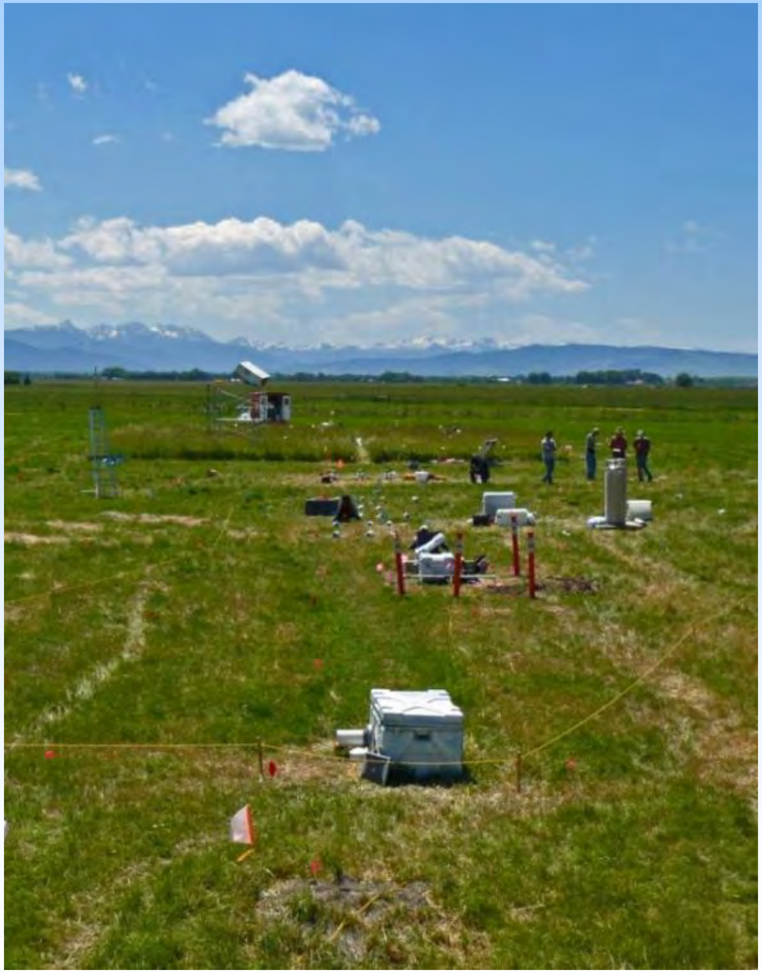


Affected by sunlight, precipitation, wind, etc. Red line shows diurnal variation, but there are also short term and much longer term variations

ZERT Zero Emissions Research and Technology

Large Number of Participants / Methods

47 investigators
31 instruments / sensor arrays
5 univ. 6 DOE labs, 4 companies



Investigator	Institution	Monitoring Technology	Number of Sensors
Arthur Wells Rod Diehl Brian Strasizar	National Energy Technology Laboratory	Atmospheric tracer plume measurements	1 tower (4m) Blimp (Apogee Scientific) with 3 tether line samplers
		Bee hive monitoring for tracer with sorption tube and pollen trap	2 hives
		Automated Soil CO_2 flux system	4 chambers
William Pickles Eli Silver Erin Male	University of California- Santa Cruz	Hand held hyperspectral measurements (plant health)	1 instrument
Yousif Kharaka James ThordsenGil AmbatsSarah Beers	United States Geological Survey*	Ground water monitoring	1 EC and temperature probe, Dissolved oxygen probe, lab analysis of water samples
Henry Rauch	West Virginia University	Water monitoring well headspace gas sampling	1 sensor
Lucian Wielopolski Sudeep Mitra	Brookhaven National Laboratory*	Ineleastic neutron scattering (total soil carbon)	1 instrument
Martha Apple Xiaobing Zhou Venkata Lakkaraju Bablu Sharma +2 students	Montana Tech*	Soil moisture, temp. Chlorophyll Content Meter , Fluorescence Meter , LI-COR 2000 to measure leaf area index Leaf Porometer to measure stomatal conductance	5 sensors
		Infrared radiometry (plant health)	2 instruments
		Atmospheric humidity and temperature, accumulated rainfall	1 sensor each
		Plant root imaging	1 camera
		Soil conductivity	1 sensor
		Handheld hyperspectral measurements (plant health)	1 instrument
William Holben Sergio Morales	University of Montana*	Microbial studies	Lab analysis

ZERT Zero Emissions Research and Technology

Large Number of Participants / Methods

Investigator	Institution	Monitoring Technology	Number of Sensors
Lee Spangler Laura Dobeck Kadie Gullickson	Montana State University	Water content reflectometers (soil moisture)	15 sensors
		Automated soil CO_2 flux system	5 long term chambers, 1 portable survey chamber
		CO_2 soil gas concentration	6 sensors
Kevin Repasky (PI) Jamie Barr	Montana State University	Underground fiber sensor array (CO_2 soil gas concentration)	4 sensors
Rand Swanson	Resonon*	Flight based hyperspectral imaging system	1instrument
Joseph Shaw (PI) Justin Hogan Nathan Kaufman	Montana State University	Multi-spectral imaging system (plant health)	1instrument
		Meteorological measurements	1 tower
Julianna Fessenden +3 students	Los Alamos National Laboratory	In situ (closed path) stable carbon isotope detection system	1 instrument
		Flask sampling for in situ isotope detection	Lab analysis
Sam Clegg Seth Humphries	Los Alamos National Laboratory	Frequency-modulated spectroscopy (FMS) open-air path	1 instrument
Thom Rahn	Los Alamos National Laboratory	Eddy covariance	1 tower
James Amonette Jon Barr	Pacific Northwest National Laboratory	Soil CO_2 flux (steady-state)	27 chambers
Sally Benson (PI) Sam Krevor Jean-Christophe Perin Ariel Esposito Chris Rella (Picarro)	Stanford University* / Picarro Instruments*	Commercial cavity ringdown real-time measurements of $\delta^{13}C$ and CO_2 in air	1 instrument
Greg Rau Ian McAlexander (LGR)	Lawrence Livermore National Laboratory /Los Gatos Research*	Commercial cavity ringdown real-time measurements of $\delta^{13}C$ and CO_2 in air	1 instrument
Jennifer Lewicki	Lawrence Berkeley National Laboratory	CO_2 soil gas concentration	8 sensors
		CO_2 atmospheric concentration	2 sensors
		Chamber soil CO_2 flux measurements	1 instrument
		Meteorological	1 tower

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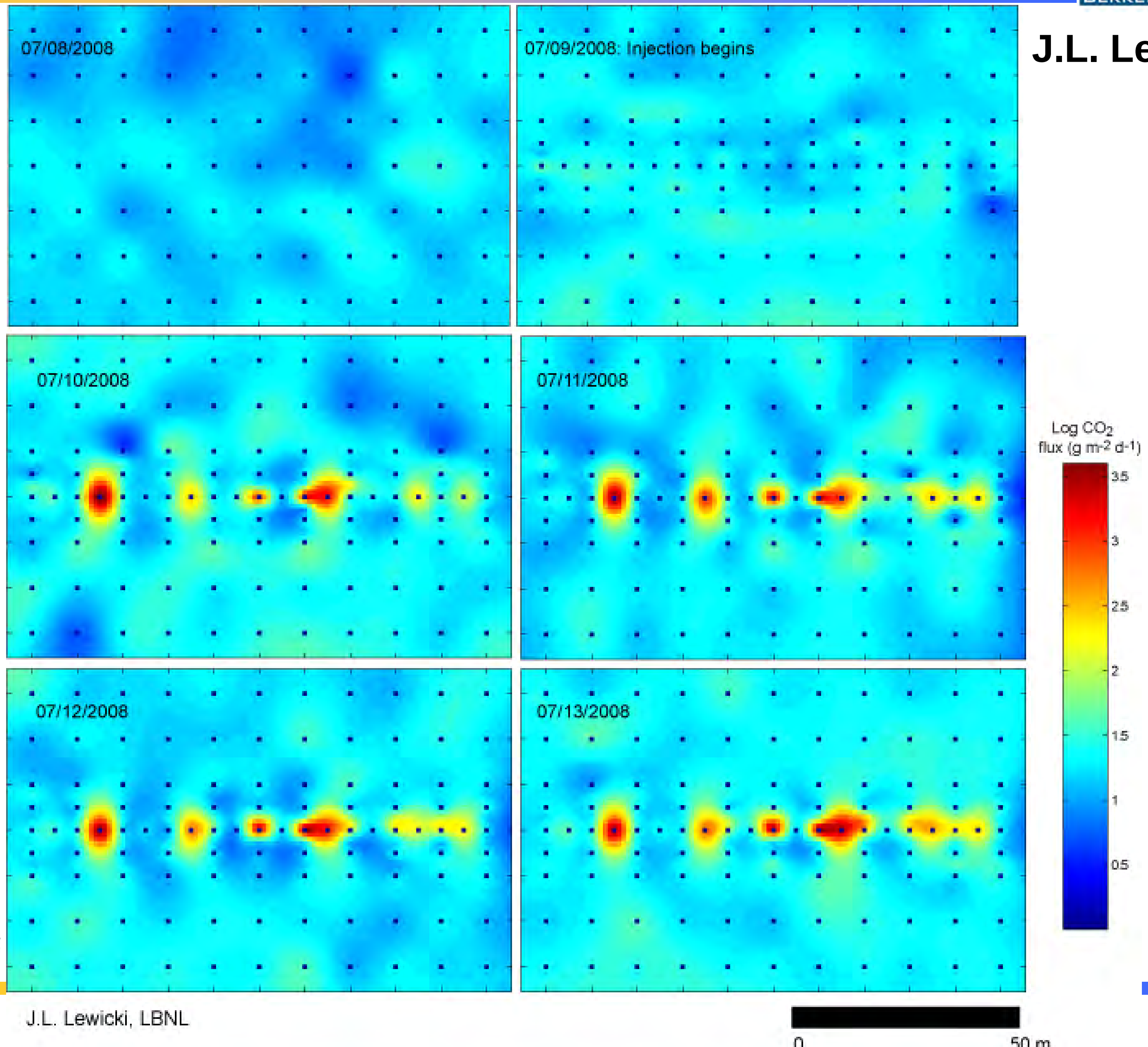
Flux Chamber

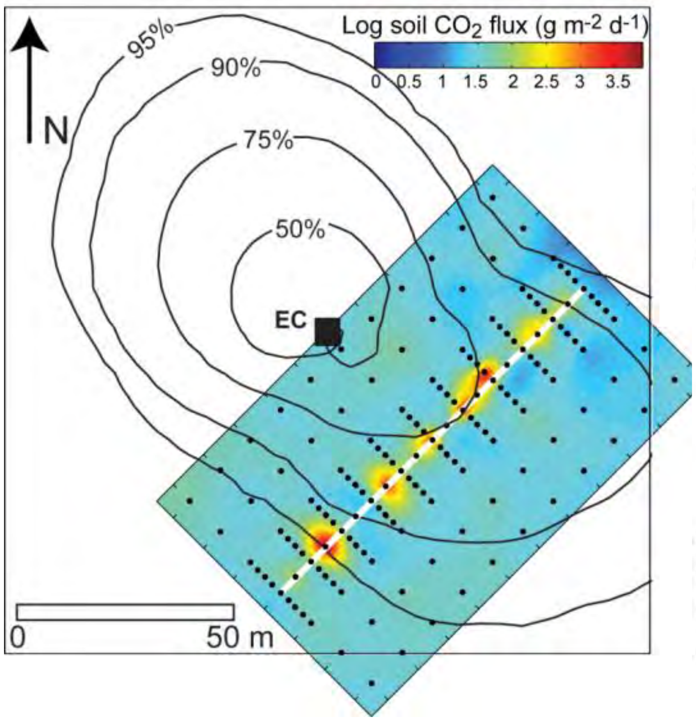
J.L. Lewicki



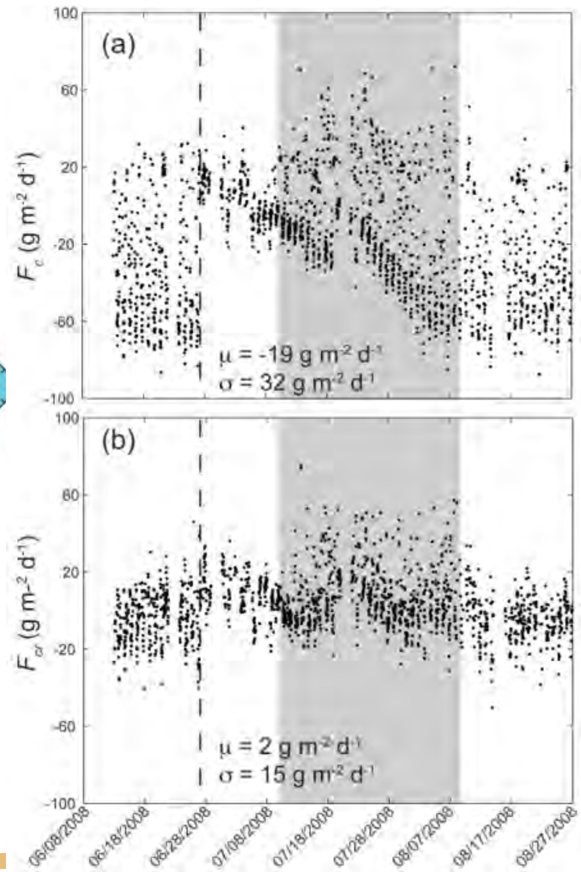
Eddy covariance net CO_2 flux monitoring

J. Lewicki (LBNL)

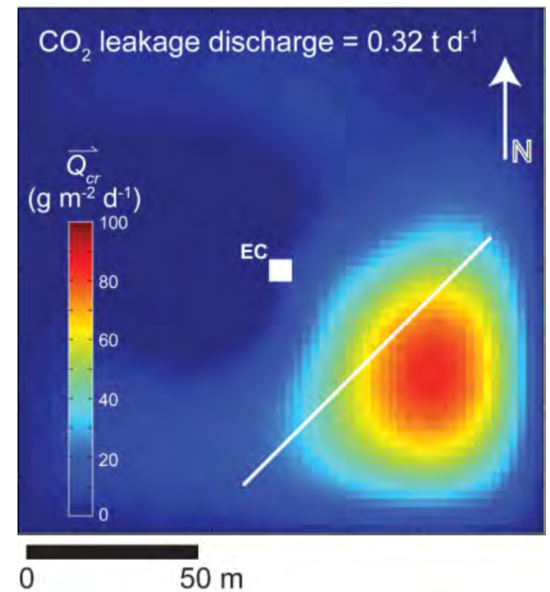
An eddy covariance (EC) station was deployed ~30 m NW of the release well in 2006, 2007, and 2008.



In 2008 (0.3 t CO_2 d^{-1} for 1 month) leakage signal was detected in raw EC CO_2 flux (F_c) data. Ecosystem CO_2 fluxes were modeled and removed from F_c to improve signal detection in residual flux (F_{cr}) data.



A least-squares inversion of measured residual CO_2 fluxes and corresponding modeled footprint functions during the 2008 release modeled the distribution of surface CO_2 fluxes, allowing us to locate and quantify (to within 7%) the leakage signal.

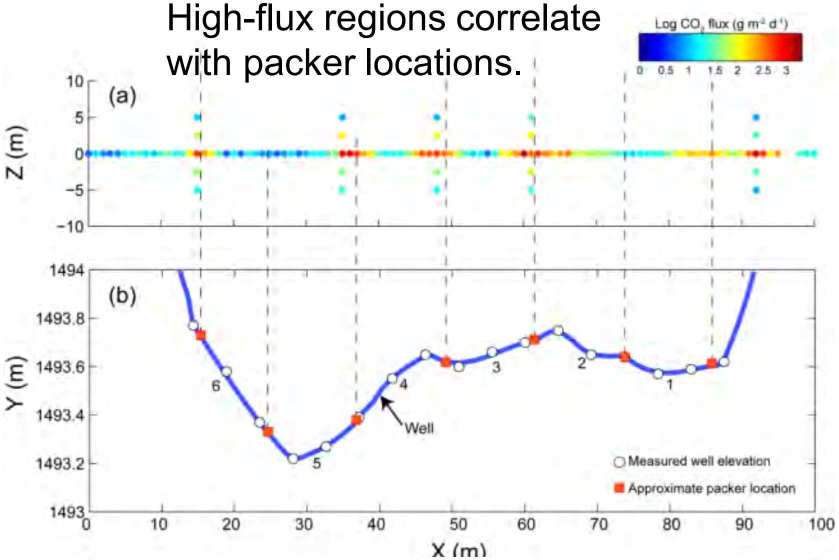


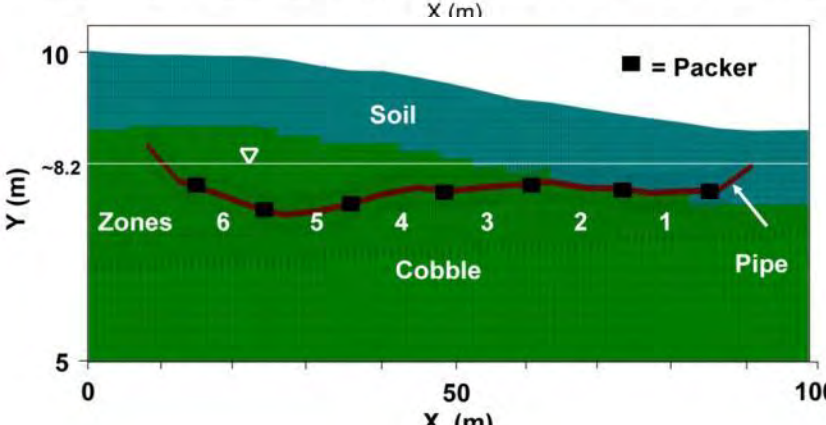
Shallow CO_2 Flow Modeling (1)

C. Oldenburg (LBNL)

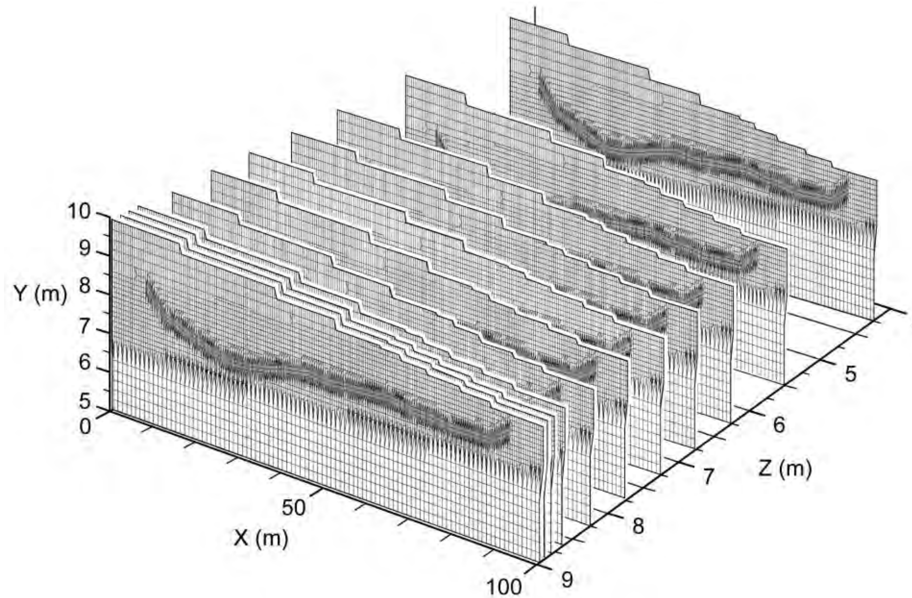
TOUGH2/EOS7CA was used to address the origin of patchy emissions at the ZERT shallow-release experiment.

High-flux regions correlate with packer locations.





A three-dimensional grid (3D) was developed that captures the changes in elevation of the pipe.



3D longitudinal grid with 52,569 gridblocks (4779 gridblocks per XY-plane).

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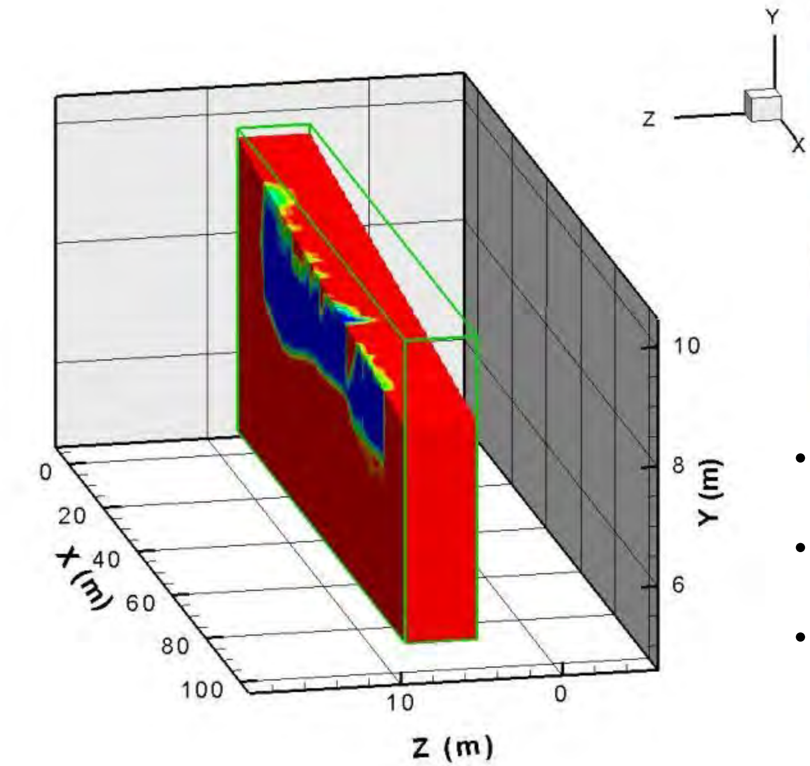
Shallow CO_2 Flow Modeling (2)

C. Oldenburg (LBNL)

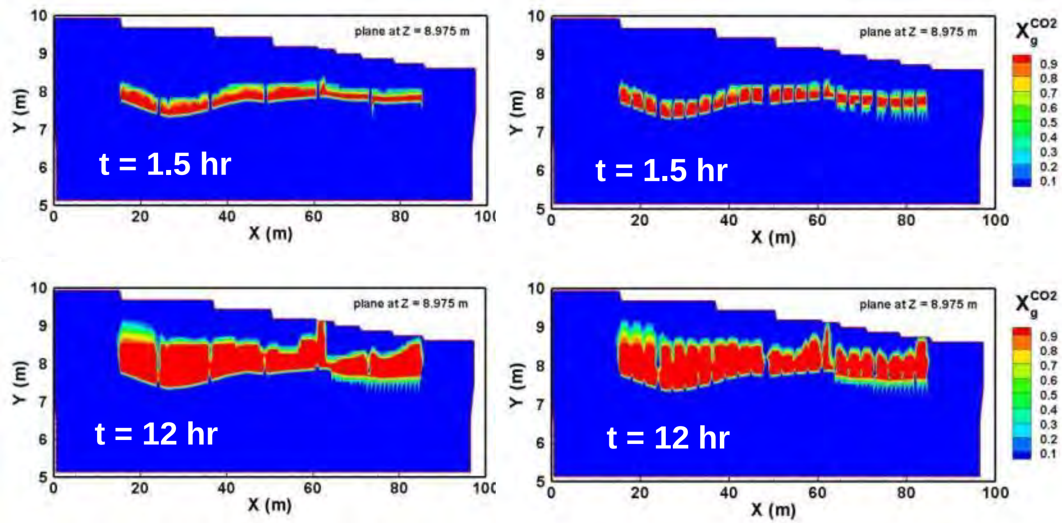
Results suggest that packer locations influence emission patterns.

q_{CO2} = 100 kg CO_2/day

Three-dimensional results of X_g^{CO2} at t = 3 days showing patchy emission pattern.

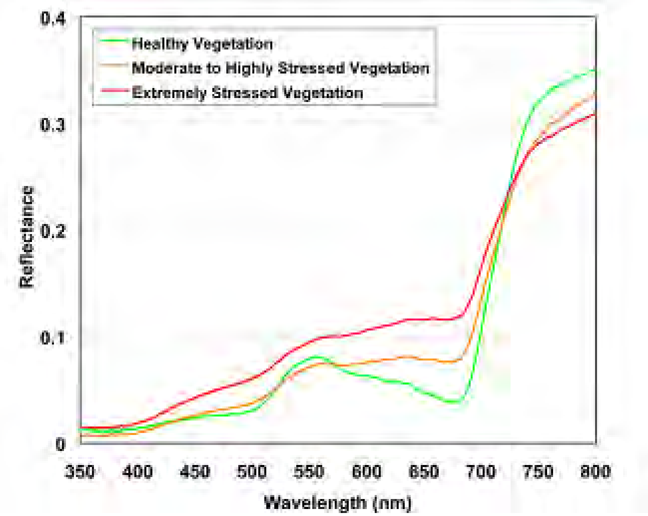


Base Case (6 zones) **Case 1 (23 zones)**



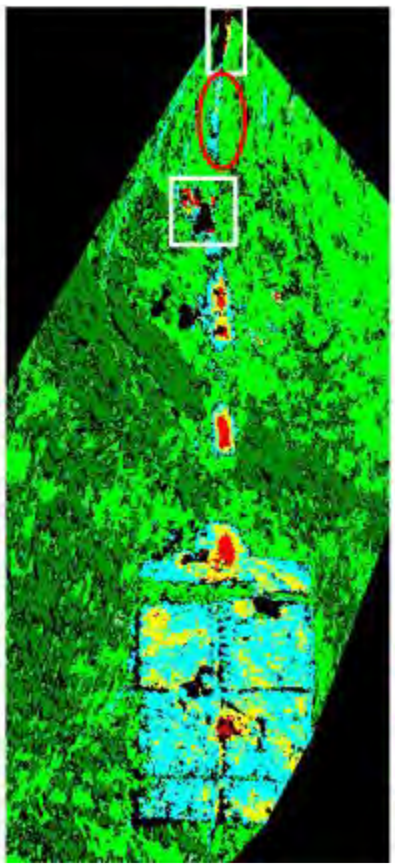
- Patches are correlated with packer locations and high-elevation regions in each zone in the soil material.
- With more packers (i.e., more zones), there are still early breakthroughs but overall emission is less patchy.
- Therefore, simulations support the hypothesis that along-pipe flow of CO_2 upwards within each zone leads to an effective point-source release that creates a persistent patchy emission.

Hyperspectral Imaging

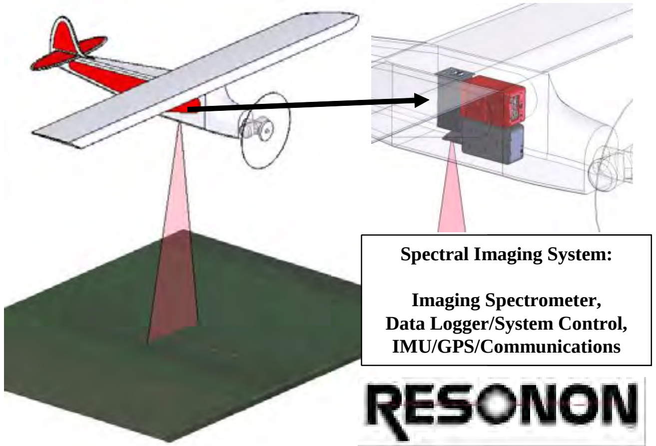


True Color

Analyzed Image



High Stress
Moderate Stress
Low or Seasonal Stress
Healthy Vegetation (Grasses)
Healthy Vegetation (Herbaceous Legumes)
Unclassified



Hyperspectral Imaging Unsupervised Classification

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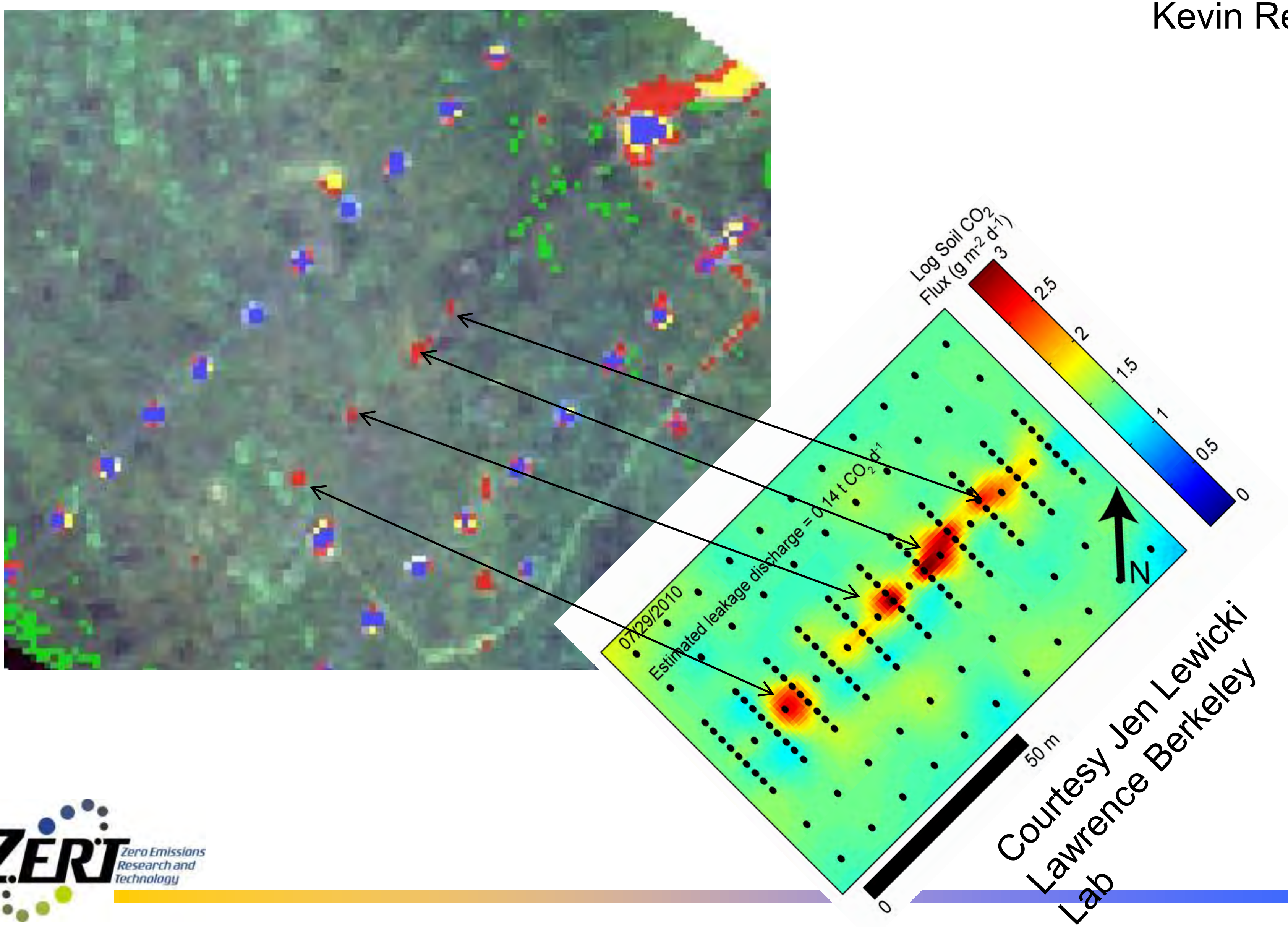
Kevin Repasky



Courtesy Jen Lewicki
Lawrence Berkeley
Lab

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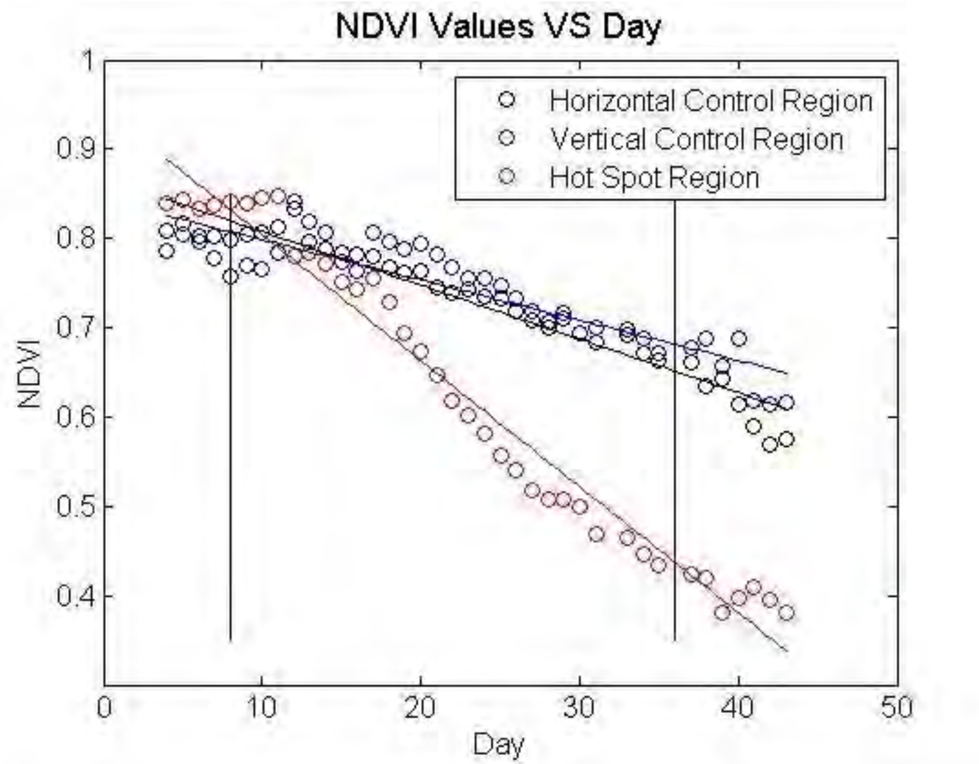
Multi-spectral imaging for detecting CO_2 leaks

J. Shaw

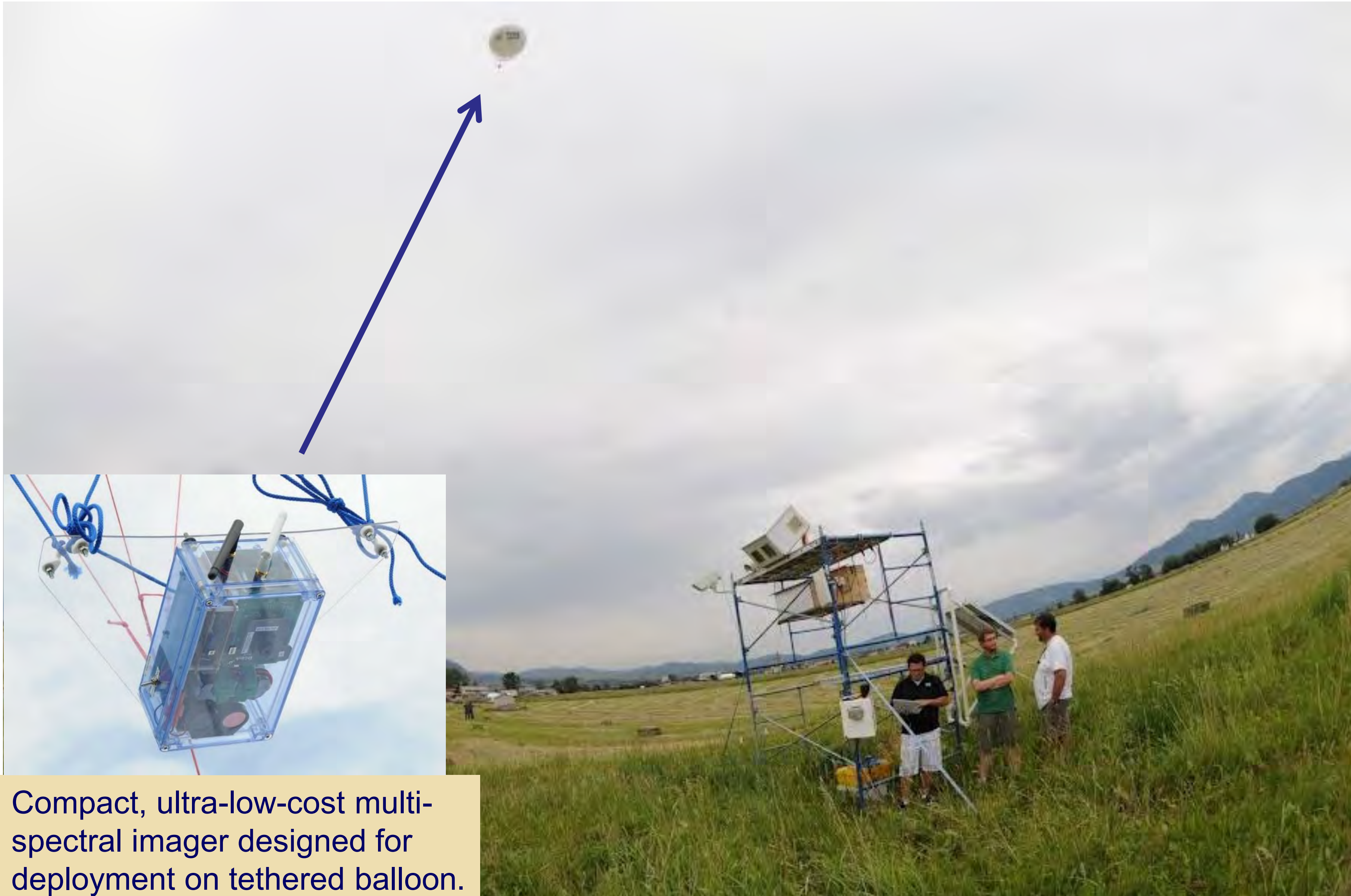
Multispectral imagers used to detect plant stress caused by CO_2 leaking from underground.



Time-series plot showing that the CO_2-affected plant health decays faster over time than the control region. This plot shows Normalized Difference Vegetation Index (NDVI), found from NIR and red reflectances as (NIR-red)/(NIR+red)

Tethered balloon multispectral imaging at ZERT

J. Shaw



Compact, ultra-low-cost multi-spectral imager designed for deployment on tethered balloon.

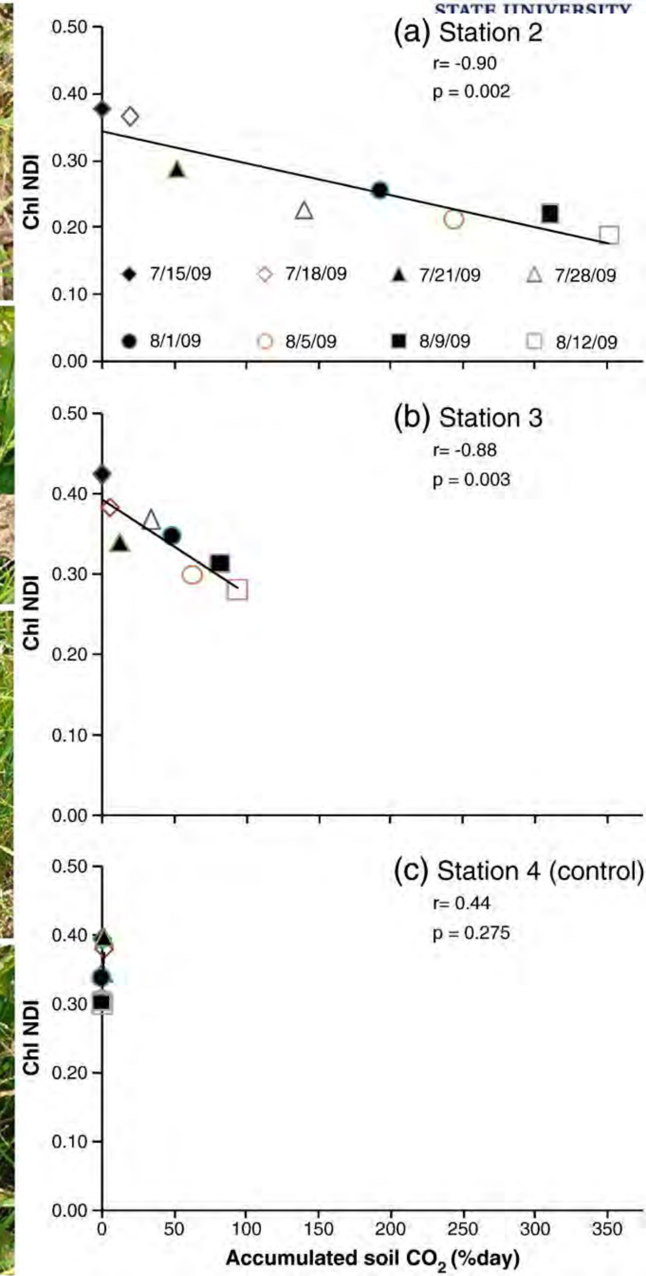
Studying the vegetation response to simulated leakage of sequestered CO2 using spectral vegetation indices

MONTANA STATE UNIVERSITY

Ecological Informatics 5 (2010) 379–389

Montana Tech

Venkata Ramana Lakkaraju, **Xiaobing Zhou, Martha E. Apple**, Al Cunningham, Laura M. Dobeck, Kadie Gullickson, Lee H. Spangler



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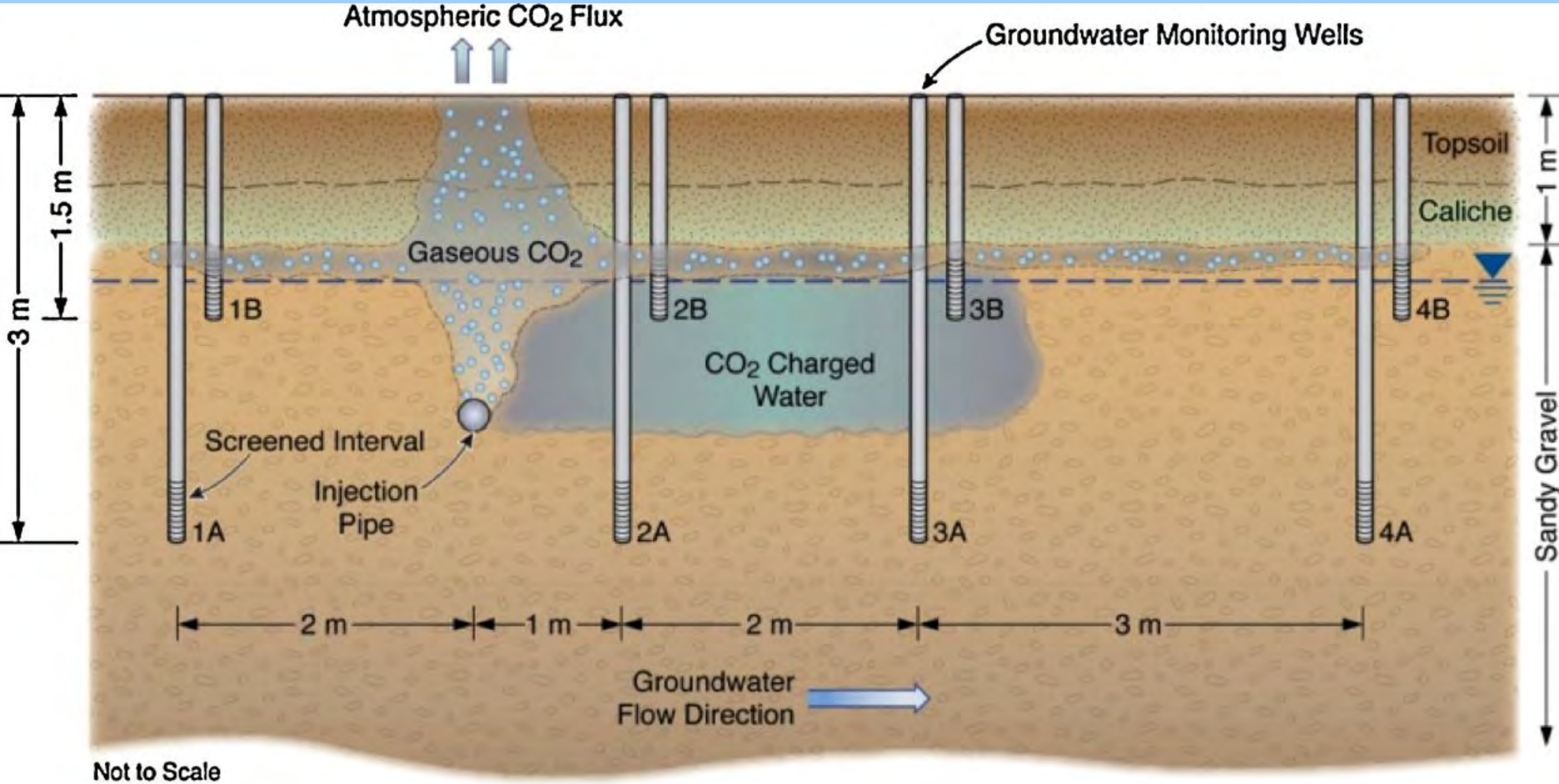
Geochemical Monitoring



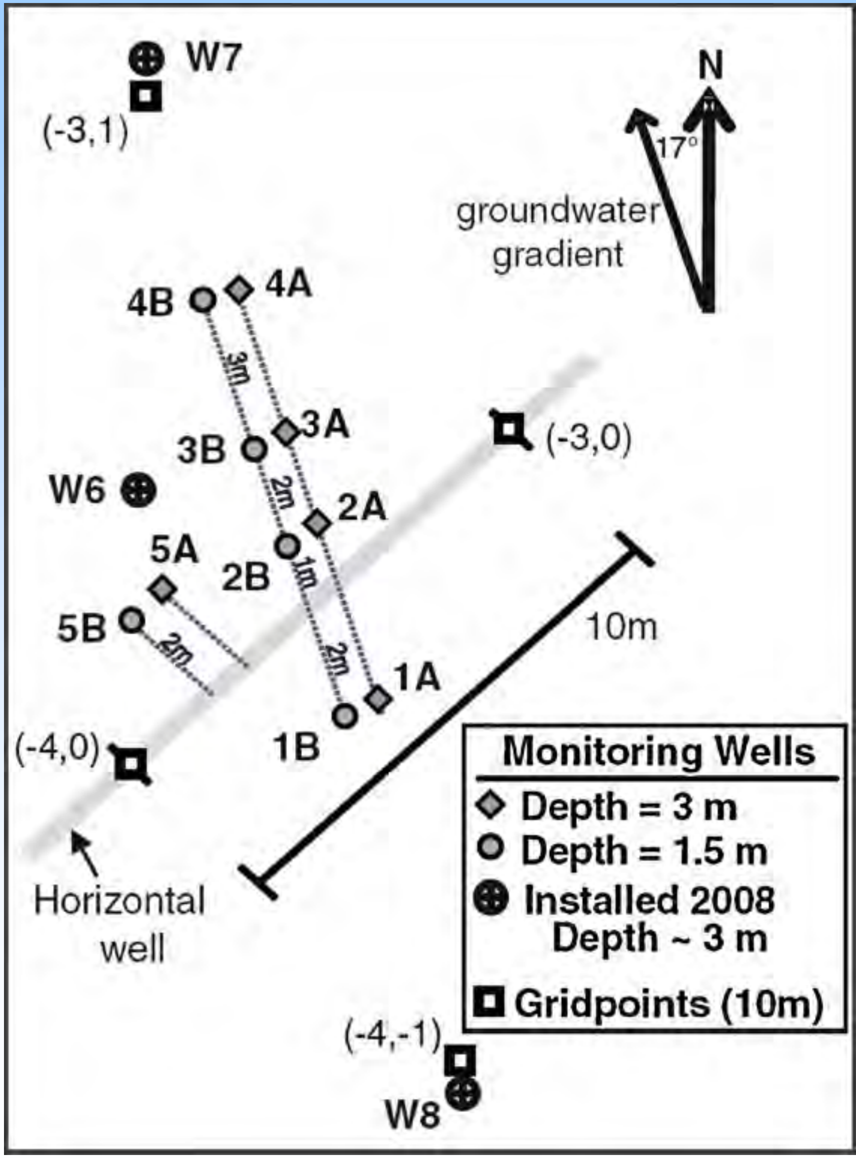
USGS, LBNL, EPRI, WVU, MSU - Environ Earth Sci (2010) 60:273–284
Liange Zheng, John A. Apps, Nicolas Spycher, Jens T. Birkholzer, Yousif K. Kharaka, James Thordsen, Sarah R. Beers, William N. Herkelrath, Evangelos Kakouros, Robert C. Trautz, Henry W. Rauch Kadie S. Gullickson

Geochemical Monitoring

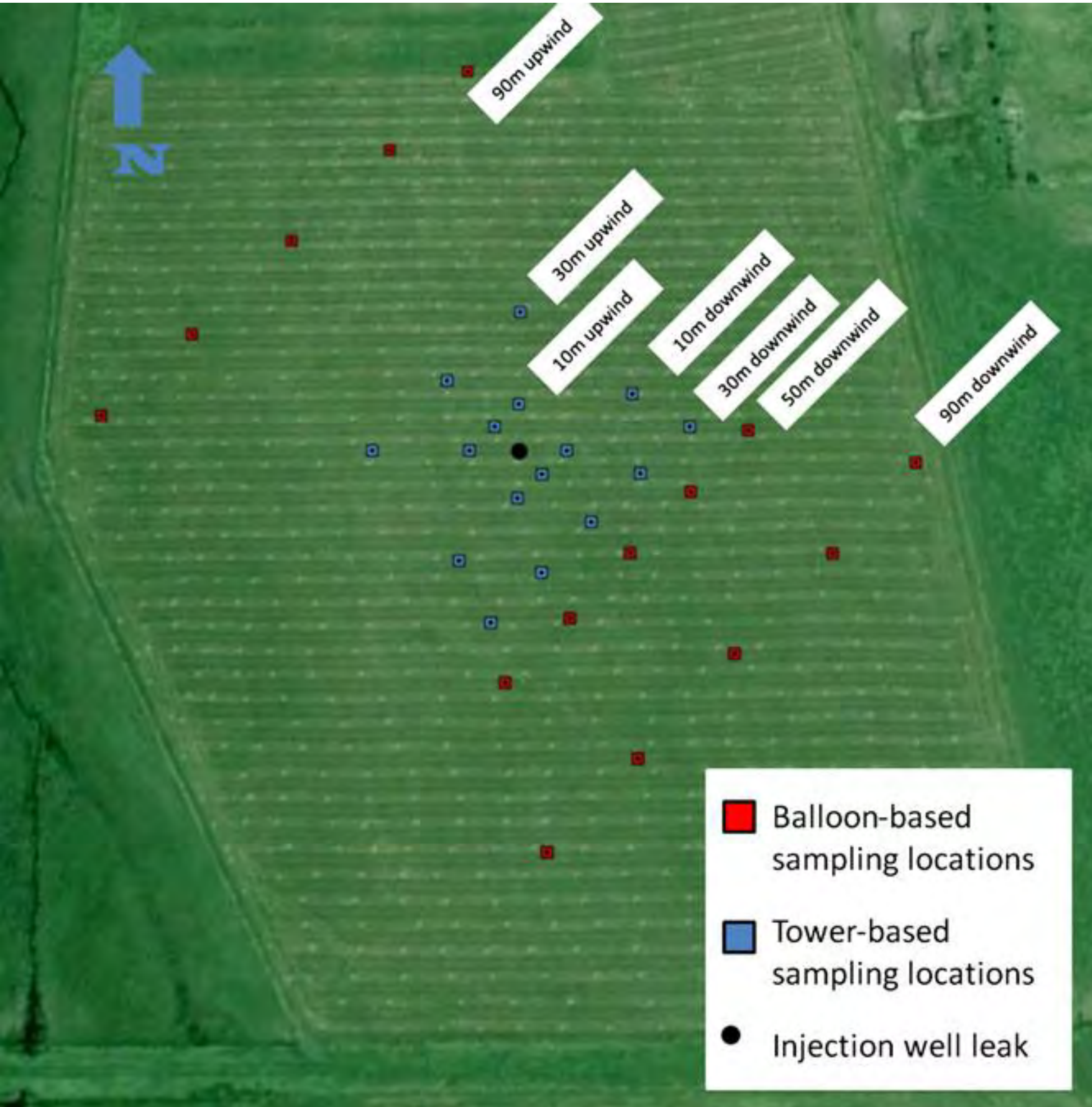
Environ Earth Sci (2010) 60:273–284
Int. J. Greenhouse Gas Control (2011)

USGS, LBNL, EPRI, WVU, MSU
Liange Zheng, John A. Apps, Nicolas Spycher, Jens T. Birkholzer, Yousif K. Kharaka, James Thordsen, Sarah R. Beers, William N. Herkelrath, Evangelos Kakouros, Robert C. Trautz

(1) calcite dissolution could be the primary process buffering pH and releasing Ca+2 in groundwater,
(2) the increase in the concentrations of major cations and trace metals except Fe could be explained by Ca+2-driven exchange reactions,
(3) the release of anions from adsorption sites due to competing adsorption of bicarbonate could explain the concentration trends of most anions, and
(4) the dissolution of reactive Fe minerals (such as fougerite) could explain the increase in total Fe concentration.



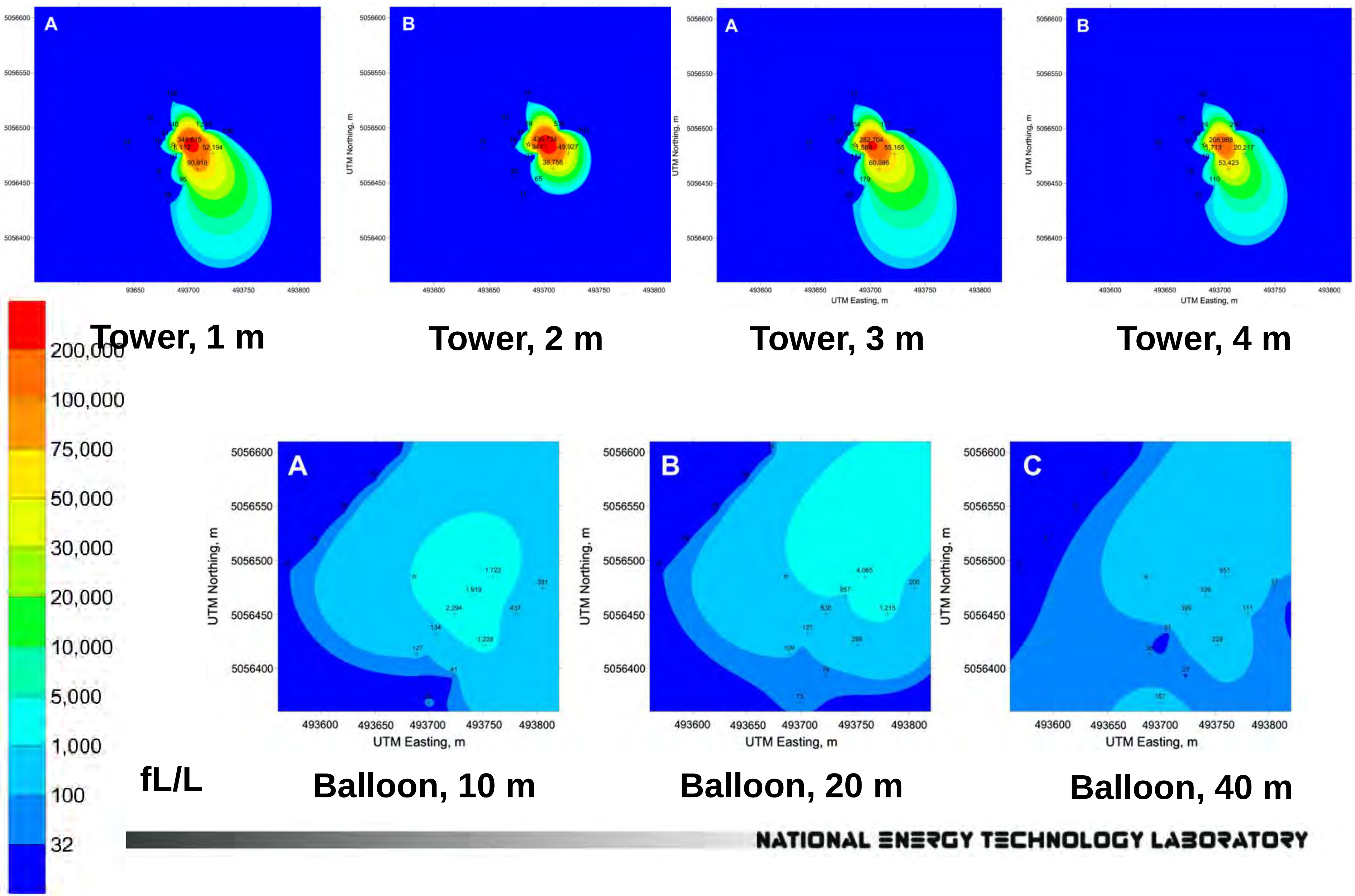
Atmospheric monitoring of a perfluorocarbon tracer at the 2009 ZERT Center experiment



NETL
Natalie Pekney , Arthur Wells , J. Rodney Diehl, Matthew McNeil, Natalie Lesko, James Armstrong, Robert Ference

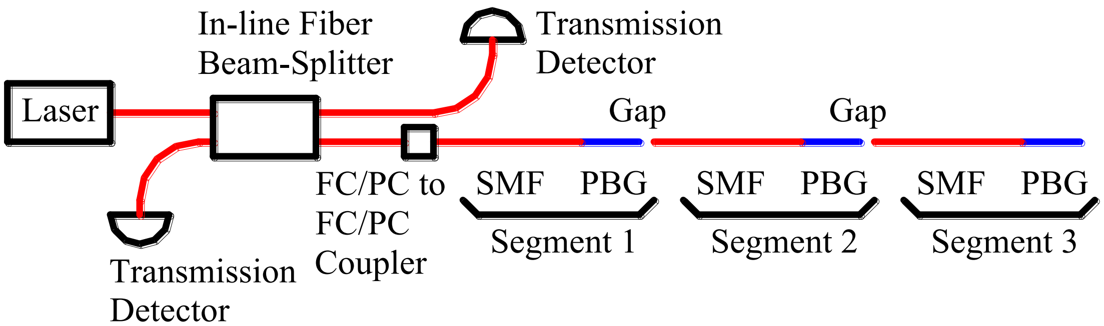
Atmospheric Environment 47 (2012) 124e132

Atmospheric monitoring of a perfluorocarbon tracer



Inline Fiber Sensor

K. Repasky

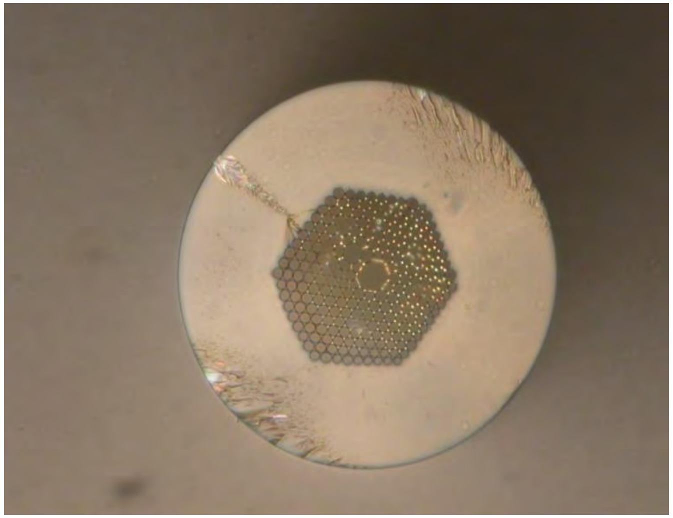


The inline fiber sensor uses a series of segmented photonic bandgap (PBG) fiber in series to for a inline fiber sensor array.

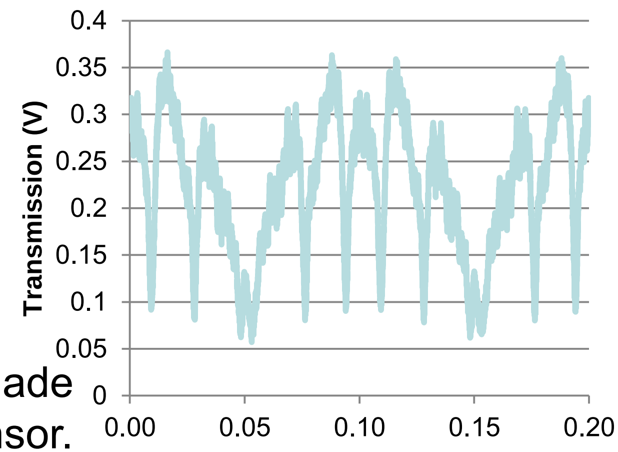
Each segment is addressed using time of flight of the laser pulse.

CO_2 diffuses into the PBG fiber to allow spectroscopic measurements of CO_2 concentration.

Challenge: PBG fiber is larger diameter than SMF and conventional splicing collapses hollow core



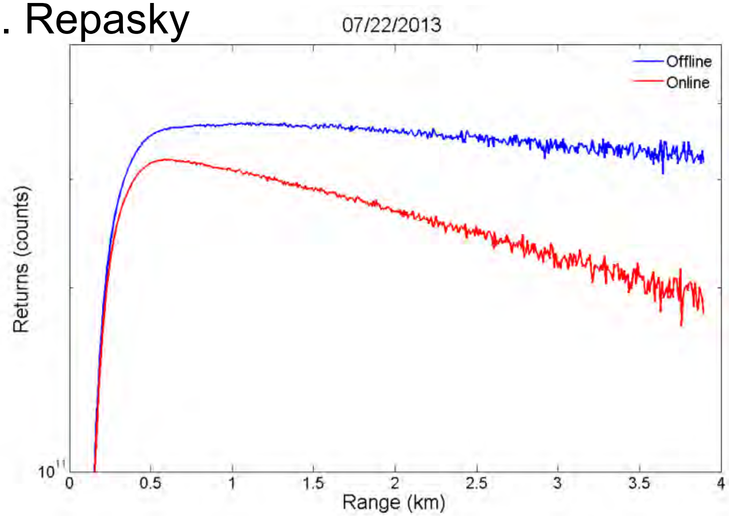
The PBG fiber allows interaction of the laser light and CO_2 in the hollow core.

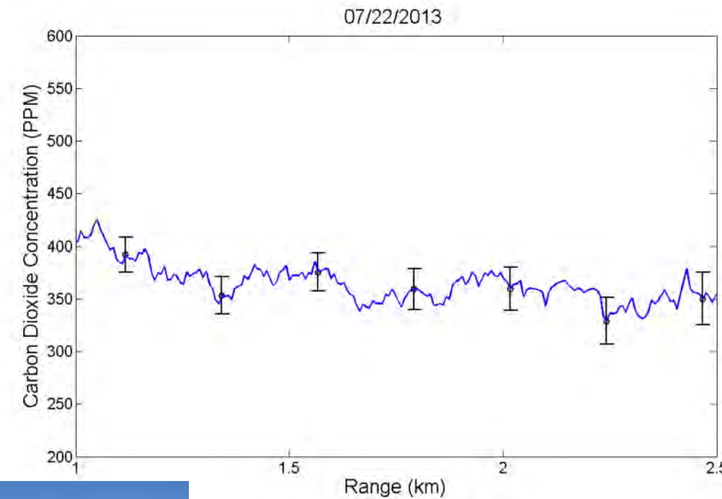


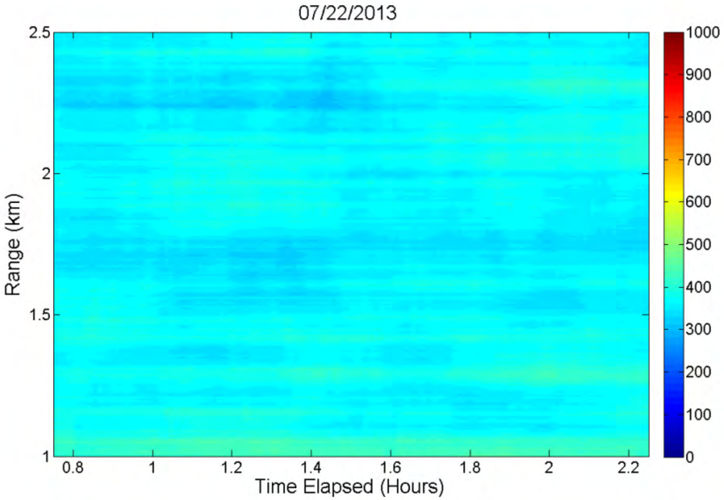
Initial un-normalized CO_2 measurements made using one segment of the inline fiber sensor.

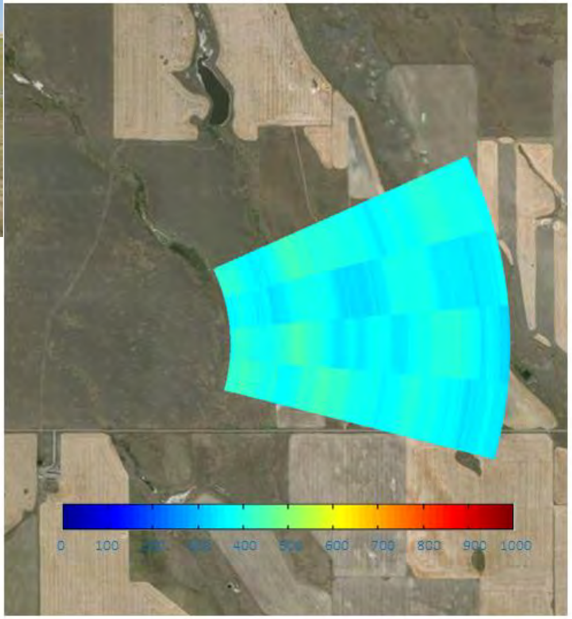
Differential Absorption Lidar

K. Repasky









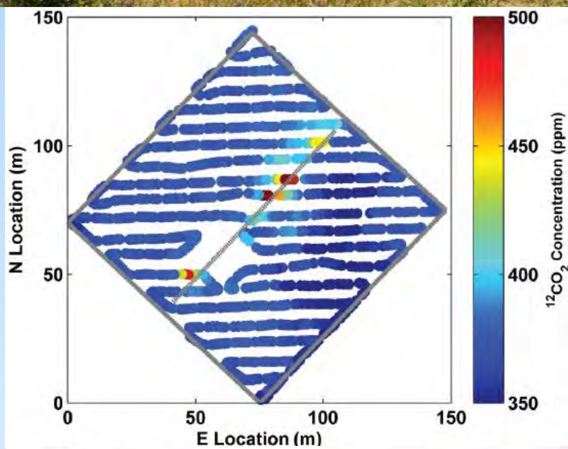
Cavity Ring Down Spectrometer Survey

Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia
Energy Procedia 63 (2014) 3975 – 3983

GHGT-12

Rapid surface detection of CO_2 leaks from geologic sequestration sites

Dylan Moriarty[a]*, Laura Dobeck[b], Sally Benson[c]
[a]Sandia National Laboratories, 1515 Eubank SE, Albuquerque, NM 87123, USA
[b]Montana State University, Montana State University, Bozeman, MT 59717, USA
[c]Stanford University, 450 Serra Mall, Stanford, CA 94305, USA



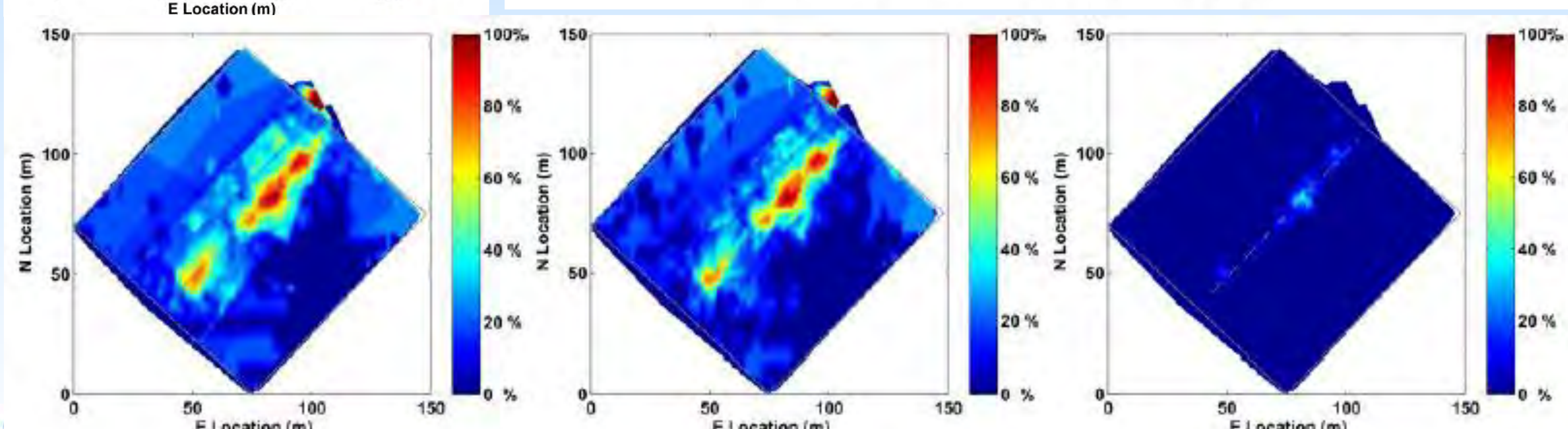


Fig. 6. Detection percentage using static threshold method for $^{12}CO_2$ (left), $^{13}CO_2$ (center), and $\delta^{13}C$ (right).

Process Based Method

International Journal of Greenhouse Gas Control 30 (2014) 42–57

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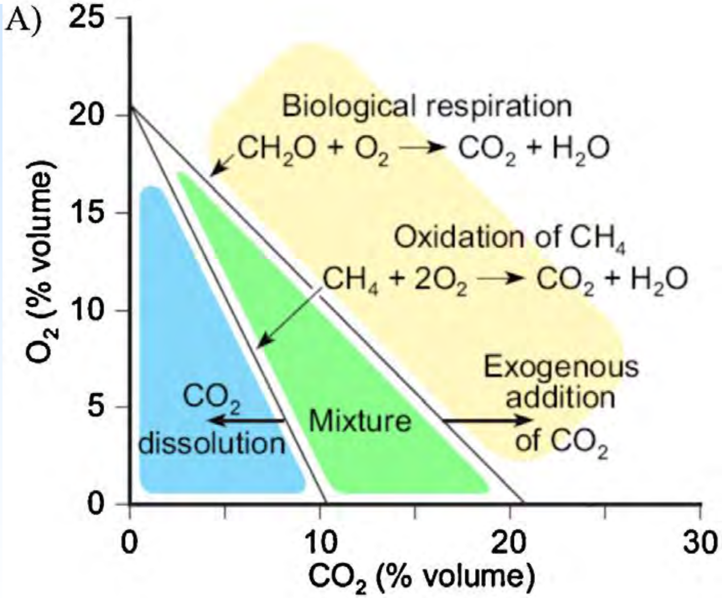
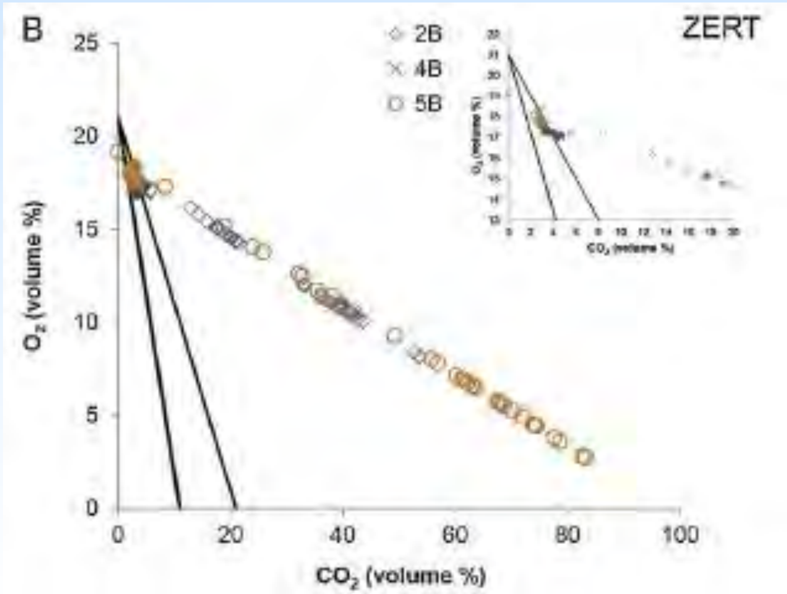
journal homepage: www.elsevier.com/locate/ijggc

Process-based soil gas leakage assessment at the Kerr Farm: Comparison of results to leakage proxies at ZERT and Mt. Etna

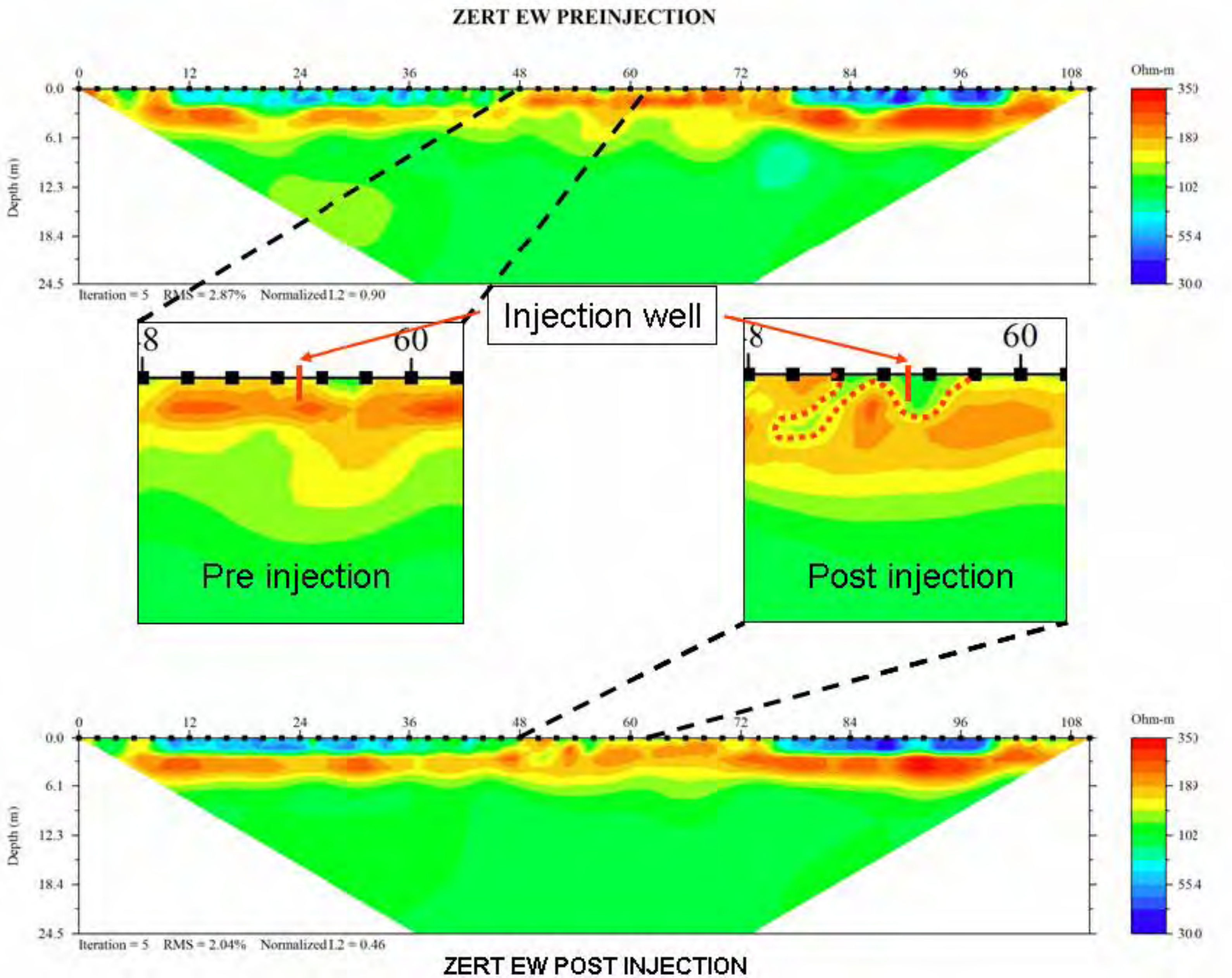
Katherine D. Romanak[a,*], Brad Wolaver[a], Changbing Yang[a], George William Sherk[b], Janis Dale[c], Laura M. Dobeck[d], Lee H. Spangler[d]

[a] Gulf Coast Carbon Center, Bureau of Economic Geology, The University of Texas at Austin, Austin, TX 78713, USA
[b] Clifton Associates Ltd. 340 Maxwell Crescent Regina, SK S4N 5Y5, Canada
[c] Department of Geology, University of Regina, Regina, Saskatchewan S4S 0A2, Canada
[d] Energy Research Institute, Montana State University, Bozeman, MT 59717, USA





Resistivity



What We Have Learned

- Many near surface methods are quantitative <u>but</u>
  - Diurnal, seasonal, annual variations in ecosystem background flux affect detection limits
  - Appropriate area integrated, mass balance is a challenge
- Nearly all methods could detect 0.15 tonnes/day release at ZERT Atmospheric signals drop rapidly away from the ground surface
- Isotopes & tracers have lower detection limits than straight CO_2 flux or concentration
- Scaling, 6 tonnes per day would be detectable over an area 40 times as large
- Surface expression was "patchy" – 6 areas of ~5m radius
- Natural analogs also seem to have "patchy" surface expression
- **<u>By comparing multiple controlled release sites we see that different ecosystems respond somewhat differently</u>**

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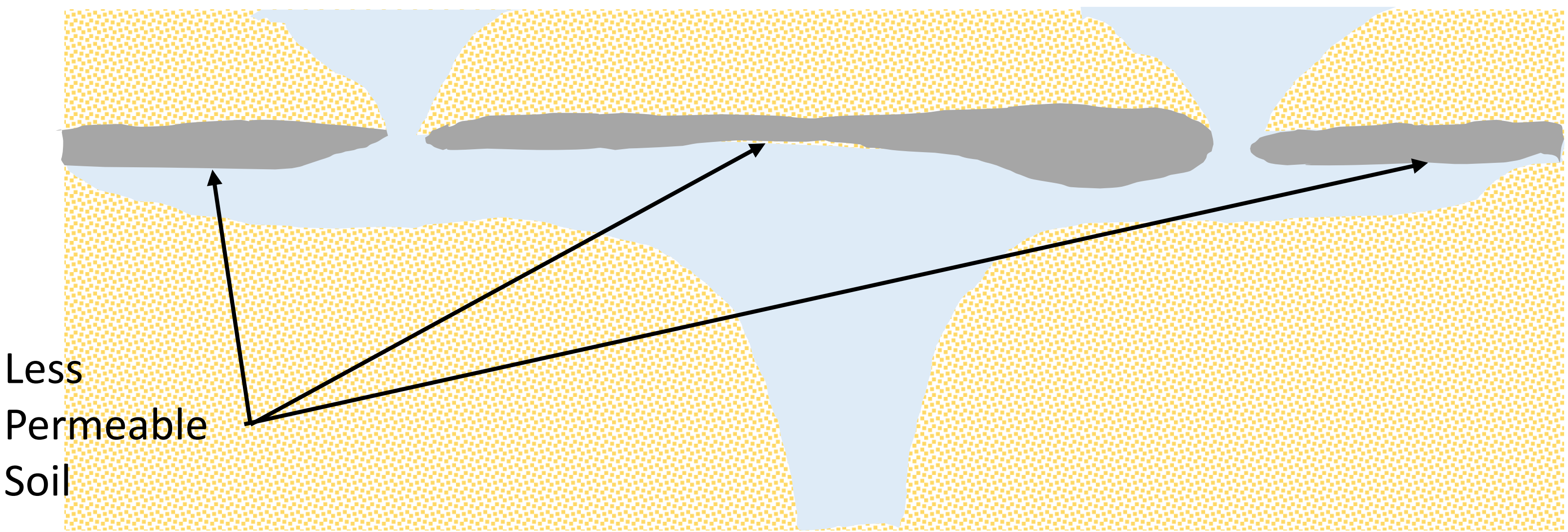
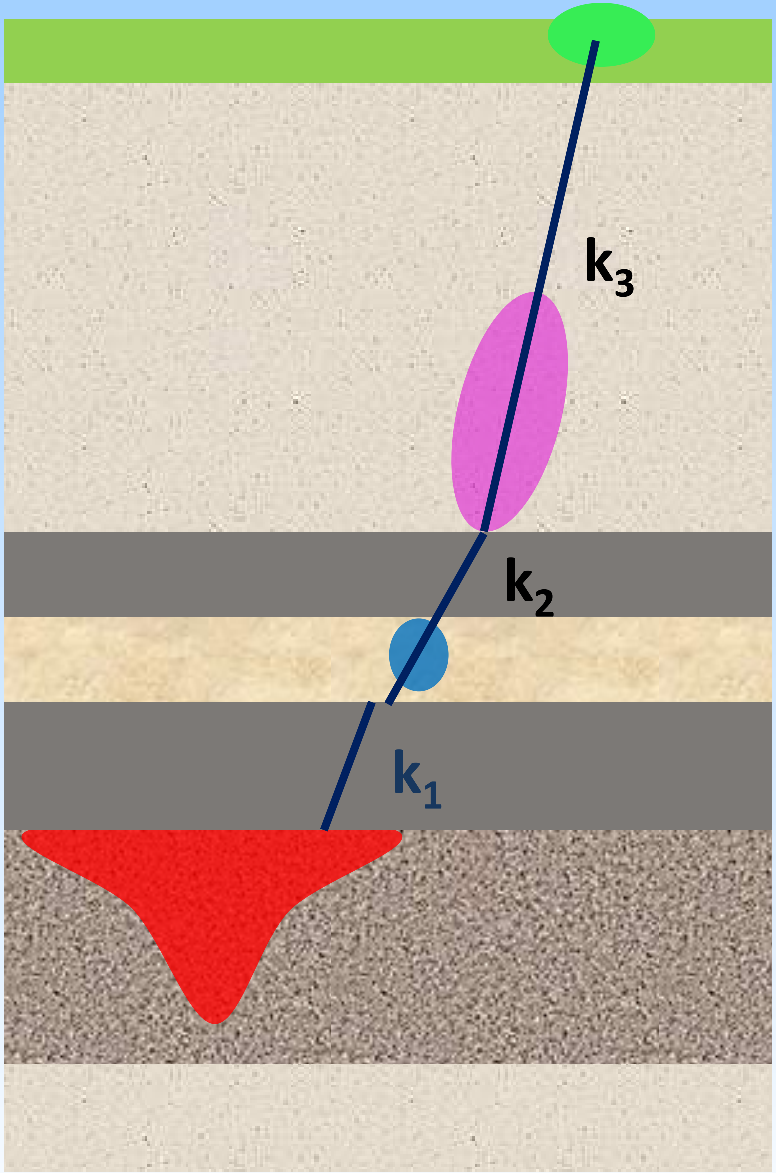
Why is the Surface Expression "Patchy"



If the horizontal permeability is significantly less than the vertical permeability, CO_2 will spread laterally until it hits a lower permeability vertical path. It can then desiccate that path creating a "chimney"

If CO_2 Escapes the Reservoir



Many processes could prevent it from reaching the surface including

1. Trapping under a secondary seal
2. Geochemical conversion of CO_2
3. Dissolution

If it does reach the surface:

1. The surface flux will not necessarily be the same as the flux leaving the reservoir
2. The surface expression could be some distance from the storage reservoir

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Monitoring – A Multi-Step Process

- Initial Detection (Finding anomalies in a large area.)
  - Wide Area – Hyperspectral Imaging, Atmospheric tomography
  - Moderate Area – Lidar, Fiber sensors, Resistivity
- Confirmation (Is anomaly due to elevated CO_2 flux?)
  - CO_2 flux and / or concentration measurements, water measurements
- Attribution (Is elevated flux due to leakage?)
  - Isotopic measurements
  - Process based measurements (relationships between multiple gases, Romanack)
- Mapping and Quantification
  - Flux chamber
  - Concentration measurements in a survey mode
- Impact Measurement – Dependent on the receptor

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What Is the Monitoring Purpose?

- Climate change mitigation?
  - 1% over 1000 yrs – climate models?
- Retention in the reservoir?
  - Subsurface techniques typically do not measure properties directly proportional to concentration / quantity
- Overall storage security?
- HSE, Resource protection (USDW)?
  - Measure to ensure levels are below impact levels
- Public assurance?
- Verification and accounting?
  - Mass flow meters only accurate to ~1%

If this is the primary focus, this could reduce need for wide – area monitoring.

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How We Have Learned

Natural Analogs

- Mammoth Mountain
- Laacher See
- Latera
- Soda Springs, ID
- Crystal Geyser, UT
- More

How analogous is the analog?

Flow through significant overburden

Fluxes may be much higher than leaky engineered system

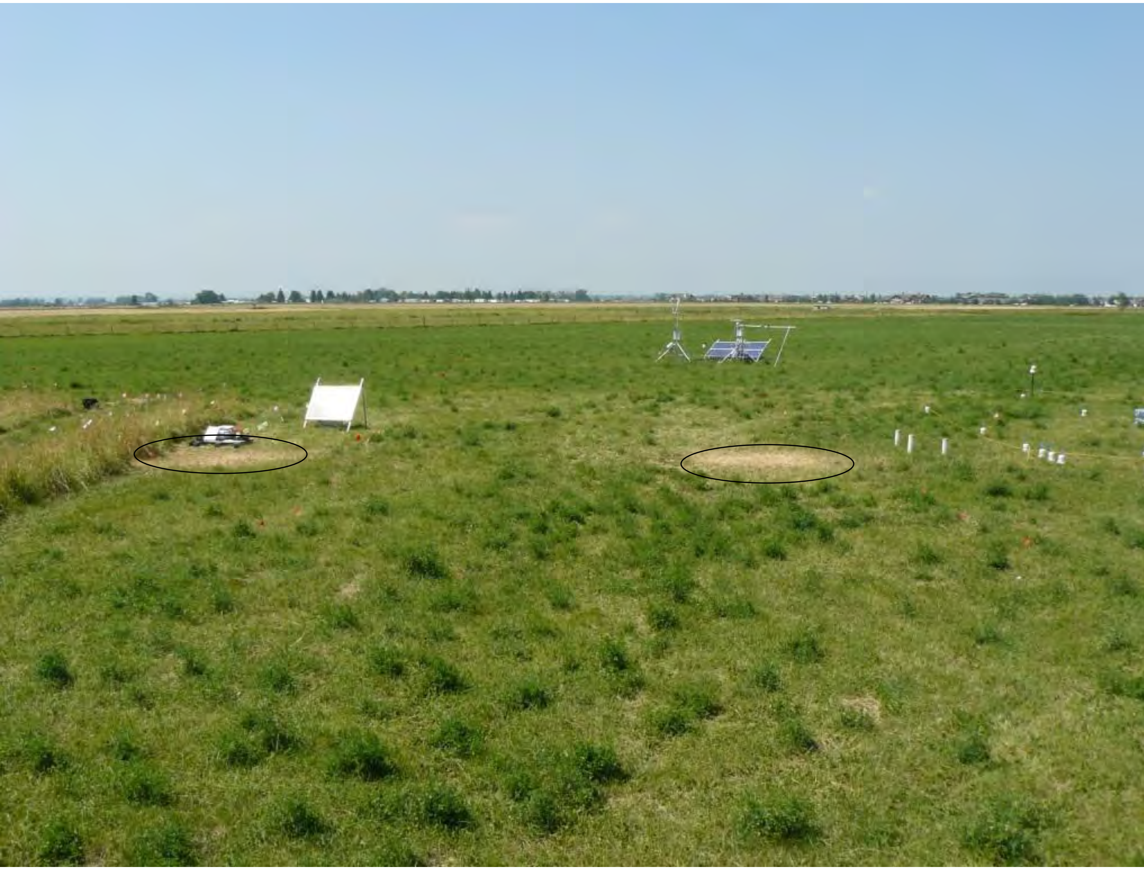
Controlled Releases

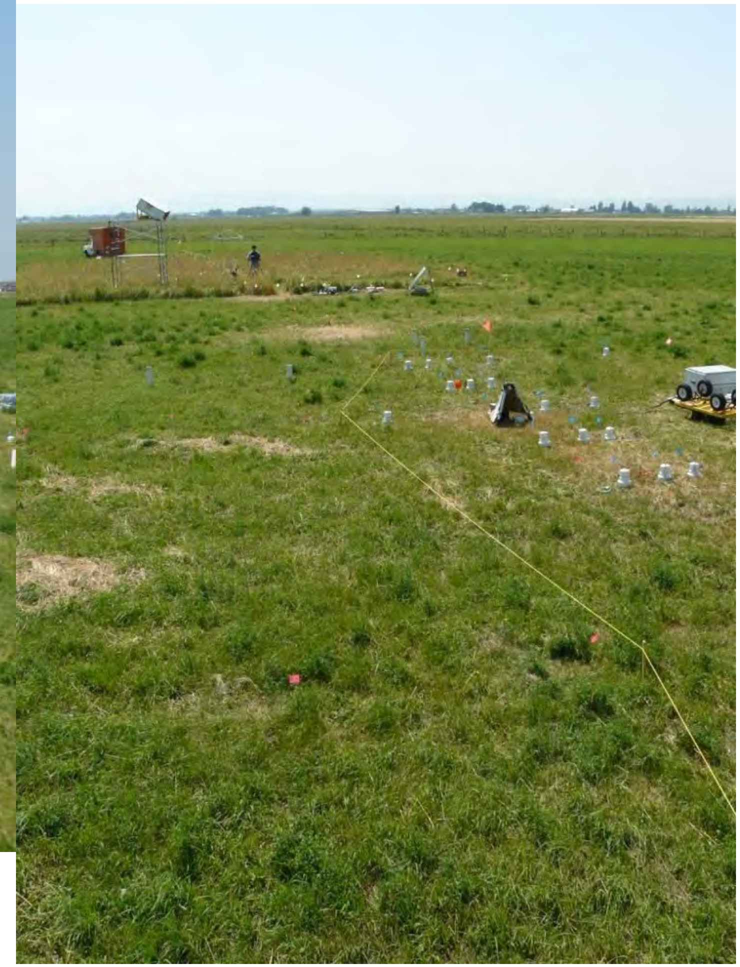
- ASGARD (Nottingham)
- ZERT (Montana State)
- Australia
- Norway
- More

Source term known

Ability to establish detection limits

Relatively little overburden





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