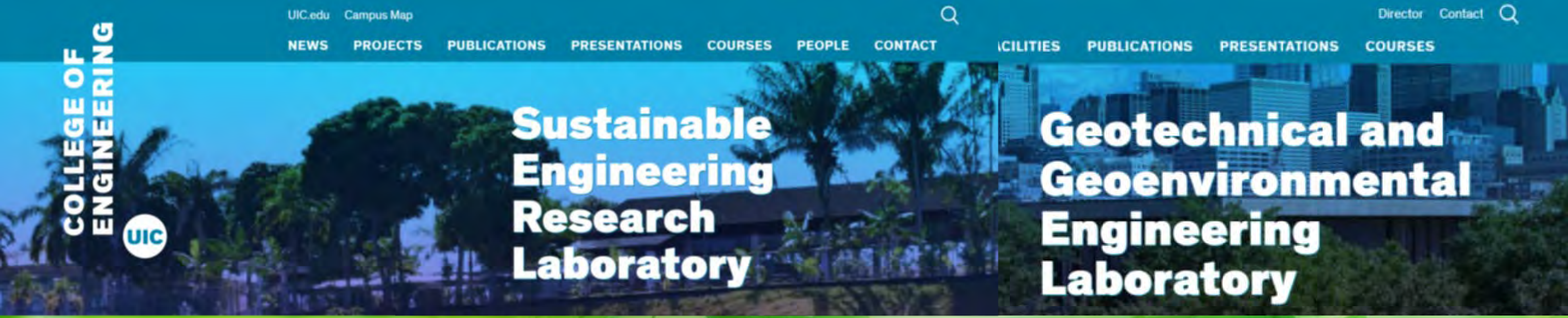


Sustainability and Resiliency-Based Innovation: Research and Practices in Geoenvironmental Engineering

Krishna R. Reddy, PhD, PE, BCEE, DGE, FASCE, ENV SP
Professor of Civil & Environmental Engineering
Director, Sustainable Engineering Research Lab
Geotechnical & Geoenvironmental Engineering Lab
University of Illinois Chicago, kreddy@uic.edu

19th Gerald A. Leonards Lecture, Purdue Geotechnical Society (PGS), Lyles School of Civil Engineering, Purdue University, West Lafayette, IN, May 5, 2023

UIC The University of Illinois at Chicago

Acknowledgement

- Purdue Geotechnical Society- Workshop and Leonards Lecture Committee
  - Antonio Bobet, Philippe Bourdeau, Vincent Drnevich, Marika Santagata, Joseph Sinfield

- Purdue University Geotechnical Engineering Faculty and Alumni

- Previous G.A. Leonards Lecturers
  - Milton Harr (2003), Victor Milligan (2004), Robert Holtz (2005), Michele Jamiolkowski (2006), Suzanne Lacasse (2007), Jean-Lou Chameau (2008), Bernard Amadei (2009), Richard D. Woods (2010), Herbert Einstein (2011), Carlos Santamarina (2012), Craig Benson (2013), Lyesse Laloui (2014), Richard Goodman (2015), David Frost (2016), Patricia Culligan (2017), Eduardo Alonso (2018), Steve Kramer (2019), Rick Deschamps (2022)

Professor Gerald A. Leonards

1921-1997

- Edited Book on Foundation Engineering (1962)
- Many Insightful Research Papers and Discussions
  - Fly ash
  - Landfill stability
  - Cyanide overflow pond dam
  - Case studies (Failures)
- Admiration of Former Students
  - Prolific geotechnical consultant
  - Unique teaching style and depth of knowledge
  - Teaching concepts through case studies (specially failures)
  - Preparedness for consulting and academia

Sustainable Engineering Research Laboratory (SERL)
Geotechnical and Geoenvironmental Engineering Laboratory (GAGEL)

Directed by Prof. Krishna R. Reddy, University of Illinois Chicago (UIC), kreddy@uic.edu

Environmental Remediation of Soils, Sediments, Groundwater and Stormwater

- In-situ remediation technologies
- Mixed and emerging contaminants
- Heterogeneous and low permeability subsurface environments
- New development or optimization of technologies:
  - Electrokinetic/electrochemical remediation
  - Air sparging/bio-sparging
  - Chemical oxidation
  - Chemical reduction by nanoparticles
  - Bioremediation/phytoremediation
  - Stabilization/solidification
  - Active and passive containment barriers
  - Integrated technologies
- Green, sustainable and resilient remediation

Waste Management and Landfill Engineering

- Beneficial use of waste and recycled materials
- Anaerobic digestion/composting
- Mechanical stability and chemical containment of landfills (coupled processes/modeling)
- Sustainable landfill liner and cover systems
- Biocovers
- Bioreactor landfills

http://gagel.lab.uic.edu/

Life Cycle Assessment and Sustainable/Resilient Engineering

- Sustainability analytics: Quantifying sustainability
  - LCA, SLCA, SSEM, QUALICS, TQUALICSR
- Resiliency analytics: Quantifying resilience
- Integrated sustainability & resilience framework
- Sustainable & resilient engineering materials
  - Scrap tires, biochar,…
- Sustainable & resilient civil infrastructure
  - Foundations, earth-retaining systems, ground improvement
  - Green infrastructure alternatives
- Sustainable & resilient waste management
  - Integrated waste management strategies
  - Landfilling versus incineration
- Sustainable and resilient environmental remediation
  - Phytoremediation versus stabilization
  - Pump-and-treat versus permeable reactive barrier
  - Dredging versus in-situ capping of sediments

Geotechnical Engineering

- Site investigations
- Structural foundations
- Earth-retaining structures
- Dams and levees
- Ground improvement techniques
- Geomechanics
- Geotechnical earthquake engineering

Research Funding Sources

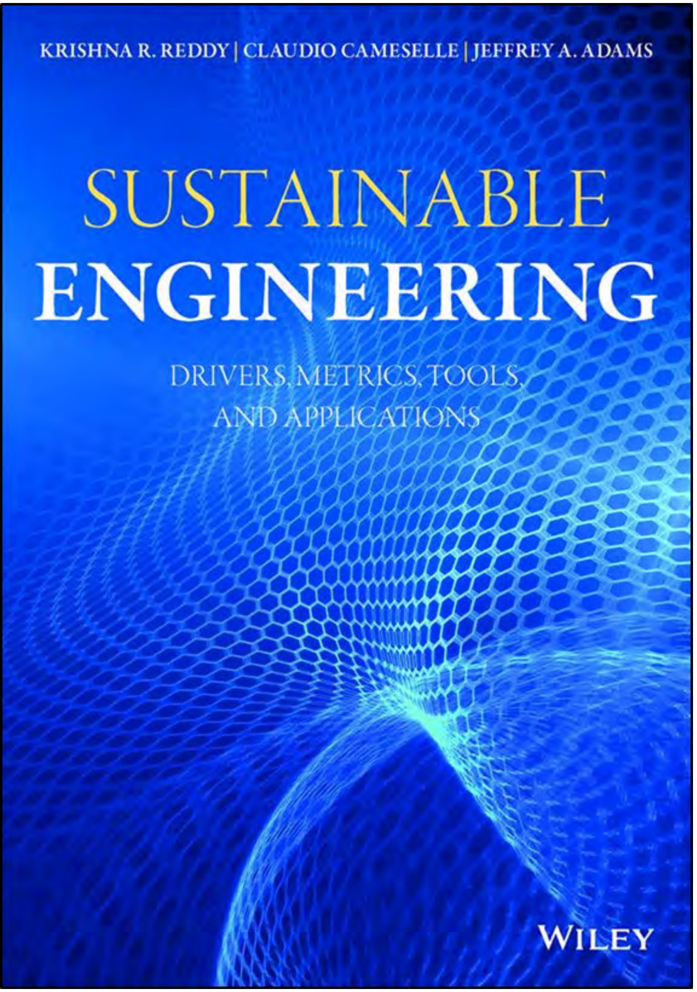
- Federal Agencies
  - U.S. National Science Foundation (CMMI Program; Program Directors: Late Dr. Cliff Astill, Dr. Pricilla Nelson, Dr. Richard Fragaszy, and Dr. Giovanna Biscontin)
  - U.S. Environmental Protection Agency
  - United States Forest Service
  - U.S. Fulbright Program

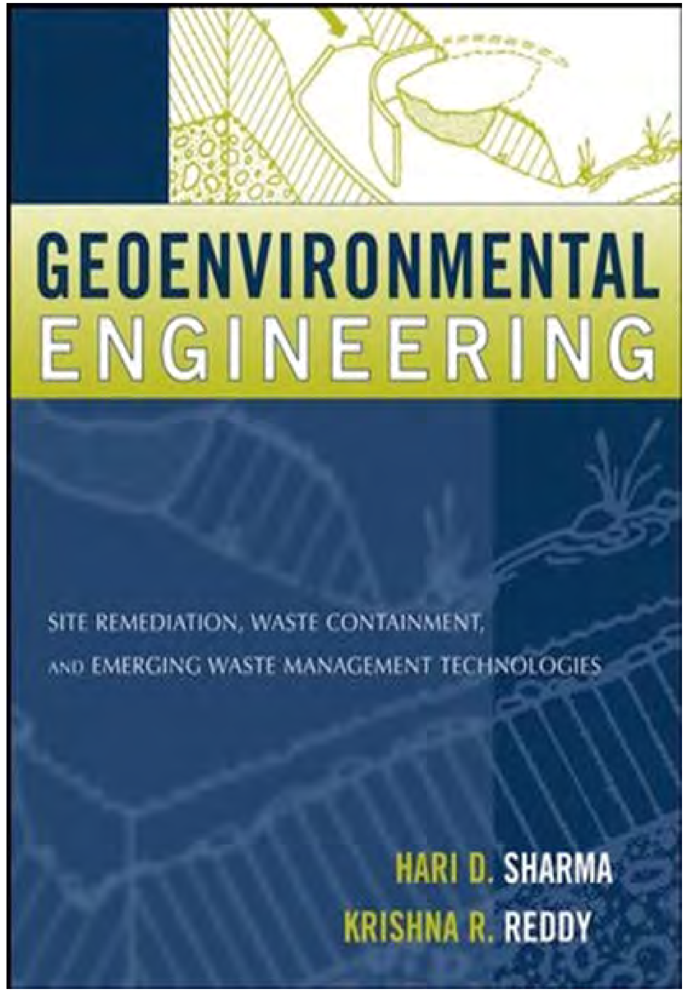
- State and Other Agencies
  - Illinois Environmental Protection Agency
  - Metropolitan Reclamation District of Greater Chicago
  - Chicago Park District
  - Environmental Research and Education Foundation
  - Argonne National Laboratory
  - Illinois Department of Commerce and Community Affairs

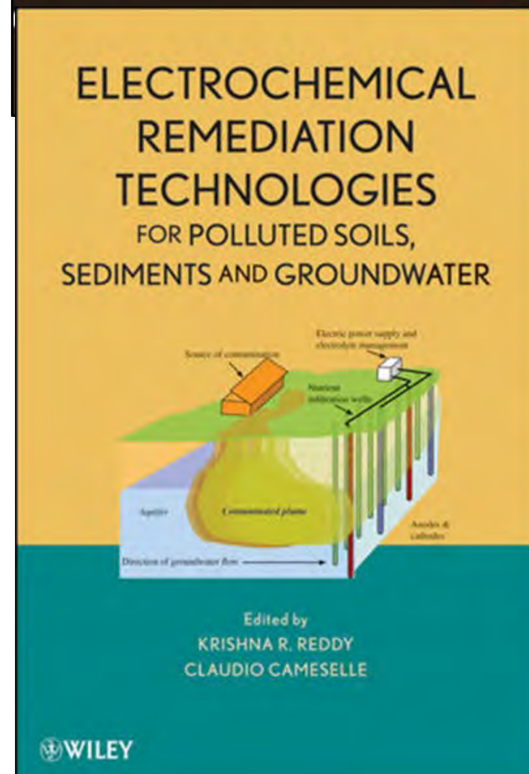
- Industry
  - Burns and McDonnel
  - STAT Analysis Corporation
  - Duke Energy
  - Interra
  - Phoenix Services
  - CREED
  - Toda America
  - Shell Oil Company

Research Students / Scholars

Publications







294 Journal Papers & 237 Conference Papers

Website: gagel.lab.uic.edu

Presentation Outline

- Sustainability and Resiliency-Based Innovation
  - What is Sustainability?
  - What is Resiliency?
  - Urgency for Innovation
  - Quantitative Framework for Resiliency and Sustainability

- Research and Practices in Geoenvironmental Engineering
  - What is Geoenvironmental Engineering?
  - Selected Innovative Research and Practices
    - Sustainable Waste Management: Bioreactor Landfills
    - Climate Mitigation: Biogeochemical Landfill Cover
    - Environmental Remediation: Sustainable Technologies

- Concluding Remarks

Sustainability?

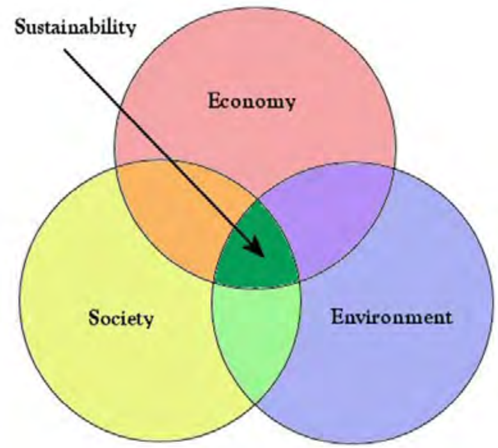
General Definition

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs

(UN World Commission on Environment and Development, Brundtland Report, 1987)

Functional Definition

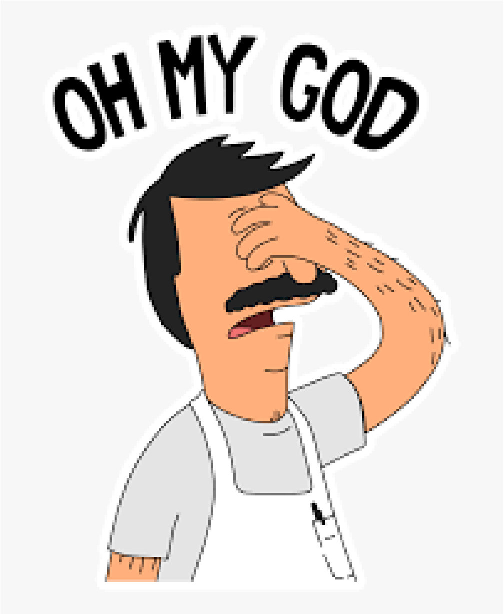
Development that meets the needs of current generation without compromising the needs of future generations by ensuring a balance between economic growth, environmental care, and social well-being



TBL: Triple Bottom Line

Why Do We Care About Sustainability?

- Increasing Population
- Increasing Consumption and Depletion of Natural Resources
- Increasing Greenhouse Gases and Changing Climate
- Growing Environmental Pollution
- Increasing Waste Generation
- Decline of Ecosystems
- Loss of Biodiversity
- Social Inequity and Injustice
- Urban Sprawl
- More...



Reddy et al. (2019). Chapter 1 in ***Sustainable Engineering: Drivers, Metrics, Tools, and Applications***, John Wiley & Sons, Hoboken, NJ

Resiliency?

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- ***The ability to prepare and plan for, absorb, recover from, and more successfully adapt to <u>adverse events</u>***

  (NRC, Disaster Resilience: A National Imperative, 2012)

- ***The ability to prepare for and adapt to <u>changing conditions</u> and withstand and recover rapidly from <u>disruptions</u>***

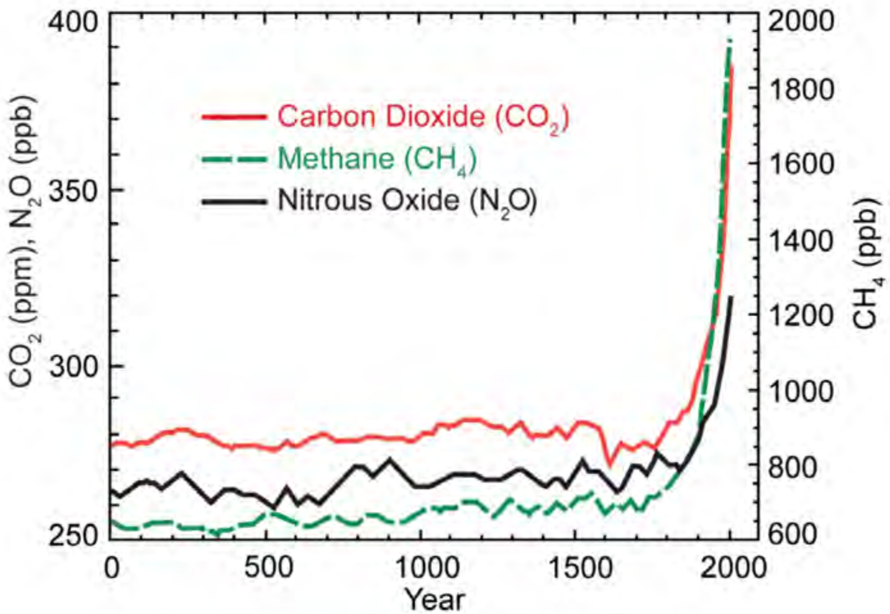
  (National Institute of Standards and Technology, 2019)

Why Do We Care About Resiliency?

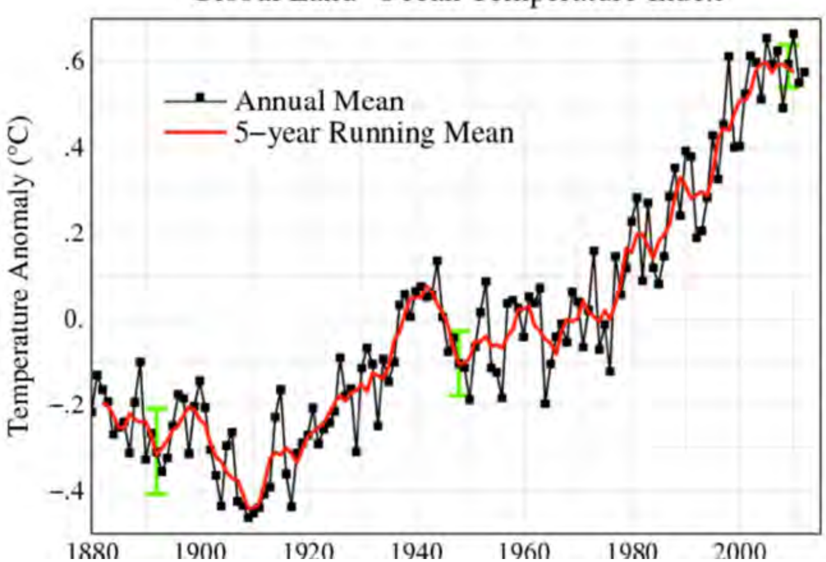
- Growing number of disruptions (adverse events, shocks and stresses)
  - Pandemic
  - Climate change
  - Economic turbulence
  - Political/social unrest
  - Technological disruption
  - Others (naturally occurring threats, accidents, terrorism, etc.)

- Will have far-reaching and long-lasting negative impacts to our lives, communities, economies, and the planet

Climate Change and Extreme Impacts



Global Land–Ocean Temperature Index



Climate Change and Extreme Impacts

Temperature

- Increased occurrence of extreme temperatures
- Sustained changes in average temperatures
- Decreased permafrost

Precipitation

- Increased heavy precipitation events
- Increased flood risk
- Decreased precipitation and increasing drought
- Increased landslides
- Sea level rise

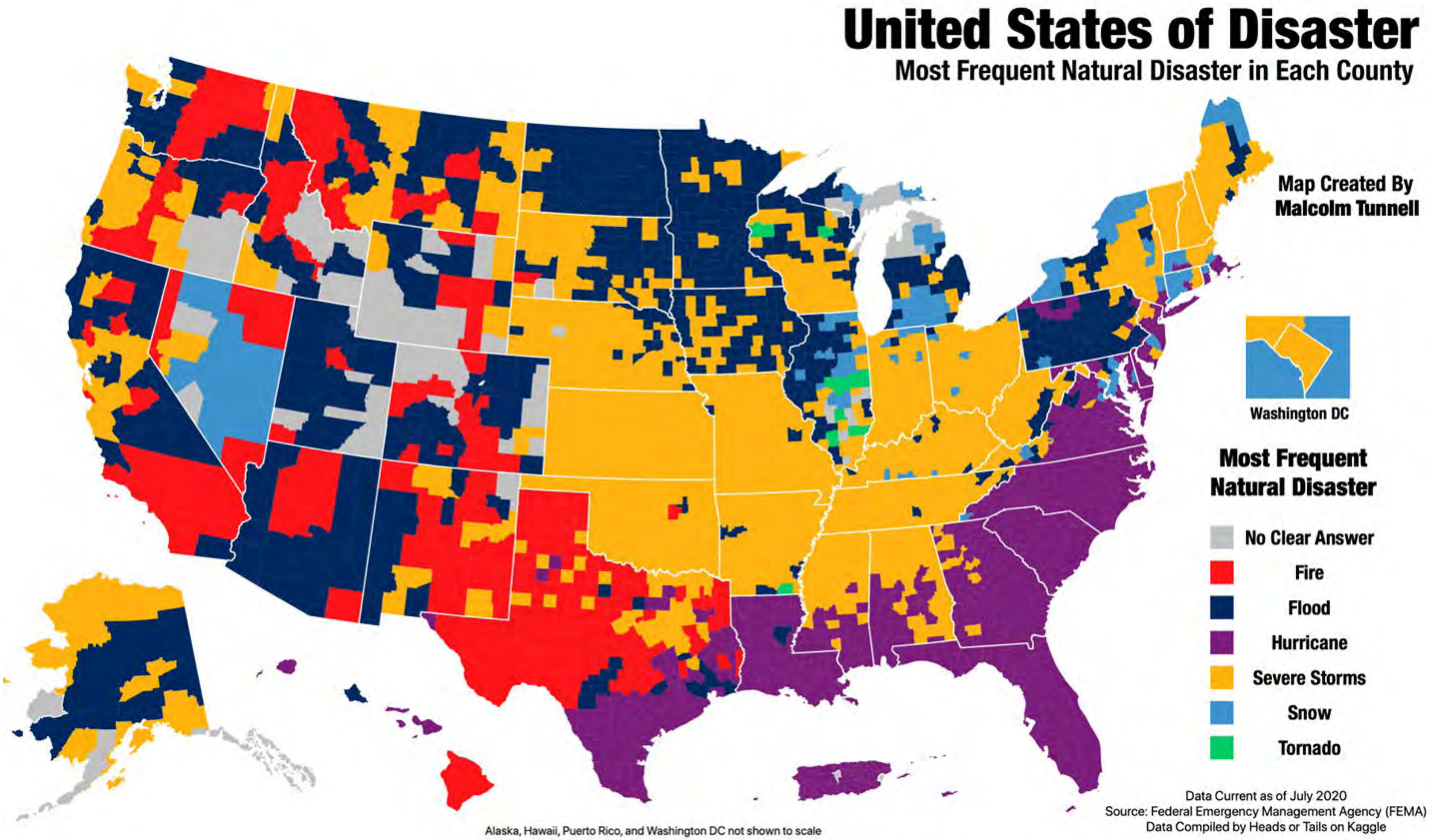
Wind

- Increased intensity of hurricanes
- Increased intensity of tornados
- Increased storm surge intensity

Wildfires

- Increased frequency and intensity

Extreme Climate Impacts



Climate Impacts on Civil Infrastructure

Climate Impacts on Civil Infrastructure

Climate Impacts on Civil Infrastructure

Climate Impacts on Civil Infrastructure
(Guntur, AP, India, June 2022)

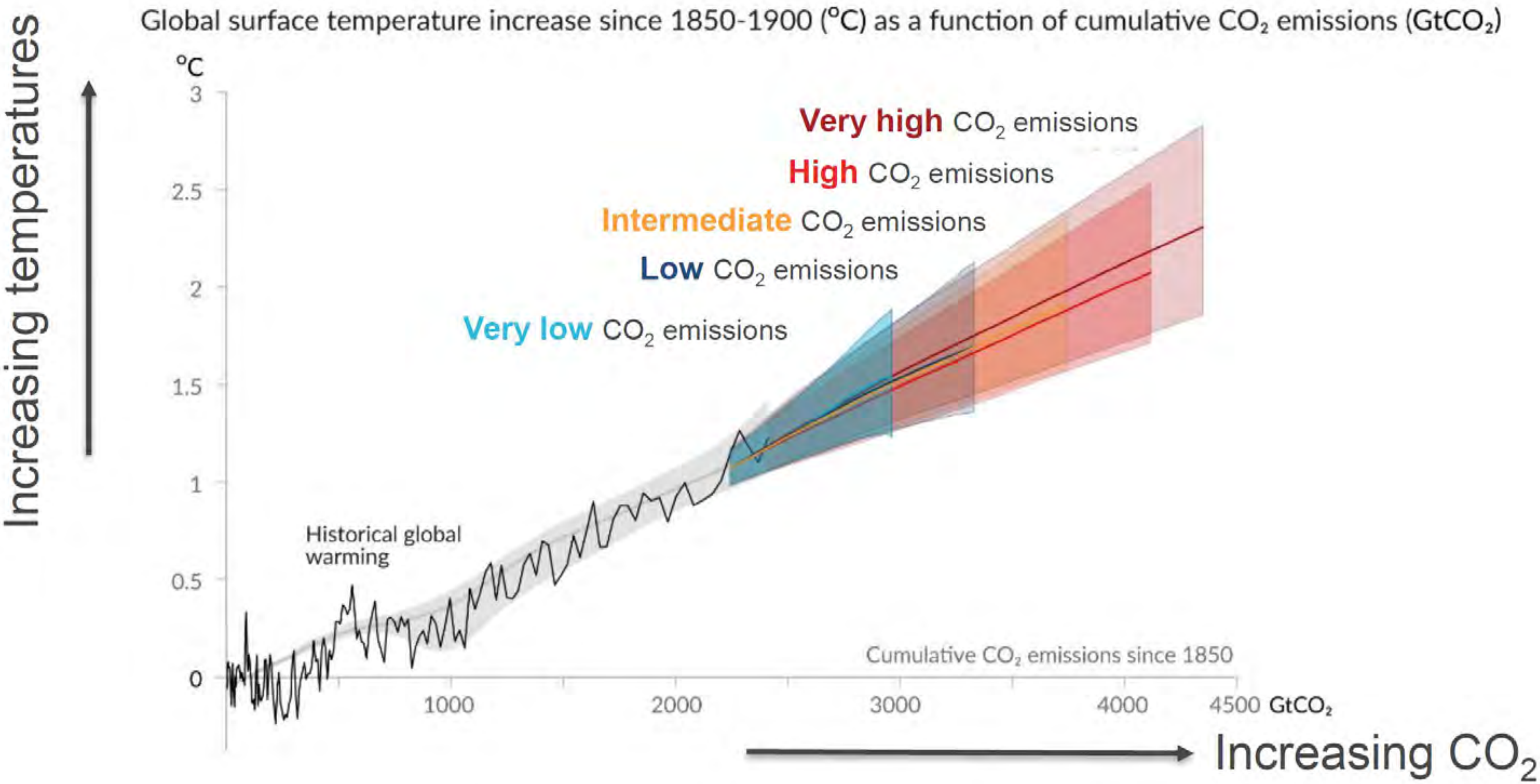
UIC

Climate Change Impacts on the Environment

Climate Change Impacts on the Environment

Future Changes: Model Scenarios

UIC



Climate Change Impacts to Become Unbearable!

Resiliency is Imperative!

Source: IPCC (2021)

Sustainability Versus Resilience

Sustainability is the capacity for:

- Protecting ecological resources
- Ensuring economic prosperity
- Enhancing societal well-being

continuity

fitness

Resiliency is the capacity for:

- Overcoming unexpected crises
- Adapting to turbulent change
- Flourishing in a chaotic world

Both Are Imperative!

Grand Goals: Achieving SDGs

United Nations: 2030 Sustainable Development Goals (SDGs)
17 Goals with 169 Targets (All Interlinked)

Recorded Webinar on SDGs

Urgency for Innovation?

- Conventional engineered materials, processes, designs, systems, etc. do not consider complex and multifaceted sustainability and resiliency challenges!

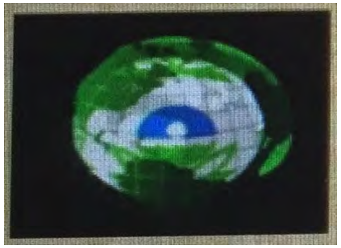
- Necessary to develop proactive, effective, sustainable and resilient engineered systems, technologies, processes, materials, etc.
  - Possible only with "**innovation**"

Innovation = ***Invention*** X ***Practical***

- Innovation can be:
  - Disruptive
  - Incremental
  - Lateral

Scale of Sustainability / Resiliency Projects

- Global Scale (e.g., Global CO_2 budgeting)



- National Scale (e.g., Energy)

- Regional Scale (e.g., Watershed)

- Business or Institutional Scale (e.g., Eco-industrial park)

- Technologies Scale (e.g., Sustainable materials, designs, products, processes, and systems)

Achieving Sustainable and Resilient Solution

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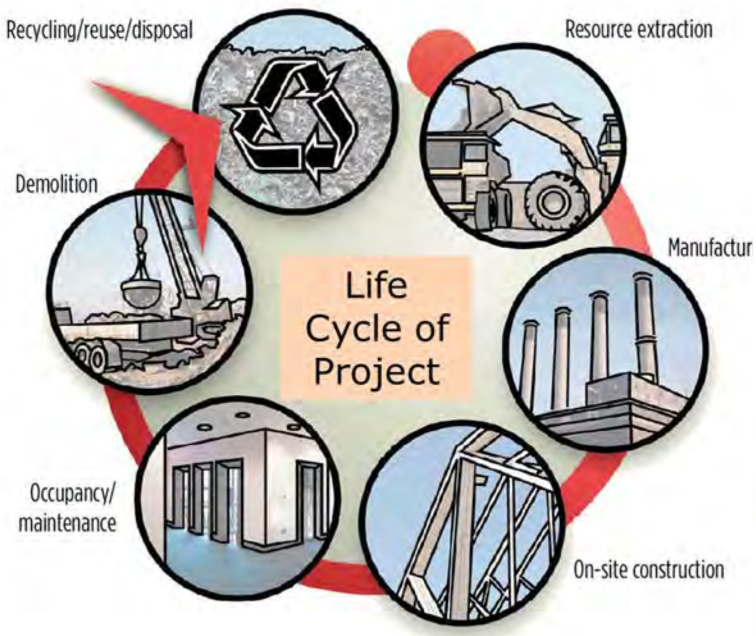
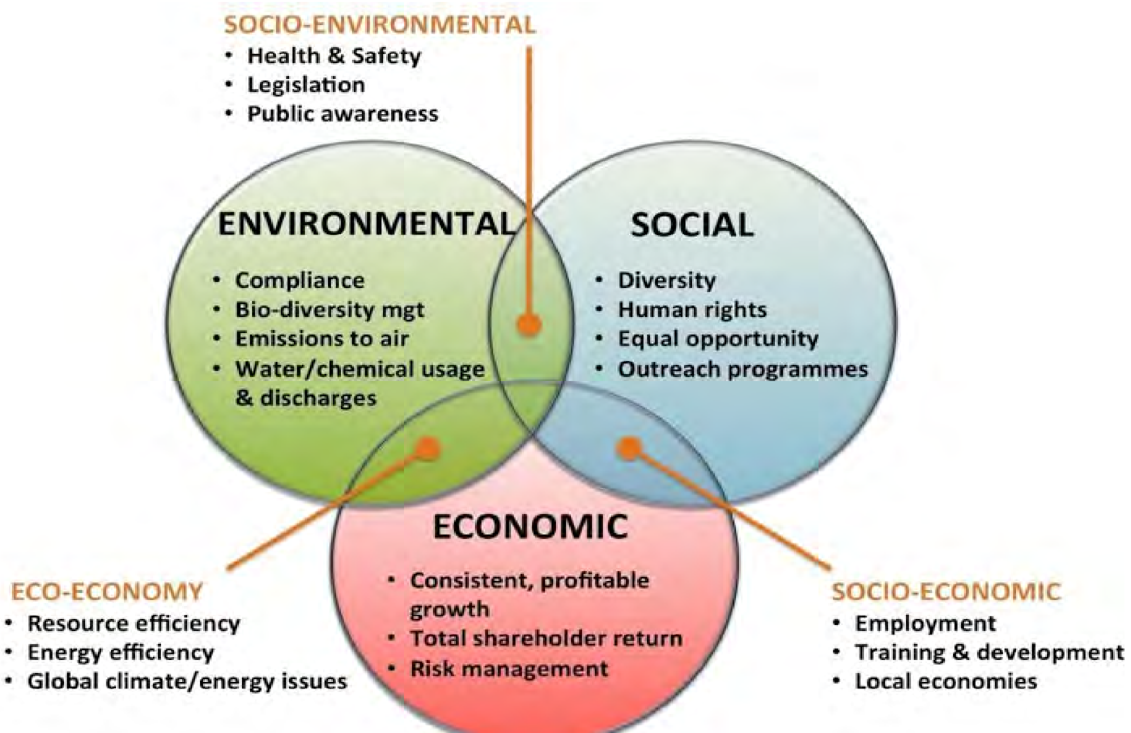
Resiliency

Vulnerability (Technical, TBL) → Adaptive Measures → Monitor & Re-Assess

Sustainability

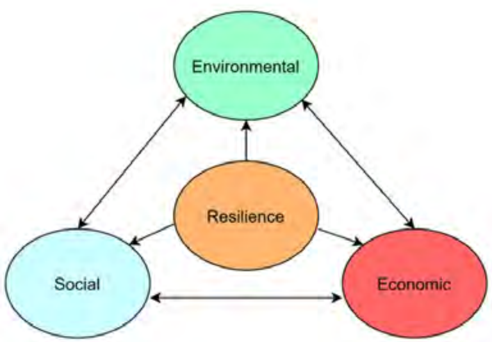




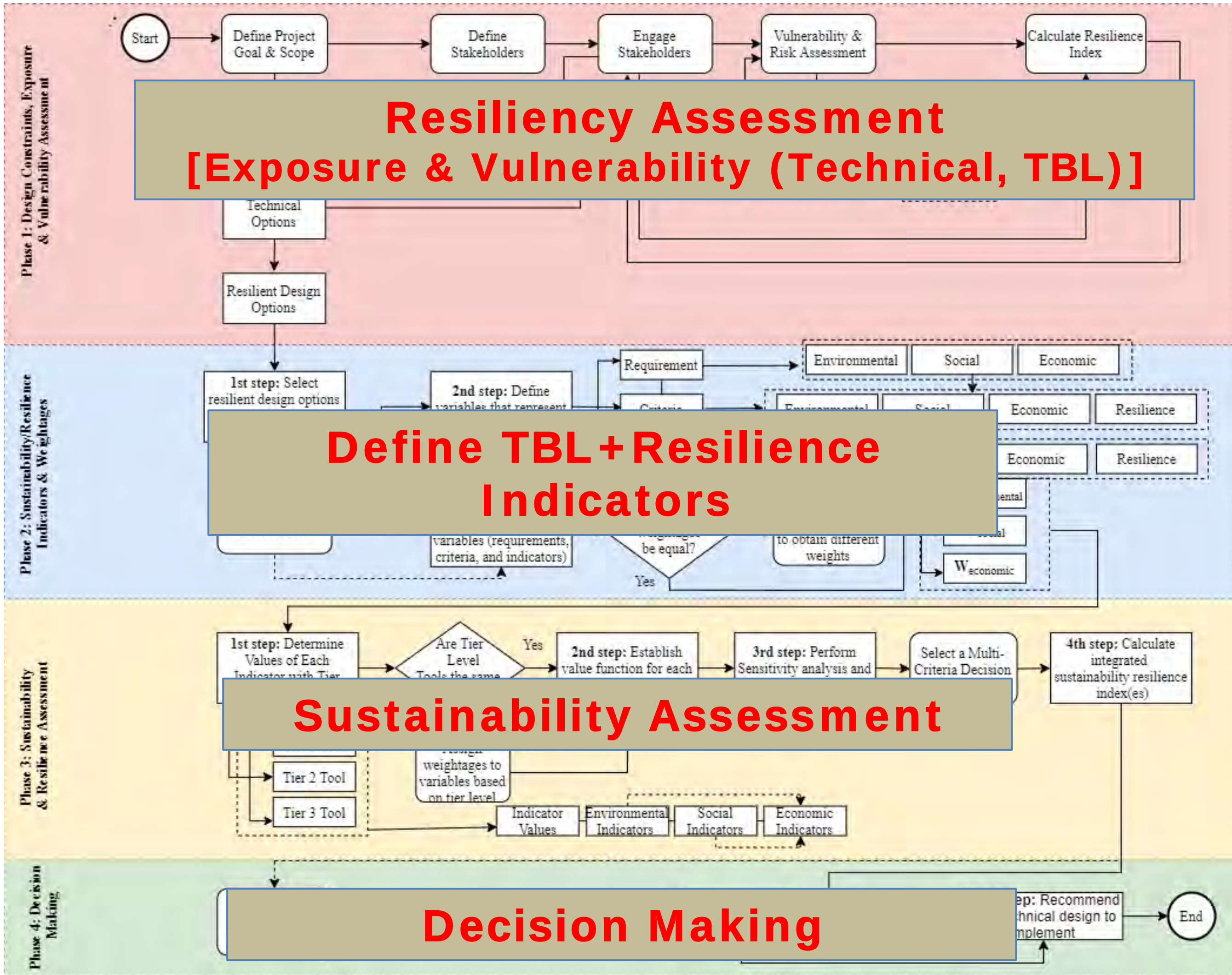
Integrated Resiliency and Sustainability Framework

UIC

- Integration of technical, resiliency, and sustainability (TBL)



- Applicability to various life cycle stages of an engineering project of any scale
- Flexible, tier-based selection of tools



Reddy, K.R., Robles, J.R., Carneiro, S.A.V., and Chetri, J.K. (2021). **Tiered Quantitative Assessment of Life Cycle Sustainability and Resilience (TQUALICSR)**: Framework for Design of Engineering Projects, In *Advances in Sustainable Materials and Resilient Infrastructure,* Springer Nature.

Case Study: Lake Sediment Remediation

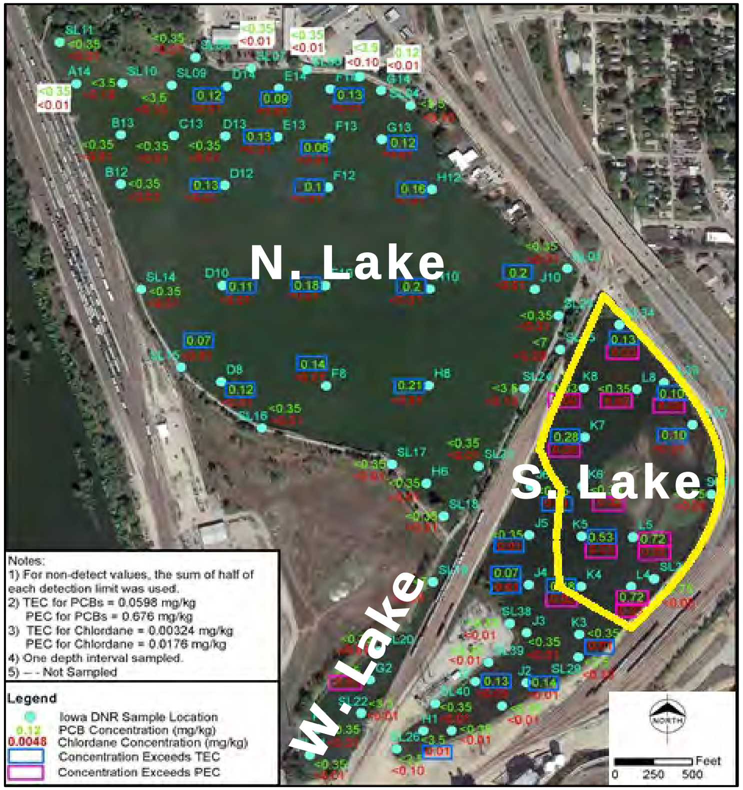
Site Description

- Cedar Lake, approx. 150 acre, located in Cedar Rapids in Iowa, USA.
- Elevated levels of PCBs and pesticides found in South Lake sediments
- Proposed to be developed as a recreational park

Potential Remedial Alternatives

Based on the CERCLA nine-point criteria for remedial option evaluation for superfund sites:

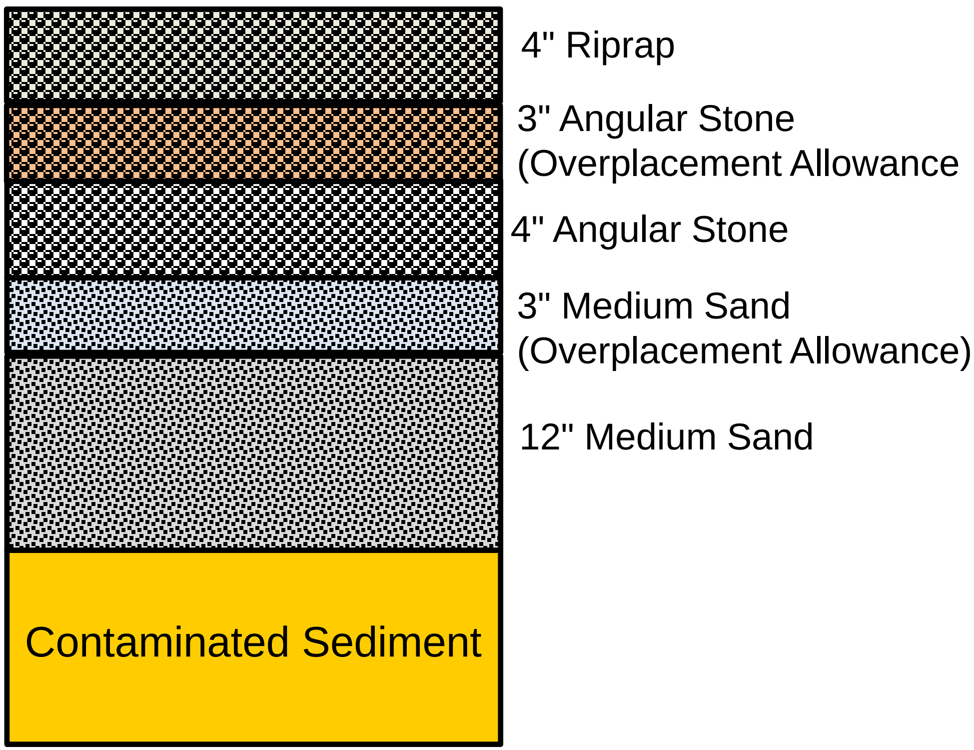
- Dredging and Disposal
- Conventional Capping
- Modified Cap with a Reactive Core Mat



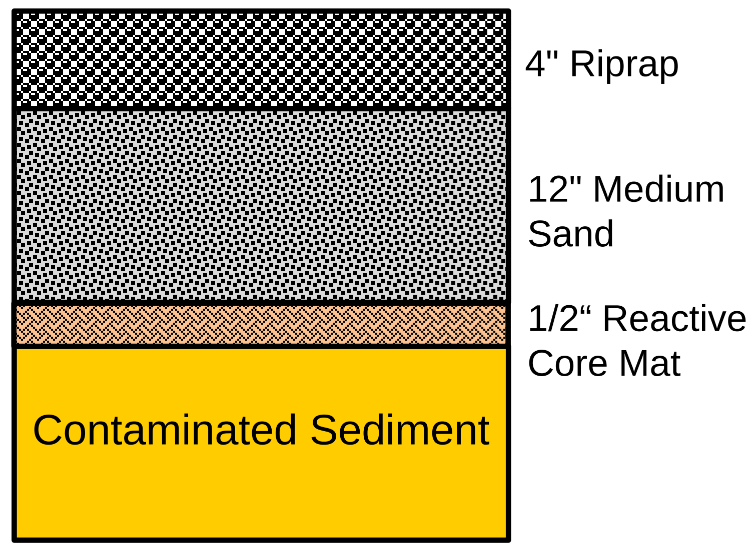
Case Study: Lake Sediment Remediation

UIC

1. Dredging and Disposal?

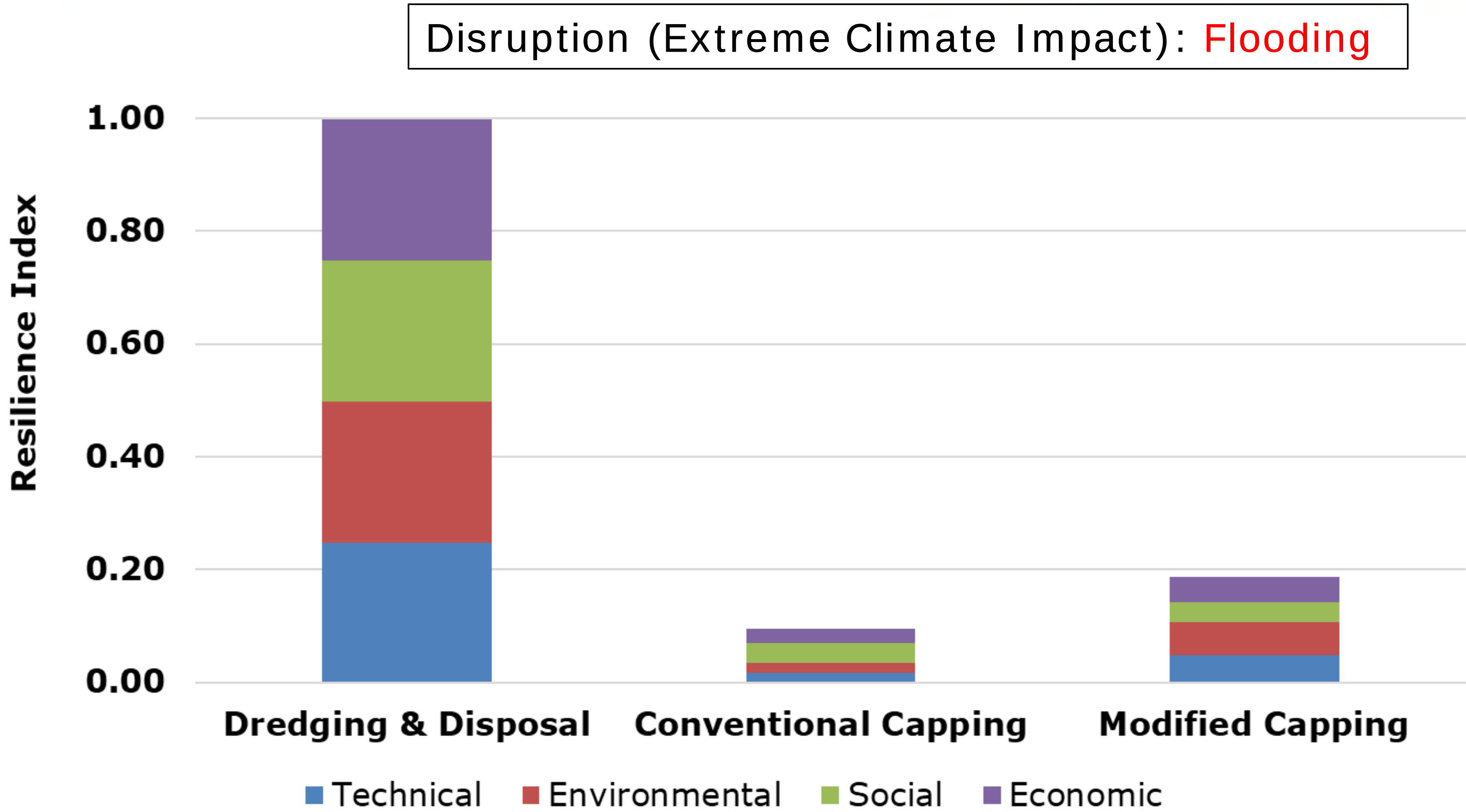


2. Conventional Capping



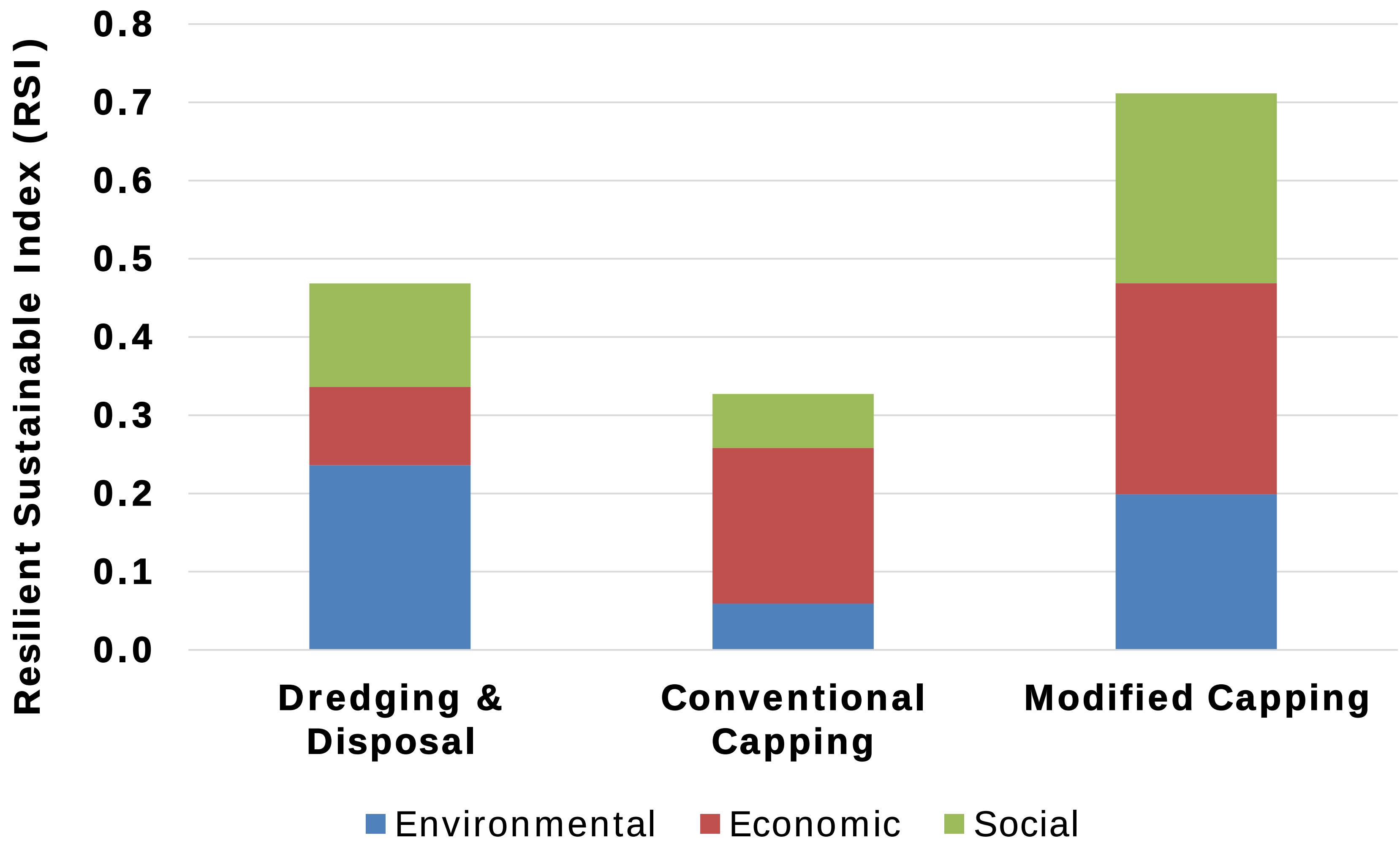
3. Modified / Reactive Capping

Resilience Index (RI)



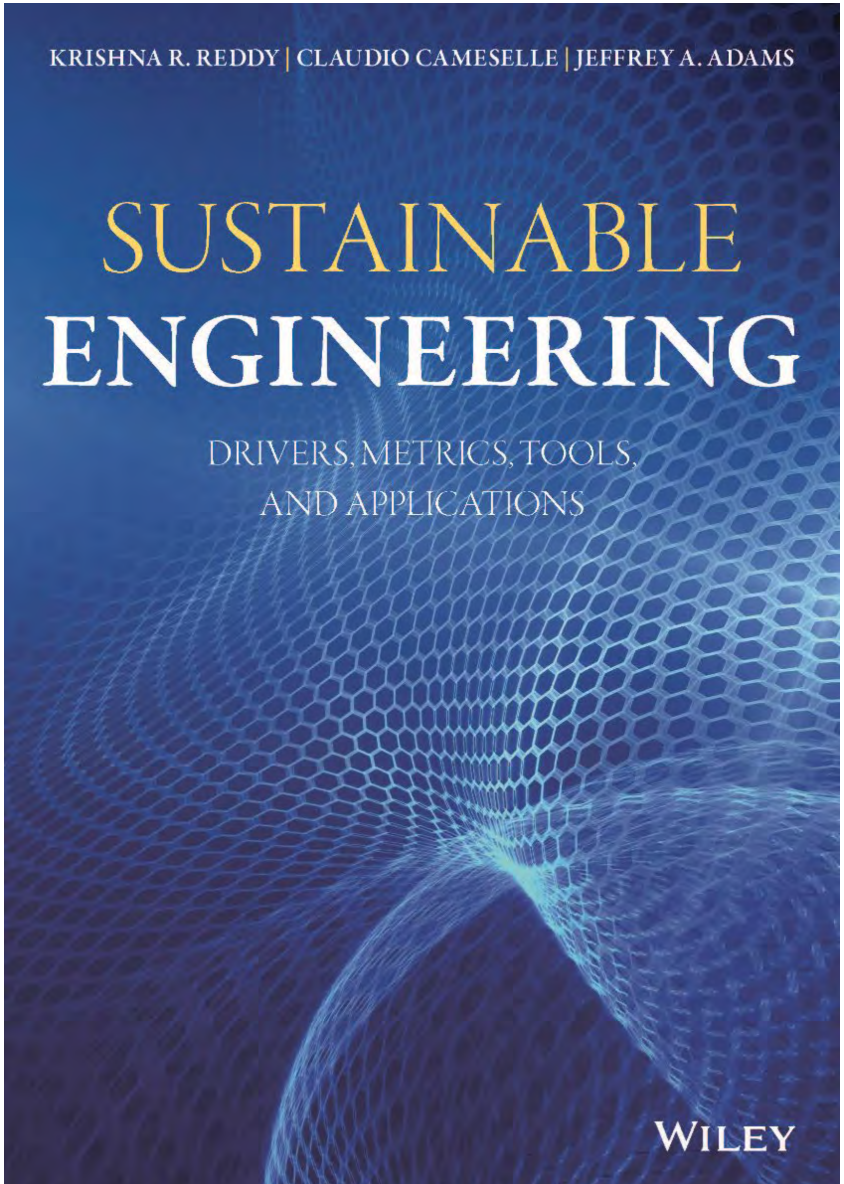
Based on this assessment, the Dredging and Disposal is the most resilient alternative!

Resilient Sustainable Index (RSI)



Ensure resiliency first & then look into sustainability?

Useful Reference



Sustainable Engineering: Drivers, Metrics, Tools, and Applications

Krishna R. Reddy
Claudio Cameselle
Jeffrey A. Adams

ISBN: 978-1-119-49393-8

2019

John Wiley & Sons

http://gagel.lab.uic.edu/

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- Sustainability and Resiliency-Based Innovation
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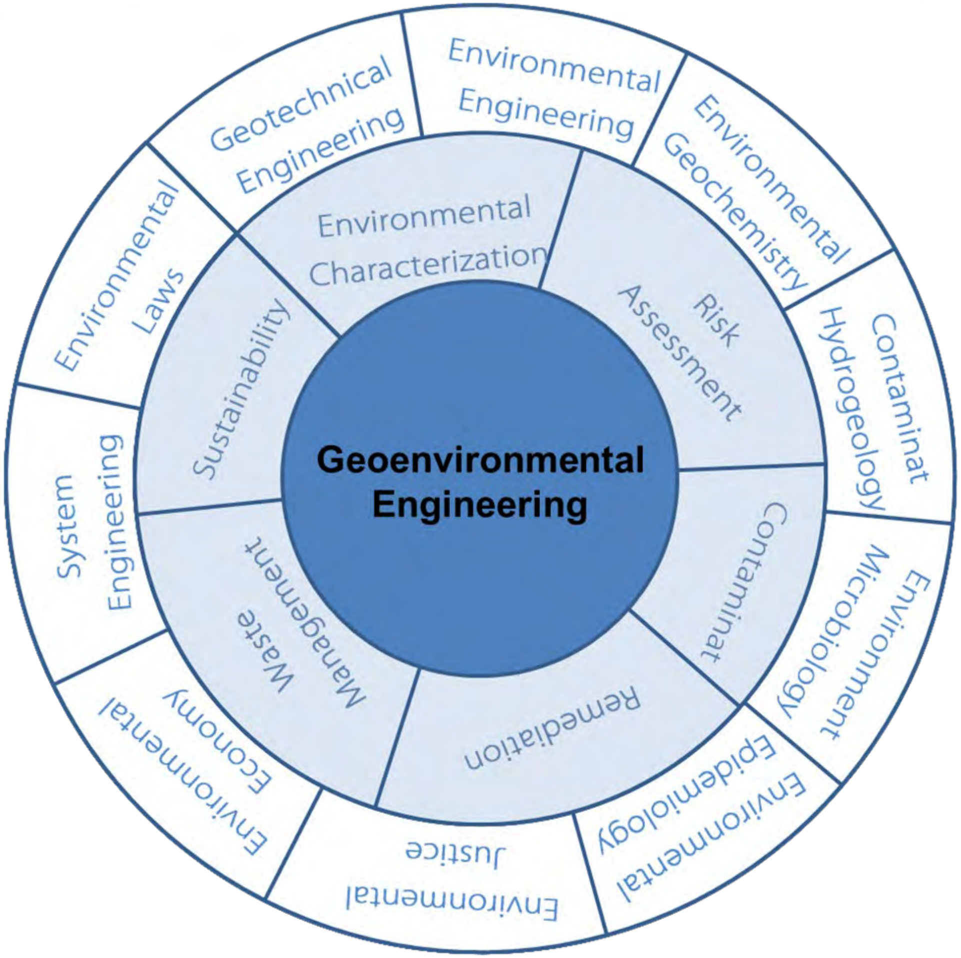
    - Environmental Remediation: Sustainable Technologies

- Concluding Remarks

Geoenvironmental Engineering?

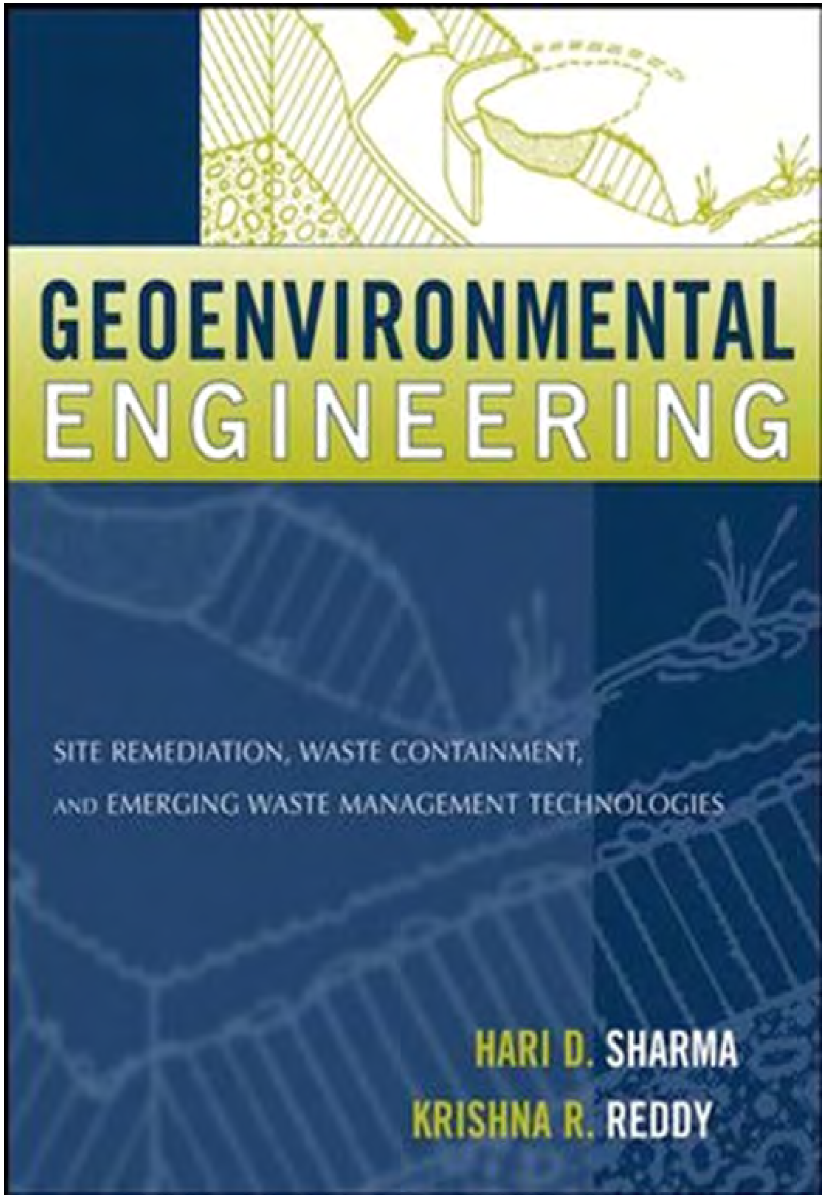


Geoenvironmental Engineering
Application of all relevant multi-disciplinary knowledge to understand and develop holistic engineered solutions to the geoenvironmental problems (waste management, polluted sites, sustainability, resiliency, etc.)

Multi-Disciplinary Technical Approach

Reddy, K.R. (2014). "Evolution of geoenvironmental engineering." *Environmental Geotechnics*, 1(3), 136-141

Useful Reference



Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies

Hari D. Sharma
Krishna R. Reddy

ISBN: 978-0-471-21599-8

2004

John Wiley & Sons

Geoenvironmental Engineering Challenges

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- **Safe Disposal of Non-Hazardous and Hazardous Wastes**
  - Characterization of Wastes (e.g., MSW, Industrial Waste, Coal Ash, Mine Tailings, Nuclear Waste,…)
  - Design of Containment Systems (e.g., Landfills and Impoundments)

- **Characterization and Remediation of Polluted Sites**
  - Site Investigations (e.g., Contaminant Sensors)
  - In-Situ Barriers (e.g., Slurry Walls, Grout Curtains, Capping)
  - Soil, Sediment, Groundwater, and Stormwater Remediation Technologies (e.g., Stabilization/Solidification, Electrokinetics)

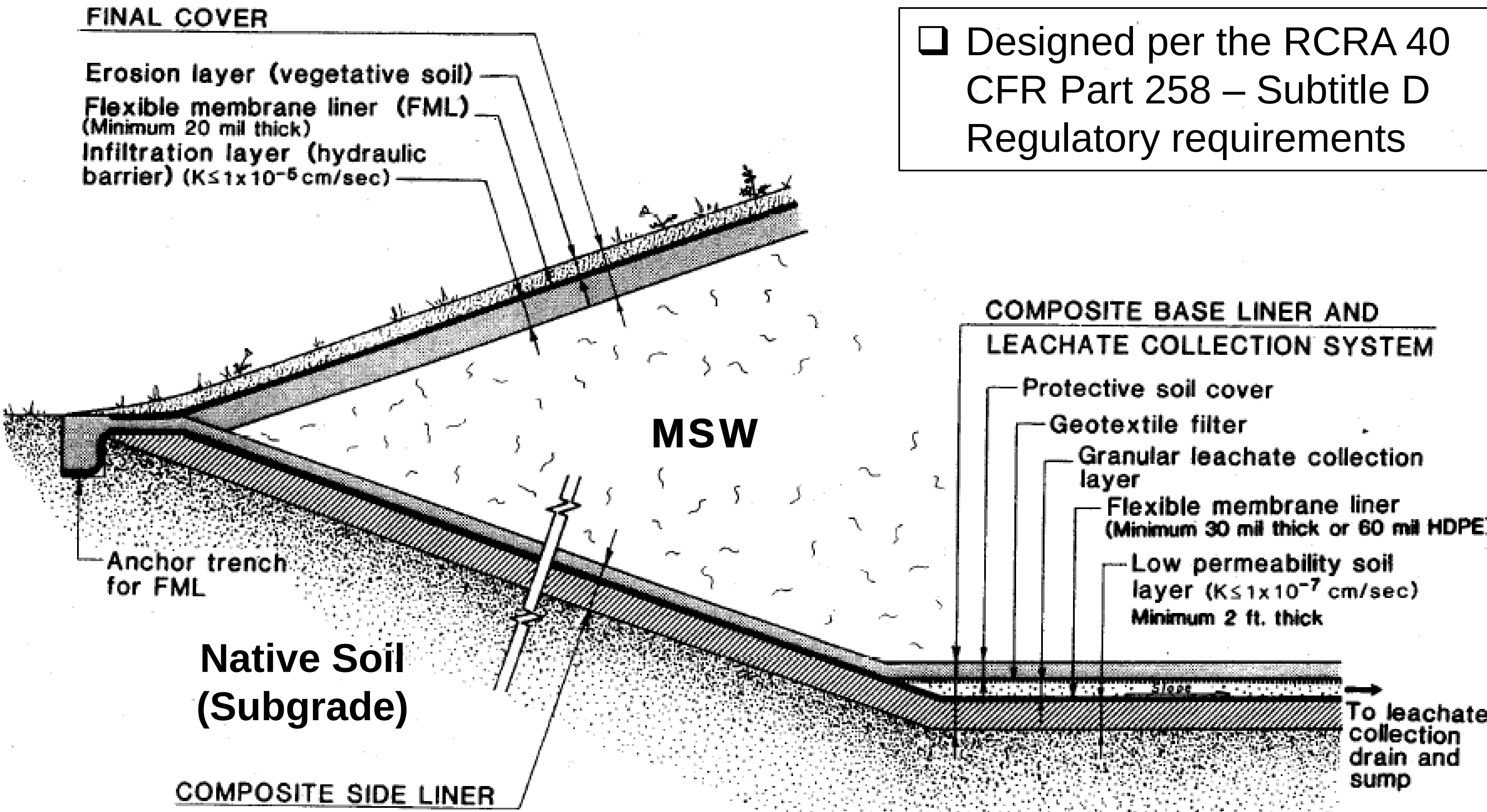
- **Enhance Environmental Sustainability and Resiliency**
  - Carbon Sequestration (e.g., Biochar, Biocovers)
  - Nature-Based Geo-Engineering (e.g., New Green Materials, Biocementation, Phytostabilization)
  - Upcycling of Waste/Recycled Materials (e.g., Scrap Tires)
  - End Use of Closed Landfills/Remediated Sites (e.g., Parks)
  - Renewable Geo-Energy (e.g., Geothermal, Landfill Gas, Biomass)

Significantly Contribute to SDGs

(including Climate Change Mitigation and Adaptation)!

Disposal of MSW: Engineered Landfill

- Designed per the RCRA 40 CFR Part 258 – Subtitle D Regulatory requirements



Landfill and its Components

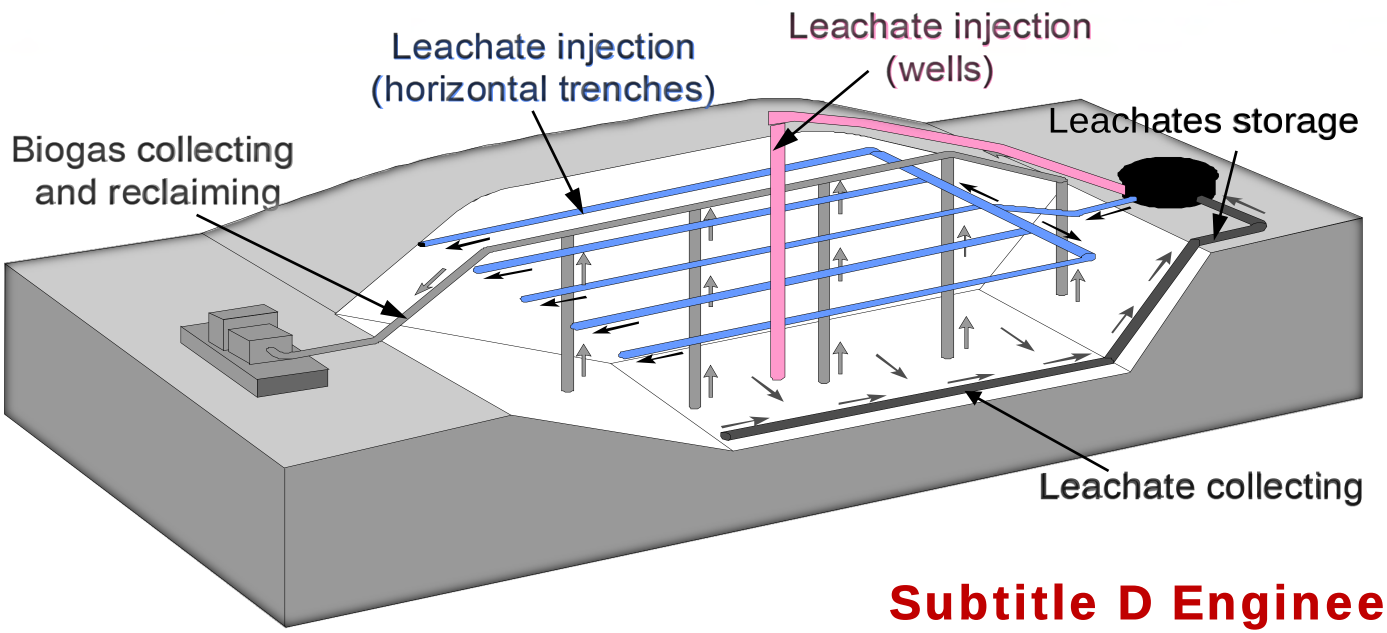
Based on field monitoring at many landfills for several decades, design proven excellent!

Source: Sharma and Reddy (2004)

Issues with Engineered Landfill

- Slow waste decomposition
- Low gas generation and settlement rates
- Prolonged waste stabilization period–high monitoring costs
- Leachate treatment and disposal costs
- Prolonged CH_4 and CO_2 emissions
- A long-term liability

Bioreactor Landfill



Subtitle D Engineered Landfill

Primary Benefits

- Promotes rapid waste decomposition
- Enhanced gas generation rates
- Increased gas to energy conversion
- High settlement rates
- Early waste stabilization

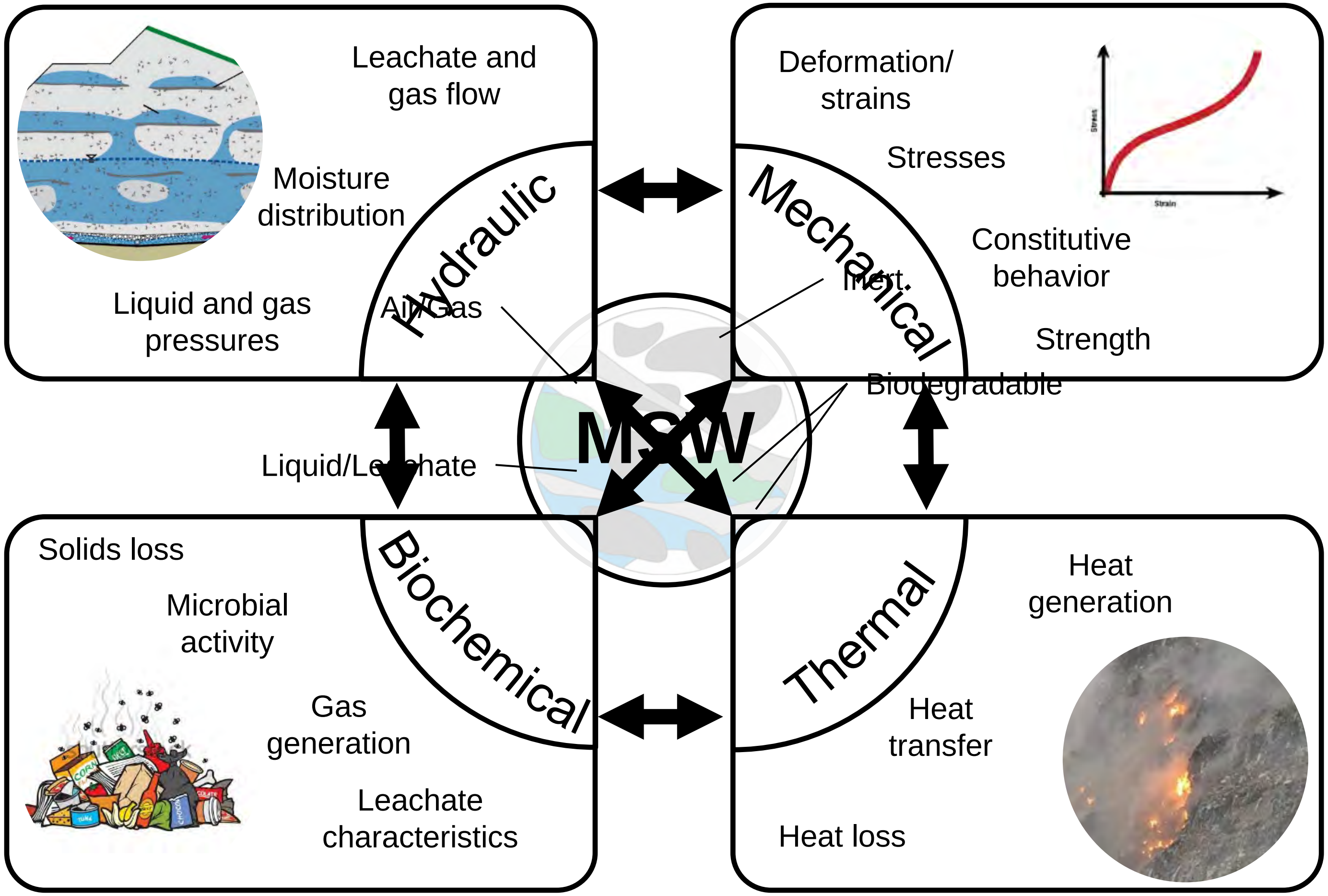
Secondary Benefits

- Reduced post-closure monitoring costs
- Reduced organic strength of leachate
- Reduced leachate treatment and disposal costs
- Landfill space reclamation for fresh waste
- Reclamation of inorganics (recyclables)

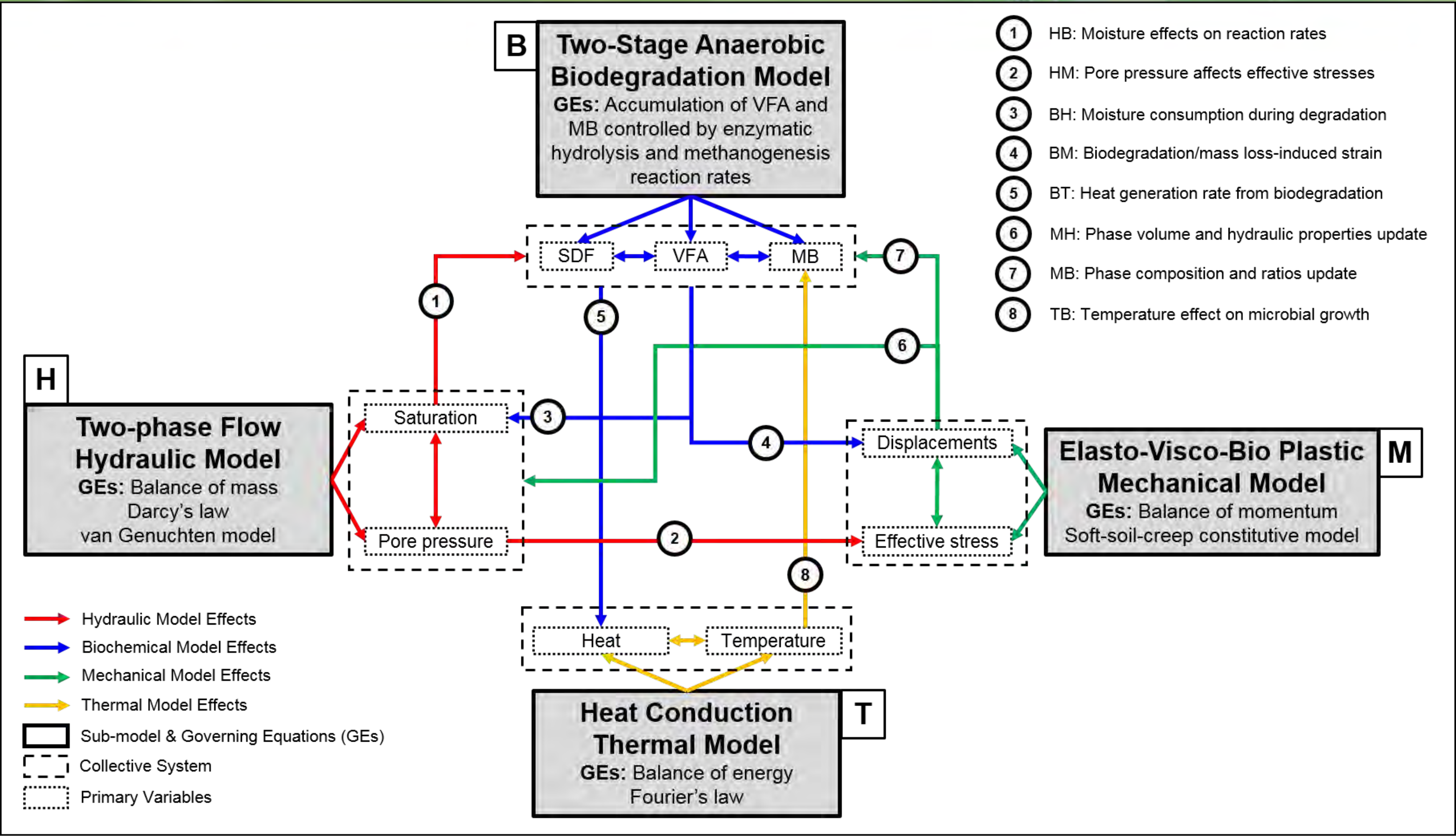
Key Practical Challenges

- Optimizing leachate injection
- Ensuring slope stability
- Consequences on gas, heat, and leachate generation
- Spatial and temporal variations in moisture, settlement, temperatures, and properties of waste
- Stability and integrity of liner and cover systems
- Time for waste stabilization

Coupled Dynamic Processes in Landfills

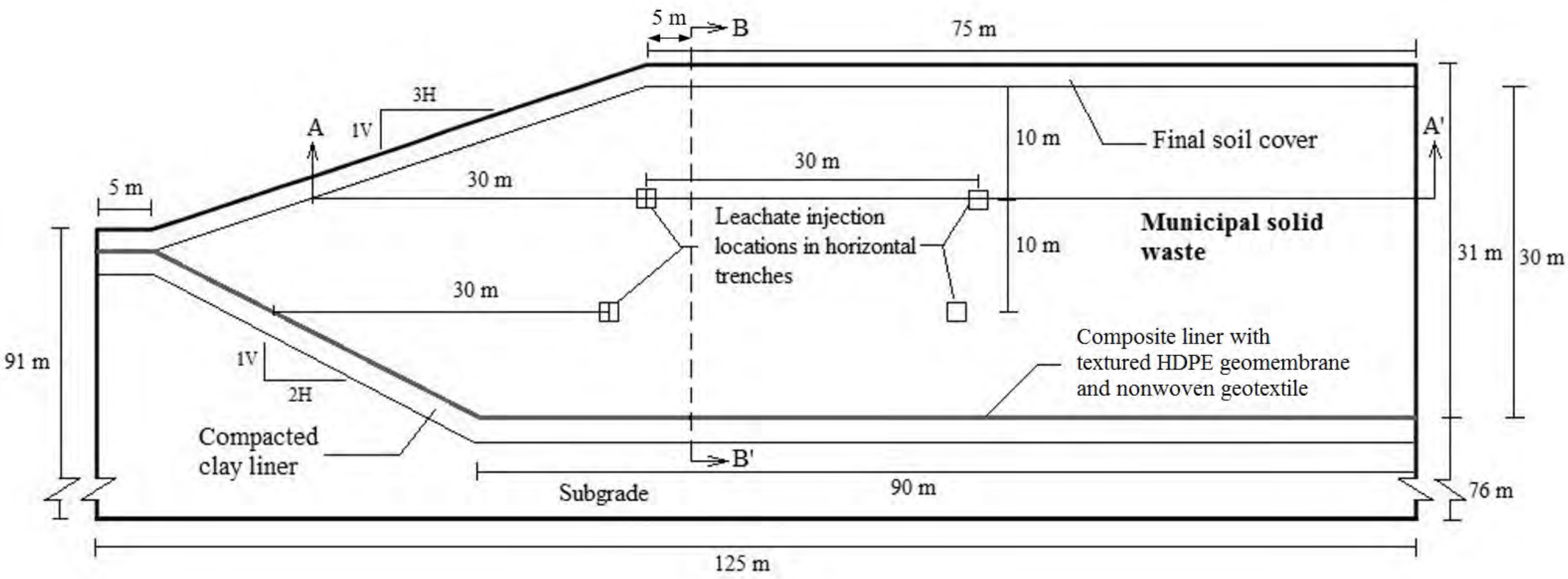


Coupled Thermo-Hydro-Bio-Mechanical Model



Kumar, G., and Reddy, K.R. (2021). "Comprehensive coupled thermo-hydro-bio-mechanical model for holistic performance assessment of municipal solid waste landfills." Computers and Geotechnics (DOI: 10.1016/j.compgeo.2020.103920)

Rockford Landfill: Model Application



- Two simulations: Conventional (**CONV**) and Bioreactor (**BIOR**)
- Leachate injection mode: **Continuous**
- Leachate injection pressure: **50 kPa**
- Total number of horizontal trenches: **4**
- Horizontal spacing between the trenches: **30 m**

Moisture and Porewater Pressure Distribution

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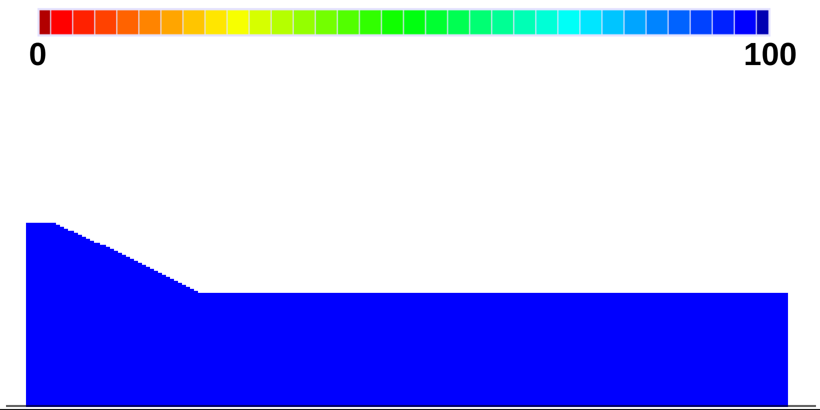
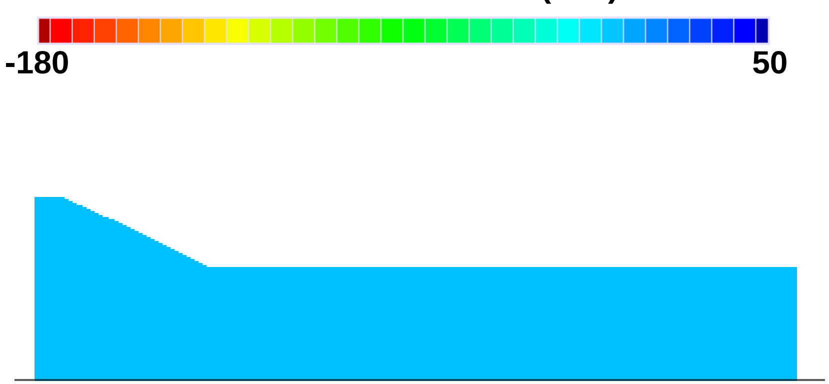
Conventional Landfill Simulation

Degree of Saturation (%)

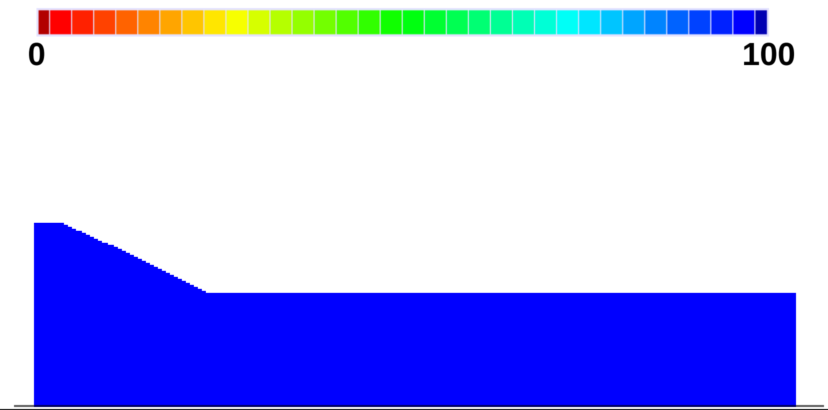


Pore Water Pressure (kPa)

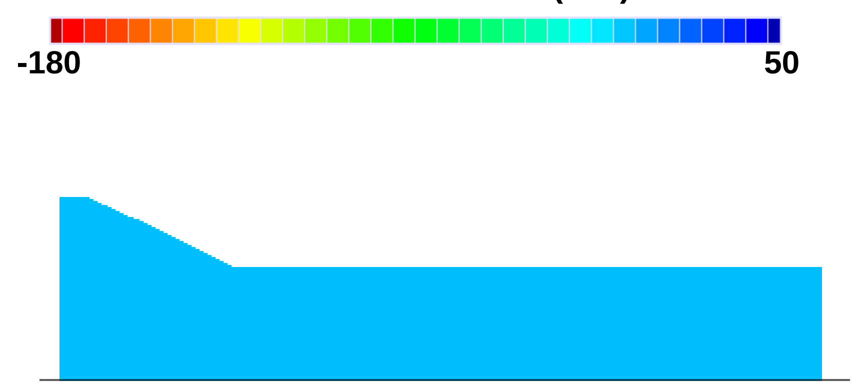


Bioreactor Landfill Simulation

Degree of Saturation (%)



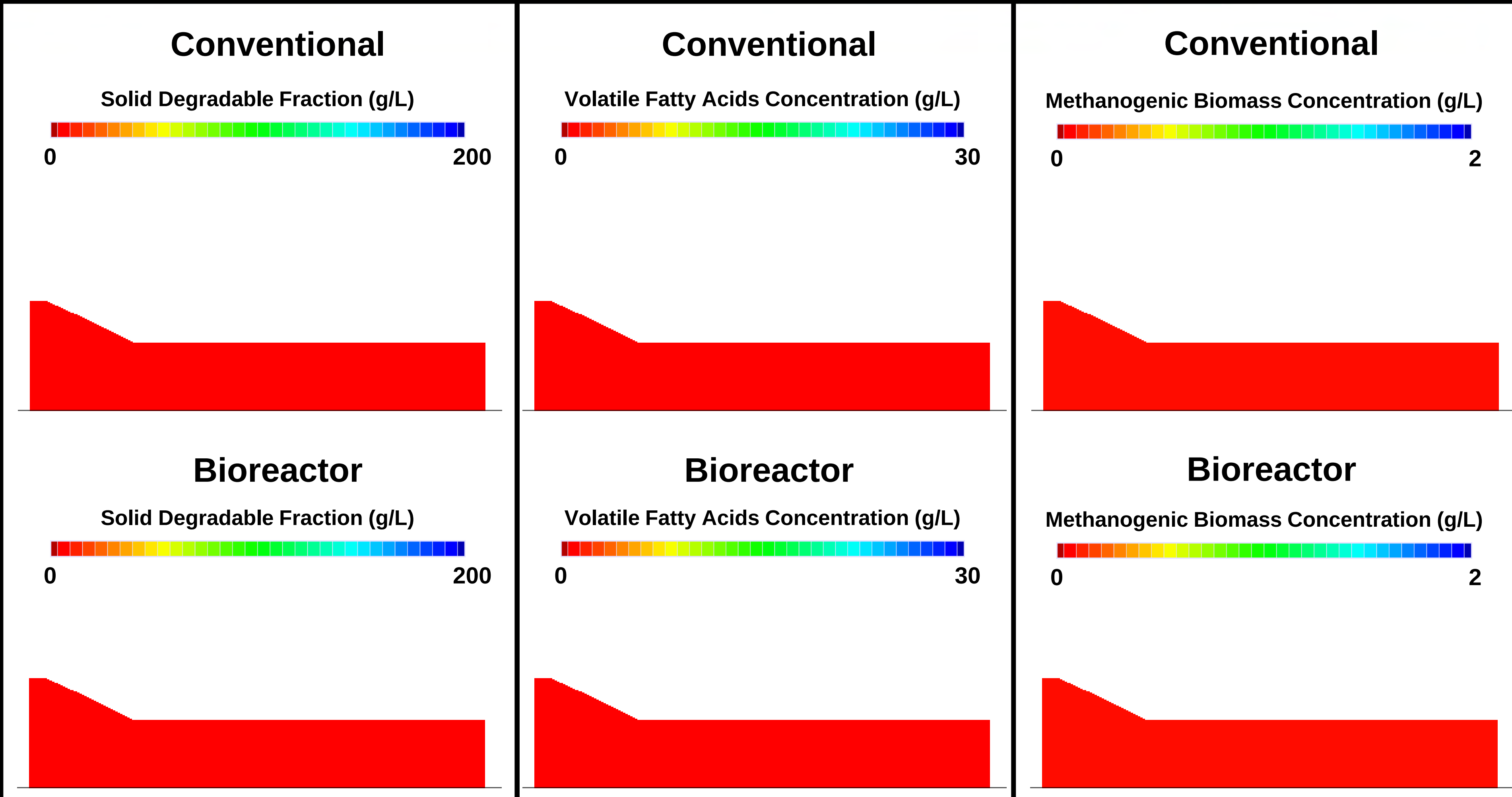
Pore Water Pressure (kPa)



Under the simulated leachate injection conditions:

- Maximum wetted area achieved = 60%
- Steady state flow reached in approximately 5 years
- Pore water pressures (PWP) near slopes were < 0

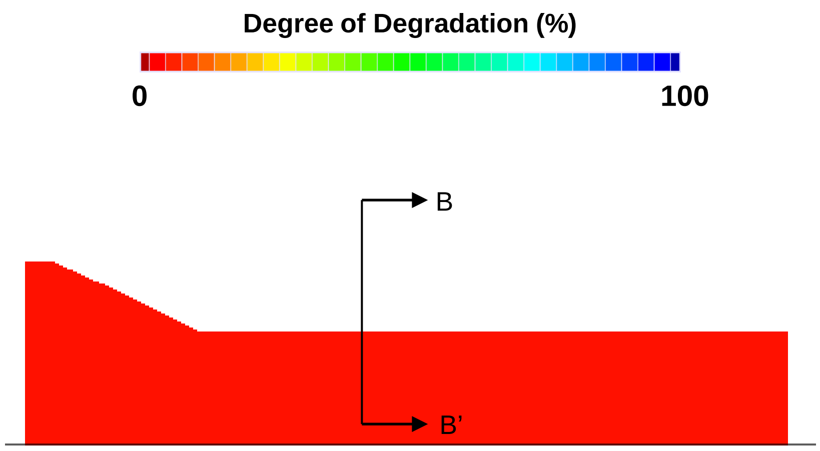
Spatial and Temporal Variation – SDF, VFA, MB

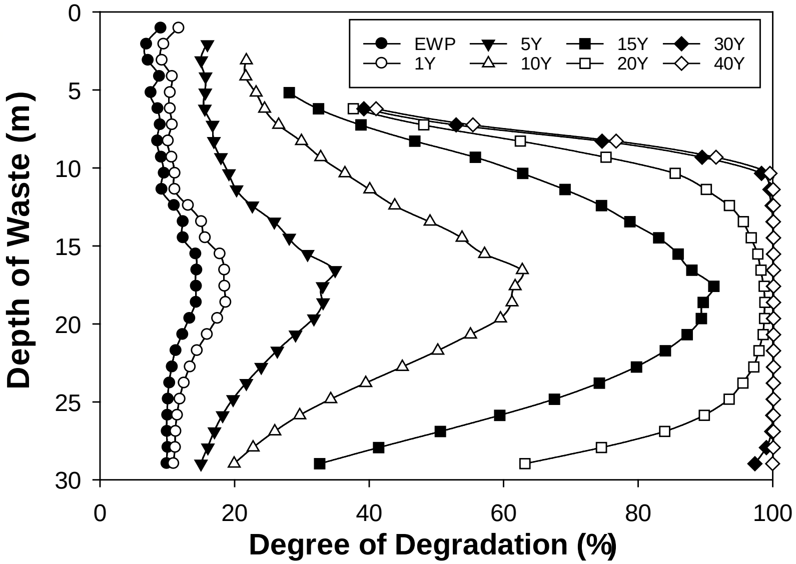


- Dynamic interactions between the biochemical and thermal processes is apparent
- Relatively high biological activity in the central region of the landfill
- Top (~8 m) of the landfill and the waste near the slope remained relatively undegraded – lack of sustained favorable temperatures

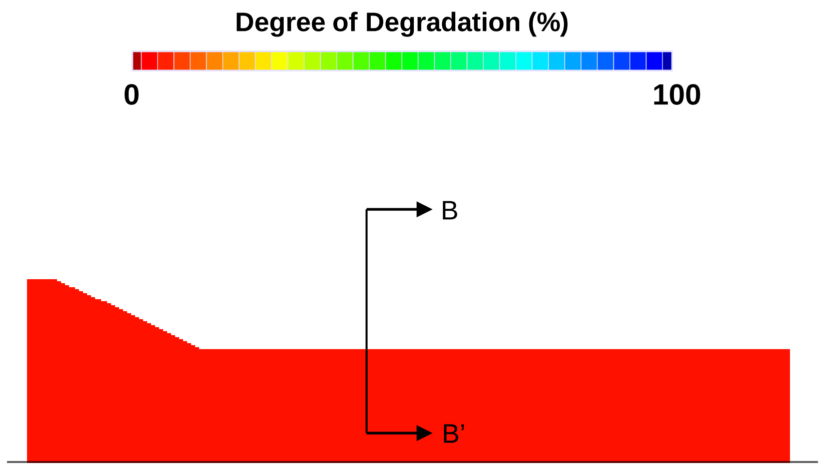
Degree of Degradation

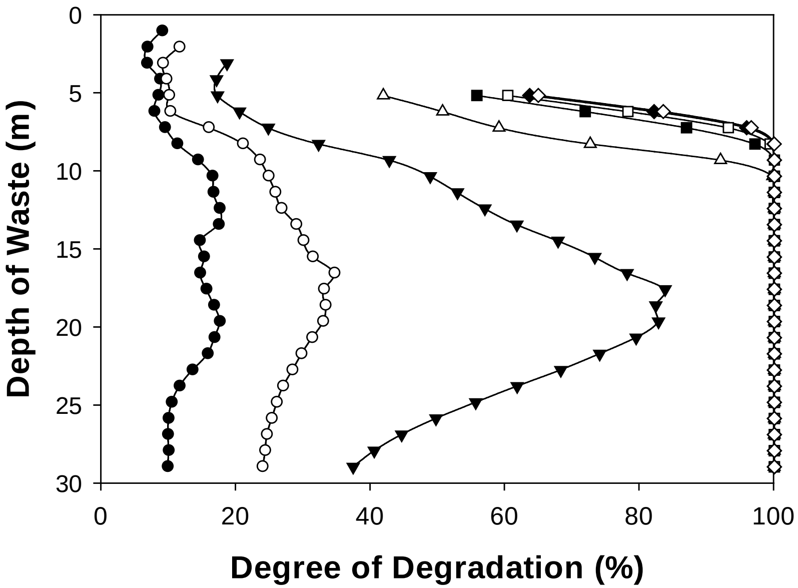
Conventional Landfill Simulation





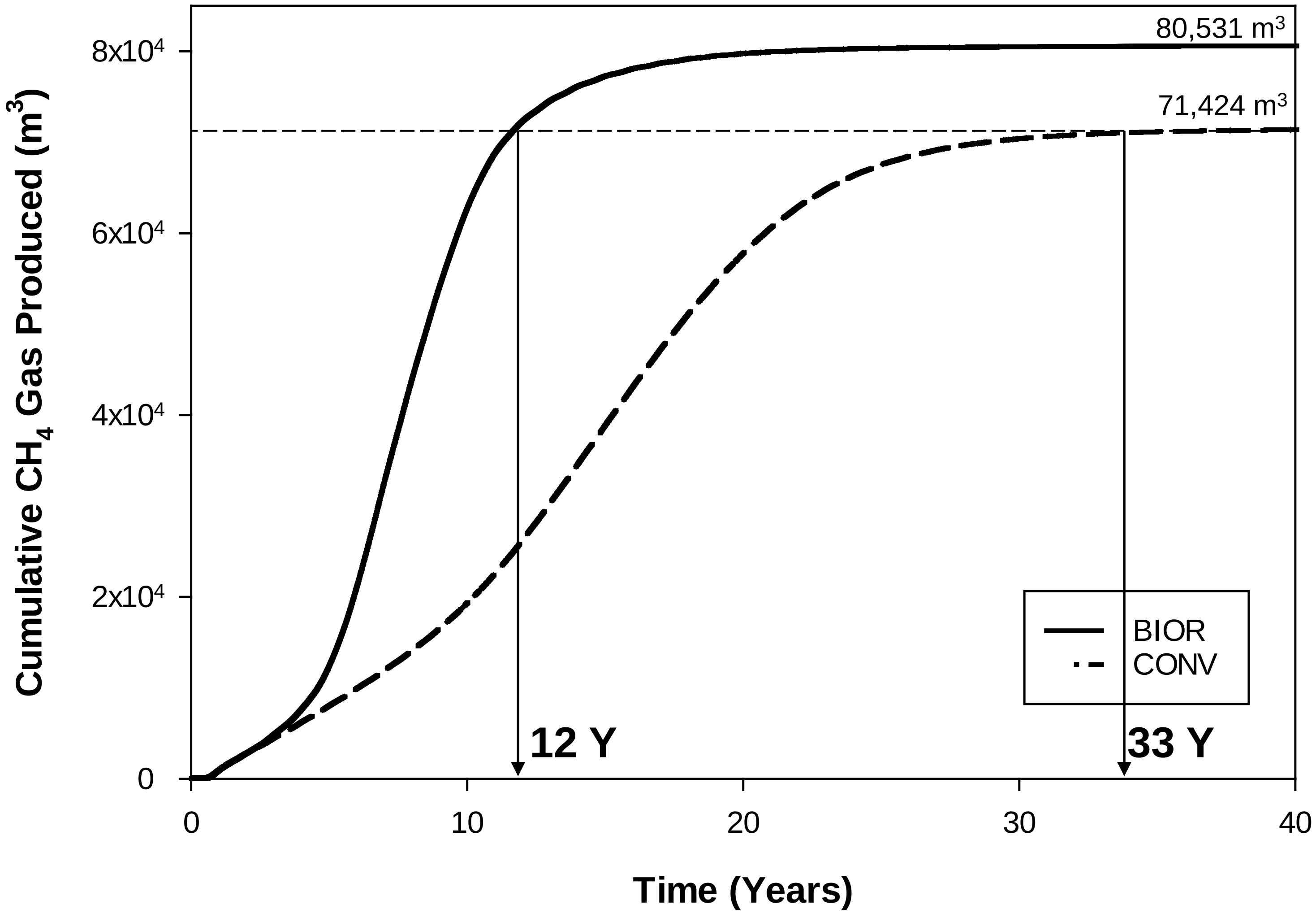
Bioreactor Landfill Simulation





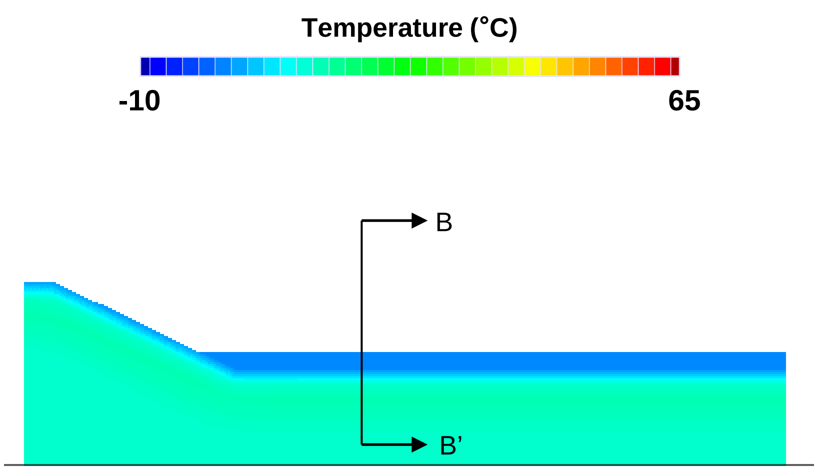
Cumulative Methane (CH_4) Gas Production

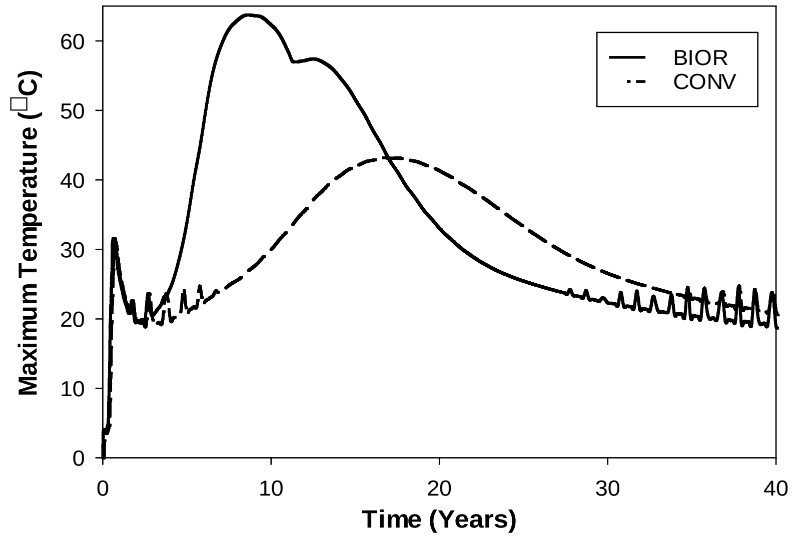
UIC



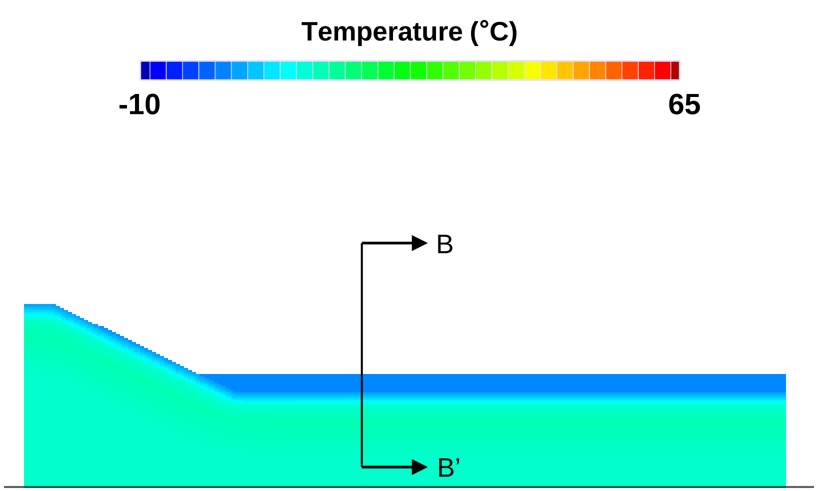
Heat Generation and Temperature Distribution

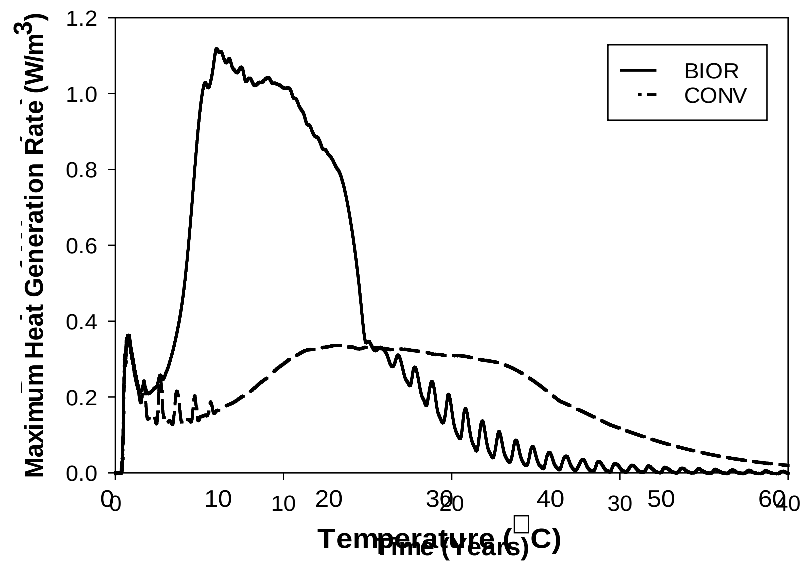
Conventional Landfill Simulation





Bioreactor Landfill Simulation



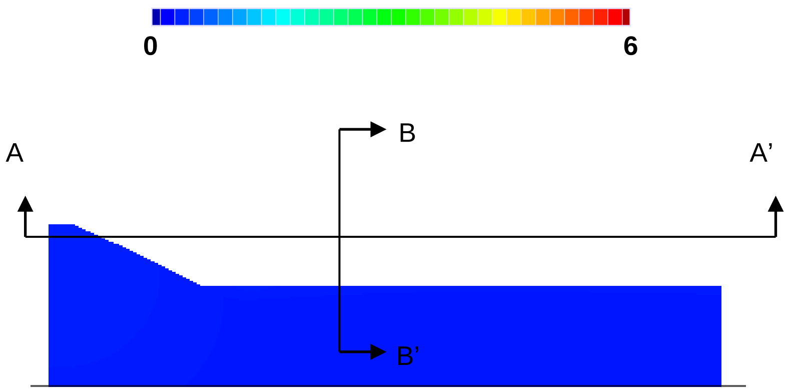


Settlement of Waste

Spatial and Temporal Distribution

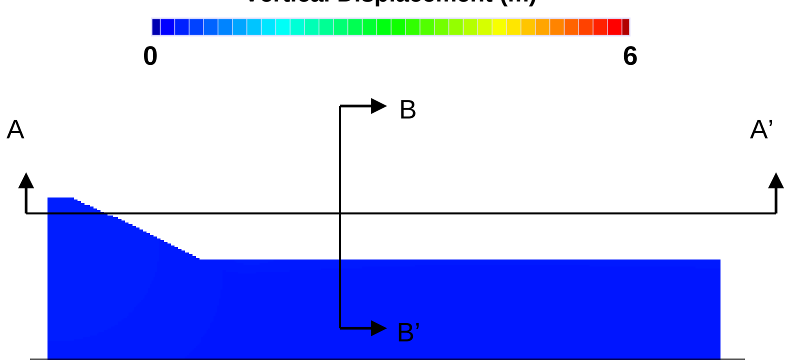
Conventional

Vertical Displacement (m)

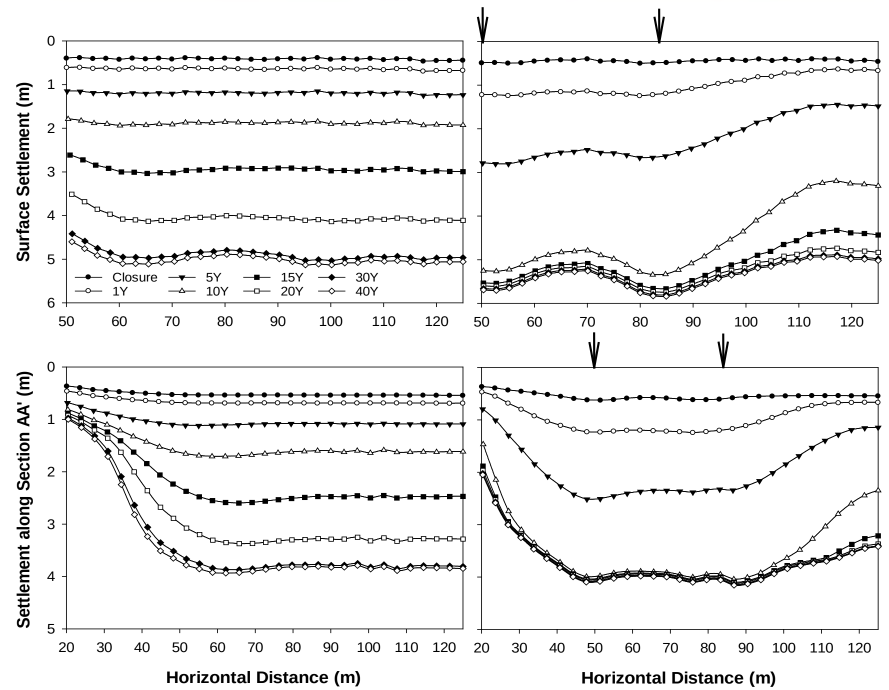


Bioreactor

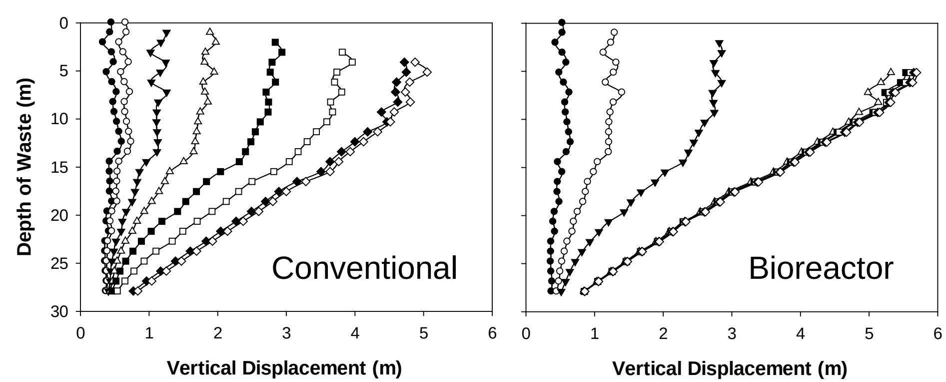
Vertical Displacement (m)



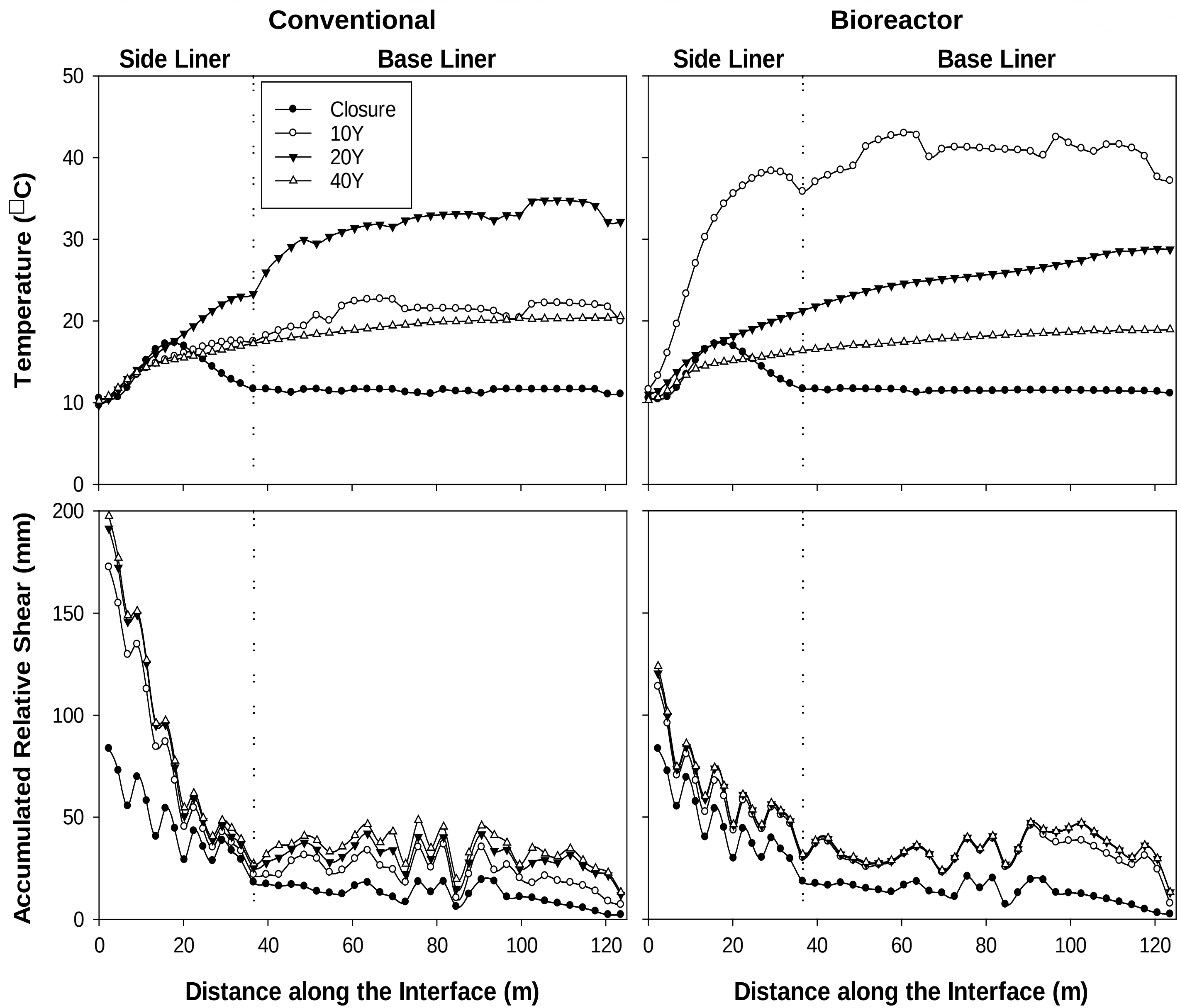
Conventional Bioreactor



Settlement along Section BB'



Interface Shear Response – Bottom Liner



Spatial Variability – Typical Realization

Lognormal distribution

$$k(x_i) = \exp\{\mu_{ln\,k} + \sigma_{ln\,k} \cdot G(x_i)\}$$

$$\mu_{ln} = ln\left(\frac{\mu}{\sqrt{1+\frac{\sigma^2}{\mu^2}}}\right)$$

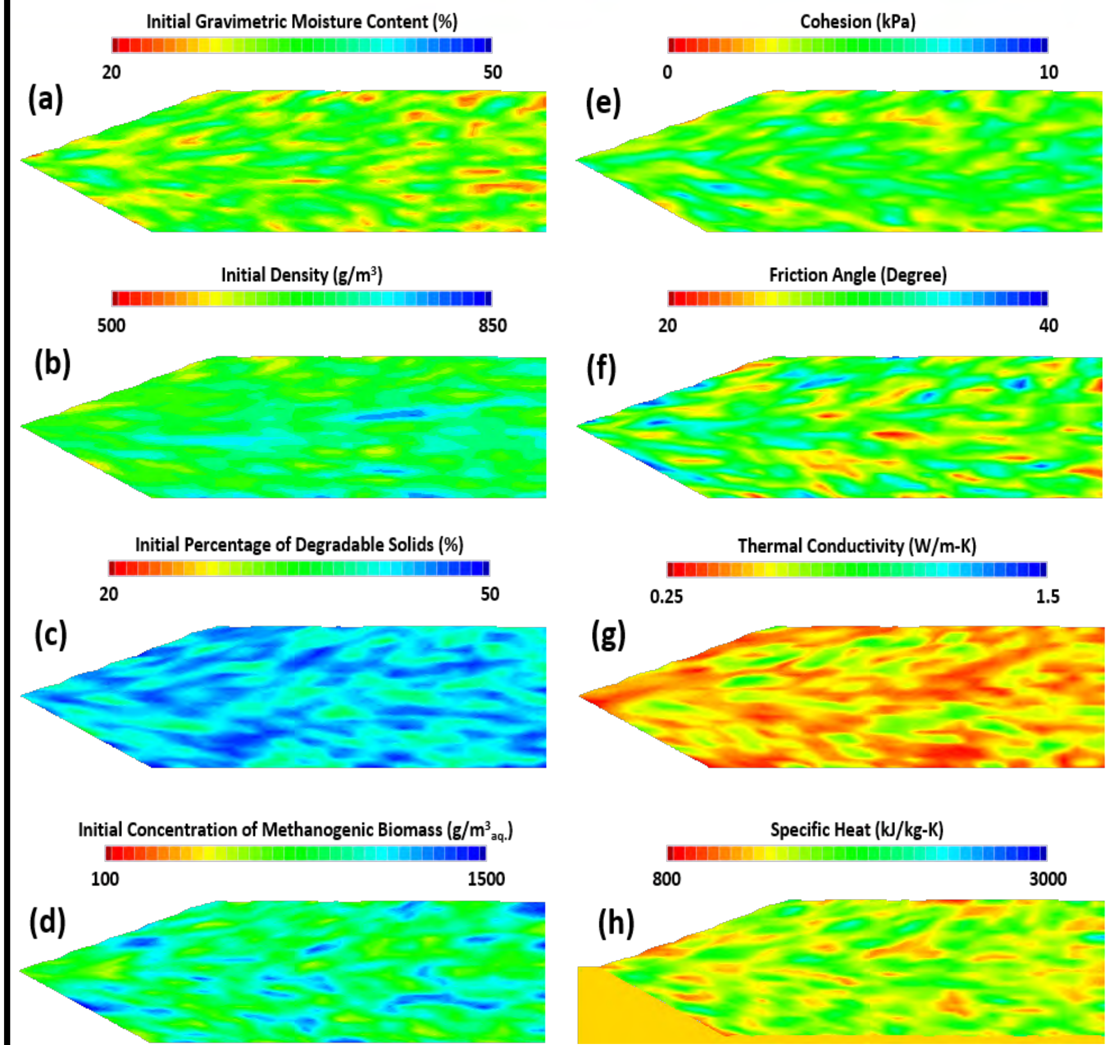
$$\sigma_{ln} = \sqrt{ln\left(1+\frac{\sigma^2}{\mu^2}\right)}$$

$k(x_i)$ - randomly generated value for a property of waste

μ_{ln} - lognormal mean

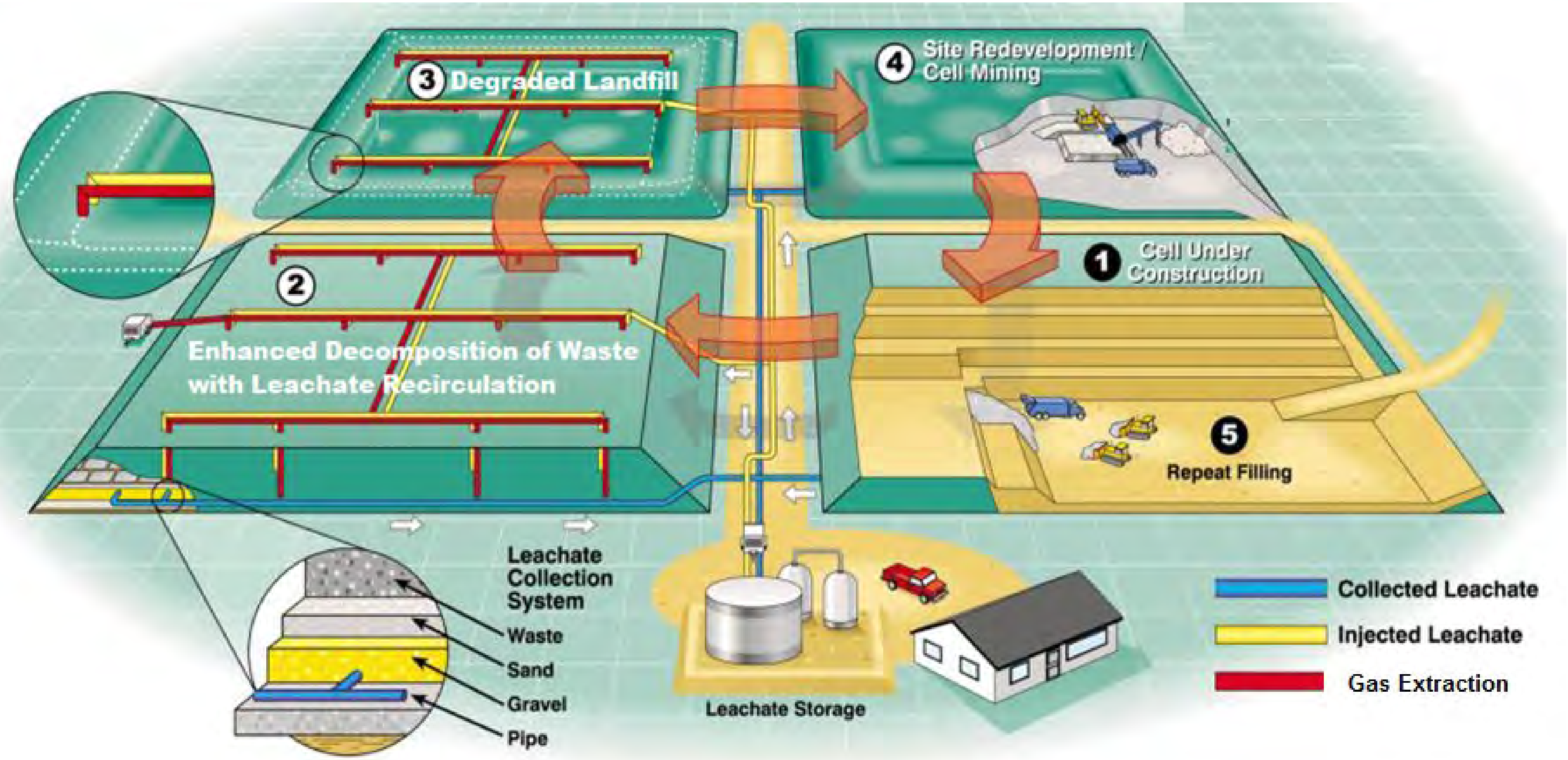
σ_{ln} - lognormal standard deviation

$G(x_i)$ - uncorrelated random variable based on Gaussian distribution



Deterministic analysis: Performed using mean values of the MSW properties

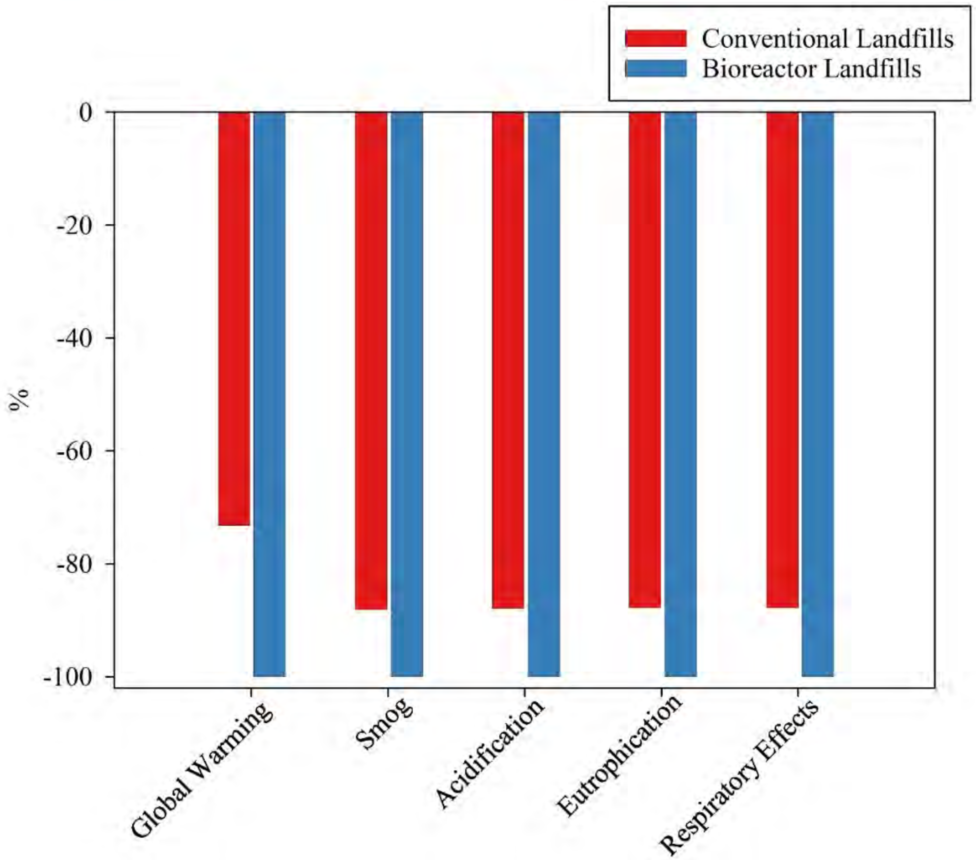
Goal: Sustainable Landfill

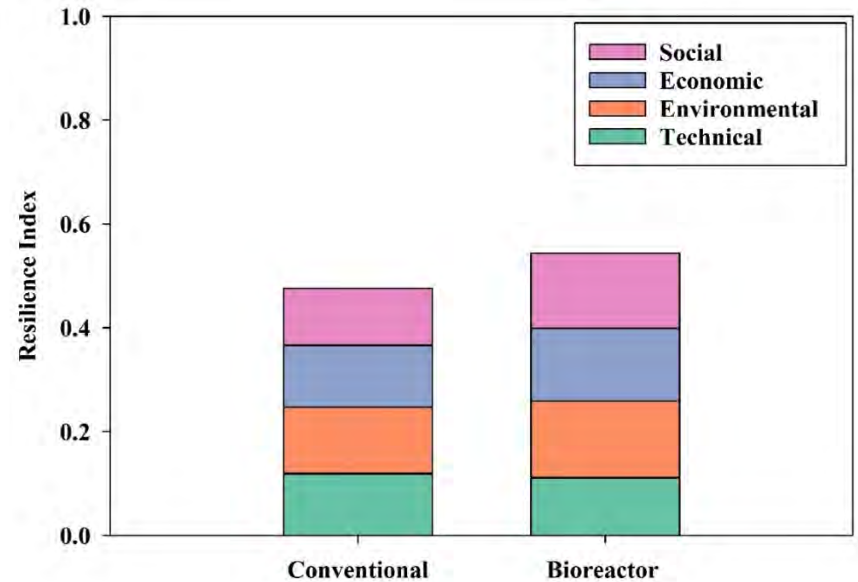


Anaerobic waste treatment in an engineered waste containment system

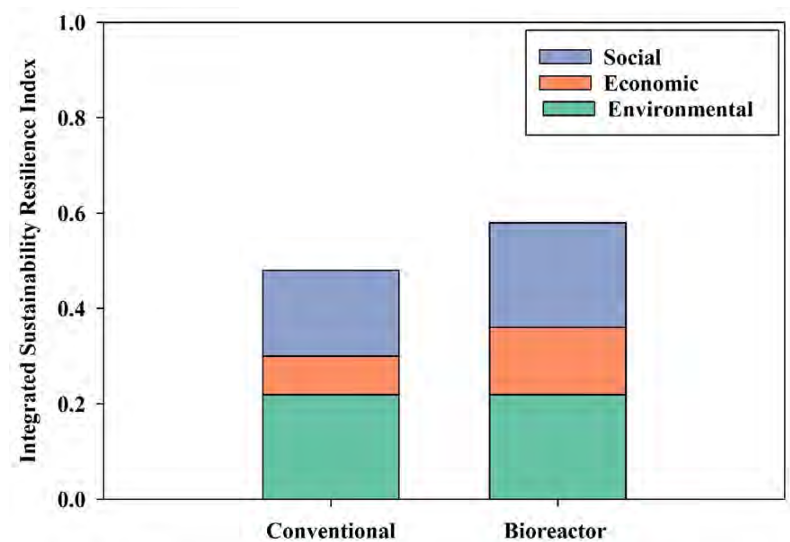
Source: ECS Inc.

Is it Sustainable?

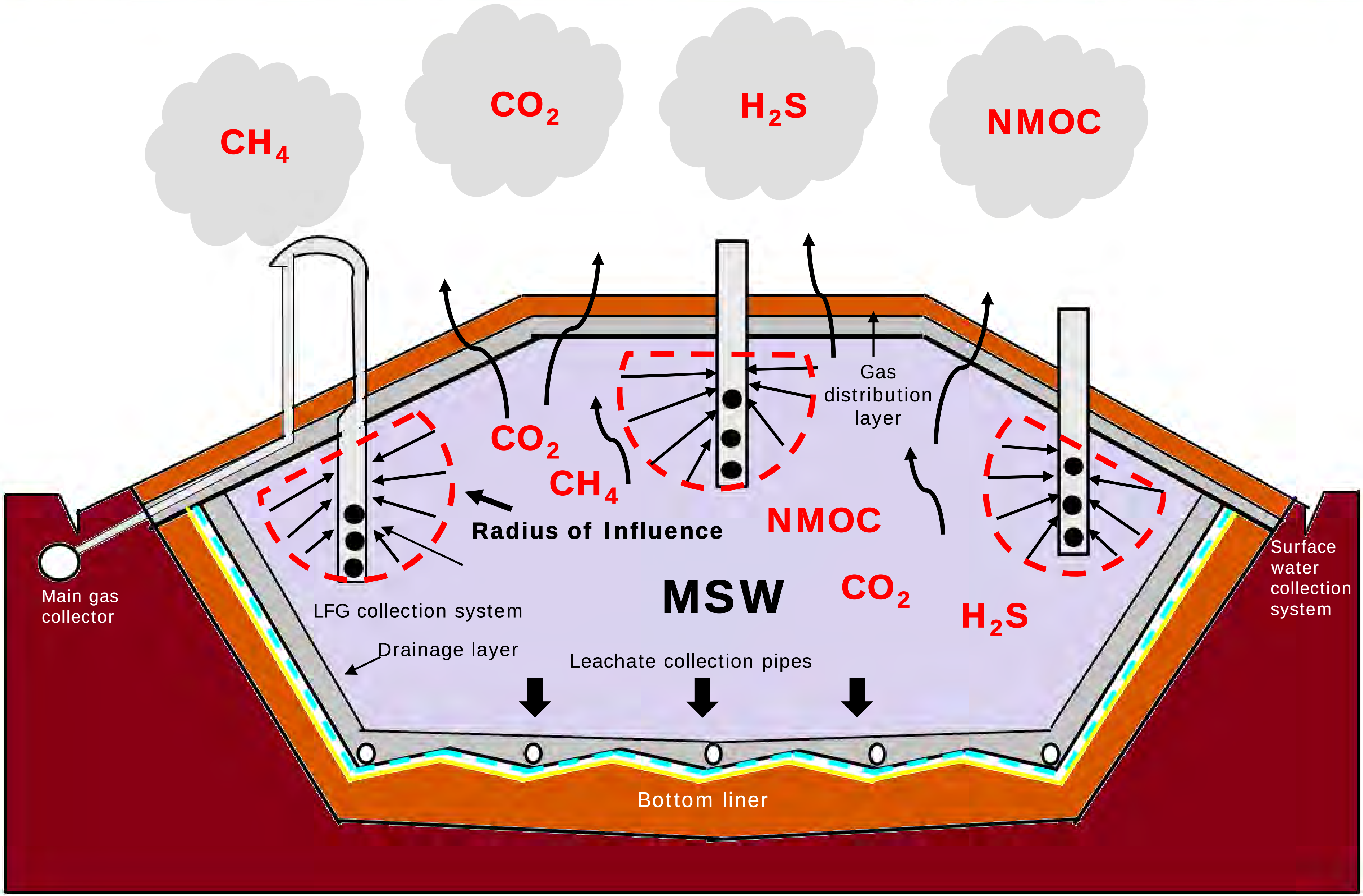




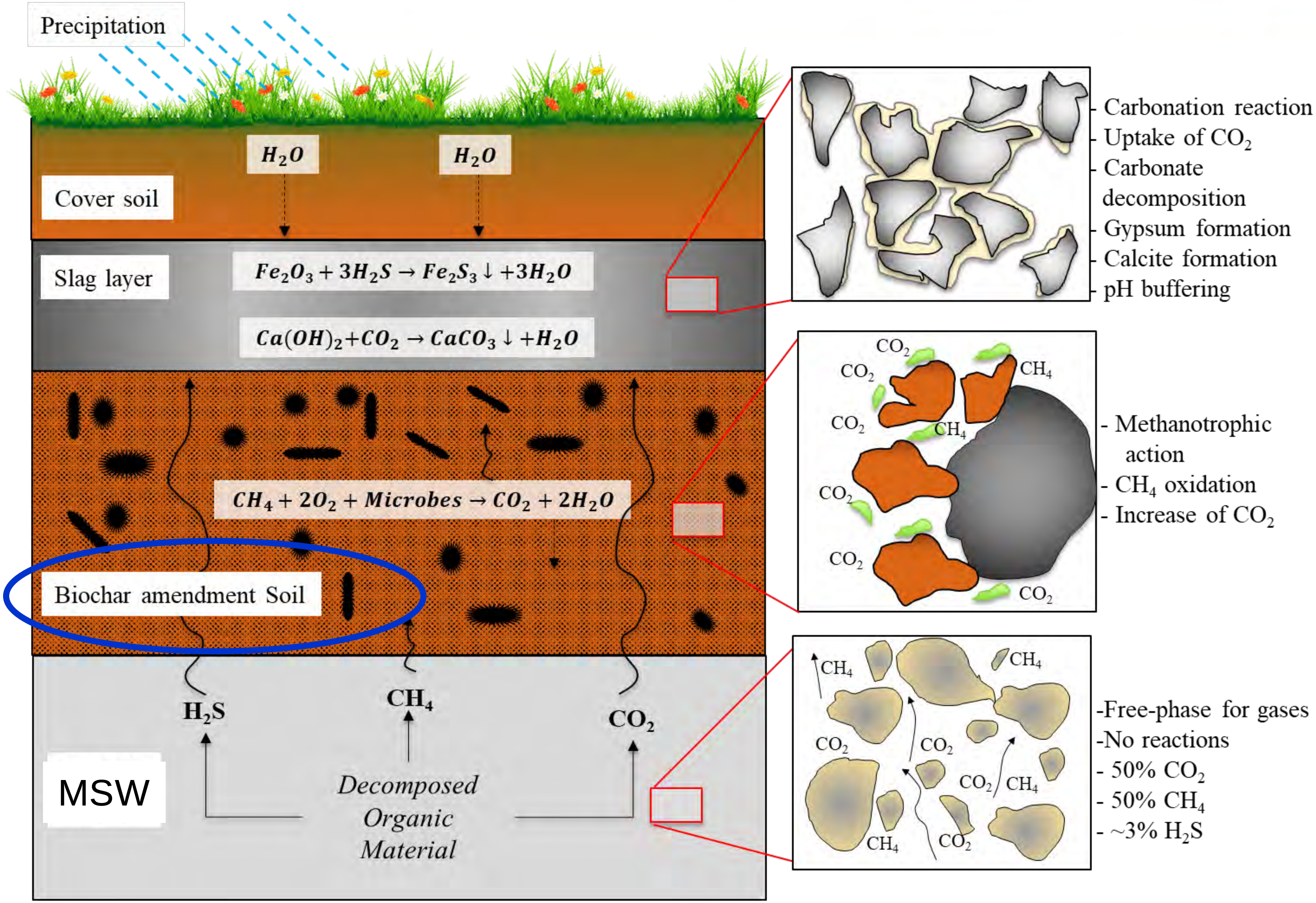
Comparison of Conventional and Bioreactor Landfills (accounting for the impacts of construction and operation of leachate recirculation system and benefits of gas-to-energy)



Engineered Landfills: Fugitive Emissions

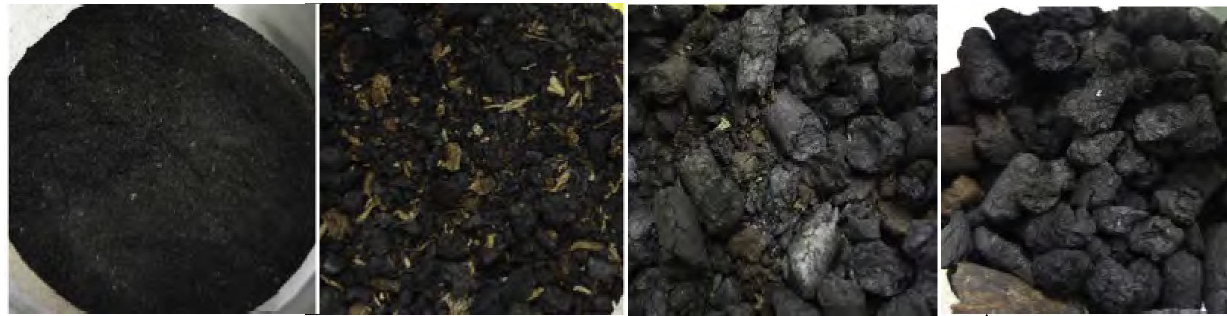


Biogeochemical Cover System



What is Biochar?

UIC



Manure → Biomass
Wood Chips → Biomass
Crop Residues → Biomass

Biomass → Pyrolysis/ Gasification → Biochar

Pyrolysis/ Gasification → Bio-oils/Gaseous fuels

Properties

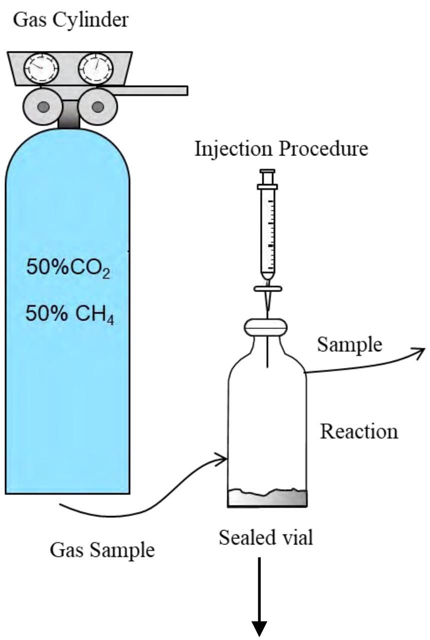
- High surface area & internal porosity
- High water and nutrient retention
- Higher resistance to biotic degradation
- Ability to adsorb gases
- Enhance microbial colonization

Applications

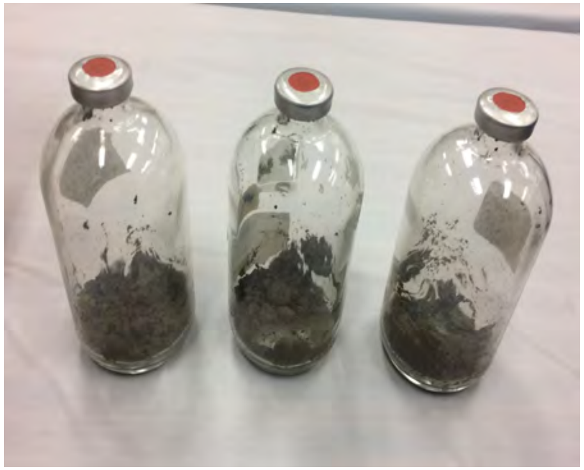
- Improvement of soil quality and carbon sequestration (agriculture)
- Environmental remediation of soils and groundwater
- We are the first ones to propose for covers

Benefit of Biochar Amendment on Methane Oxidation?

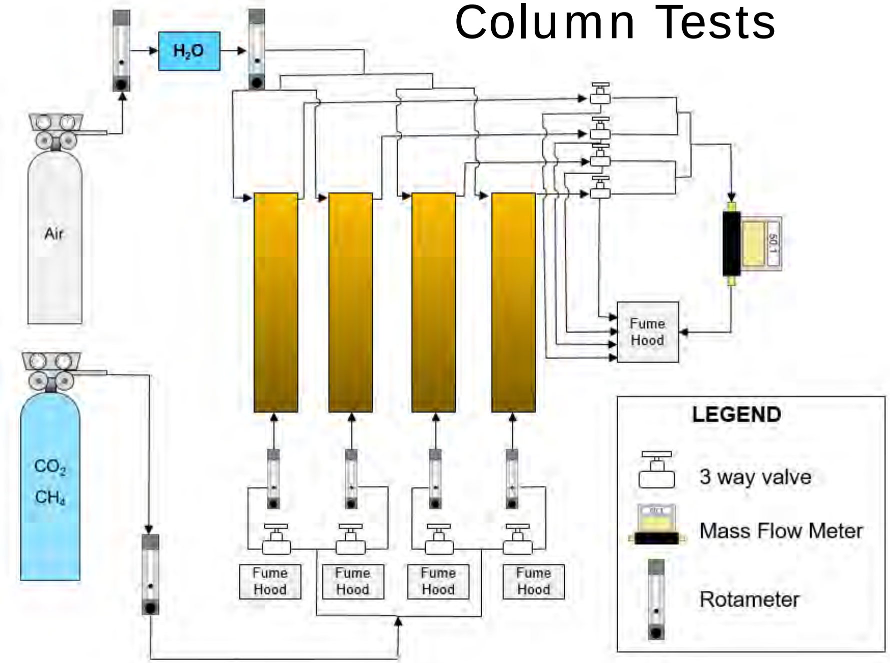
Batch Tests



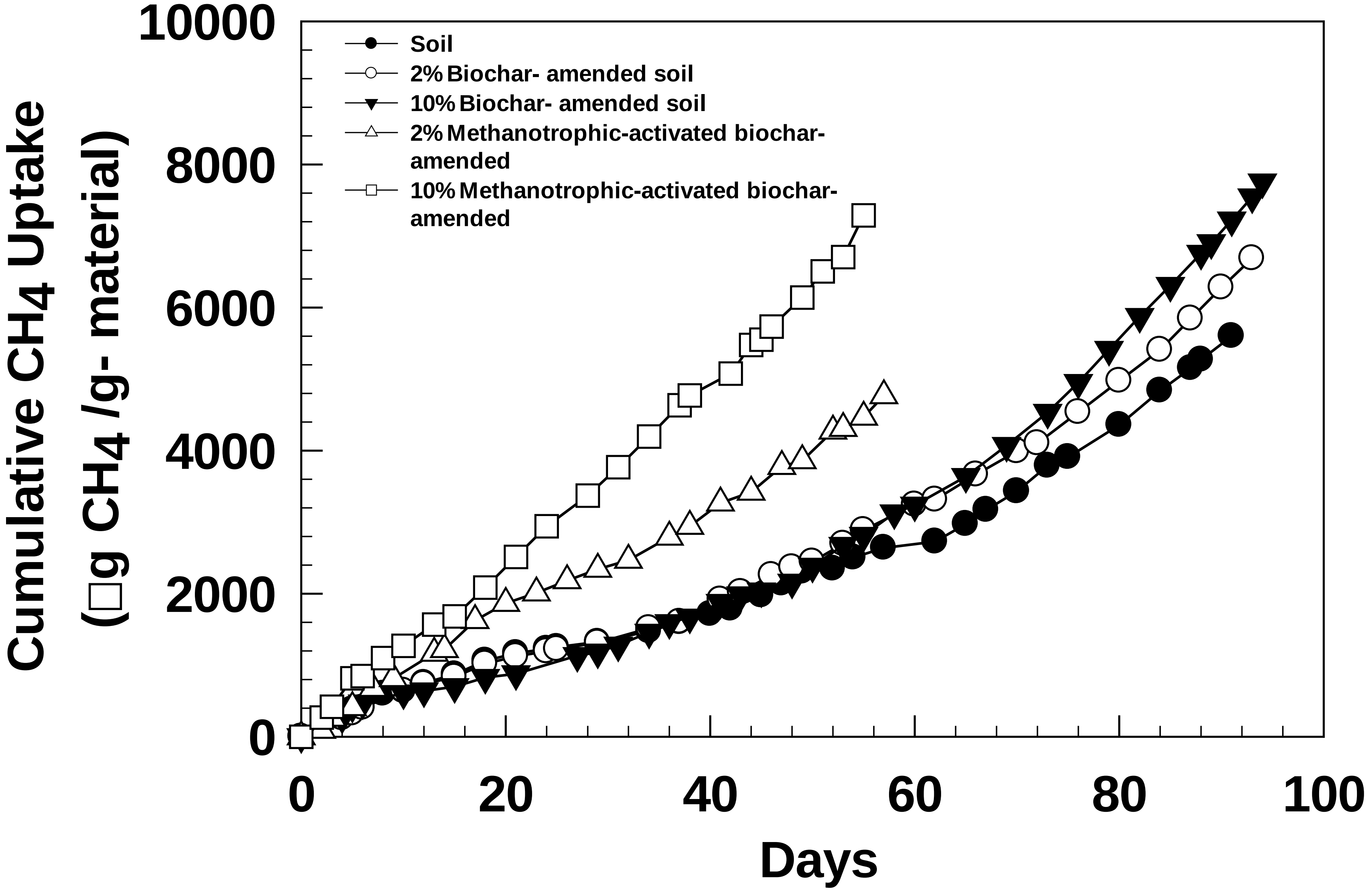
Gas Chromatography



Column Tests

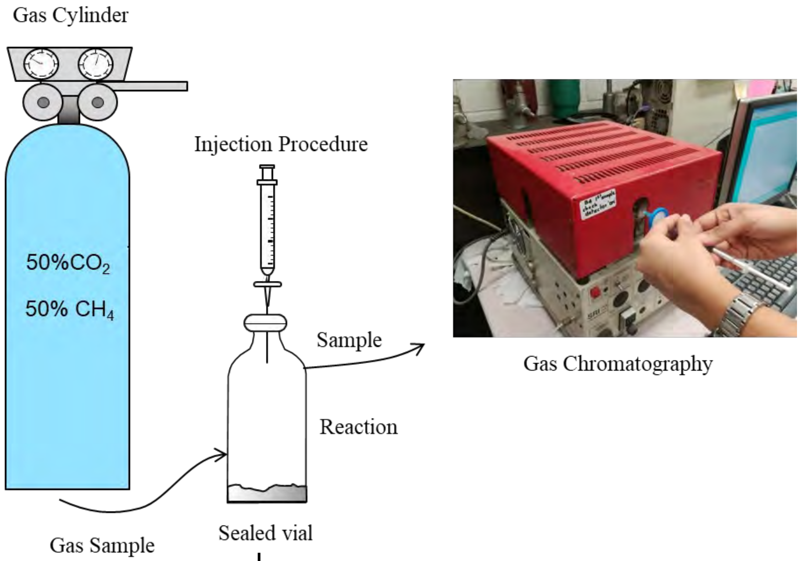


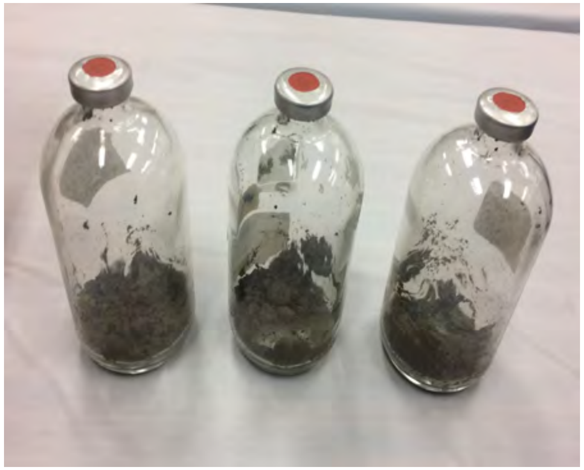
Biochar-Amended Soil: Methane Oxidation



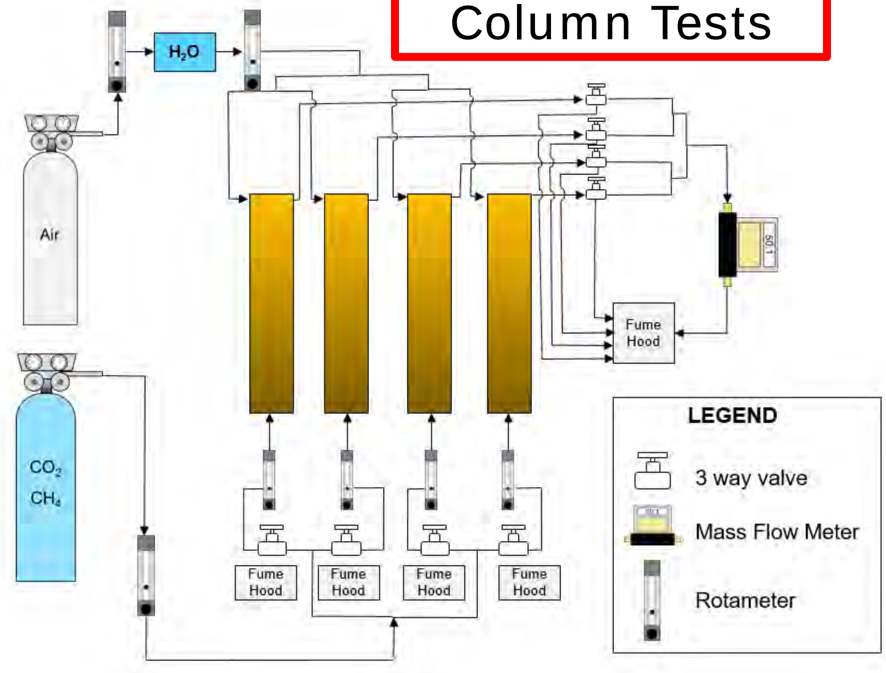
Benefit of Biochar Amendment on Methane Oxidation?

Batch Tests

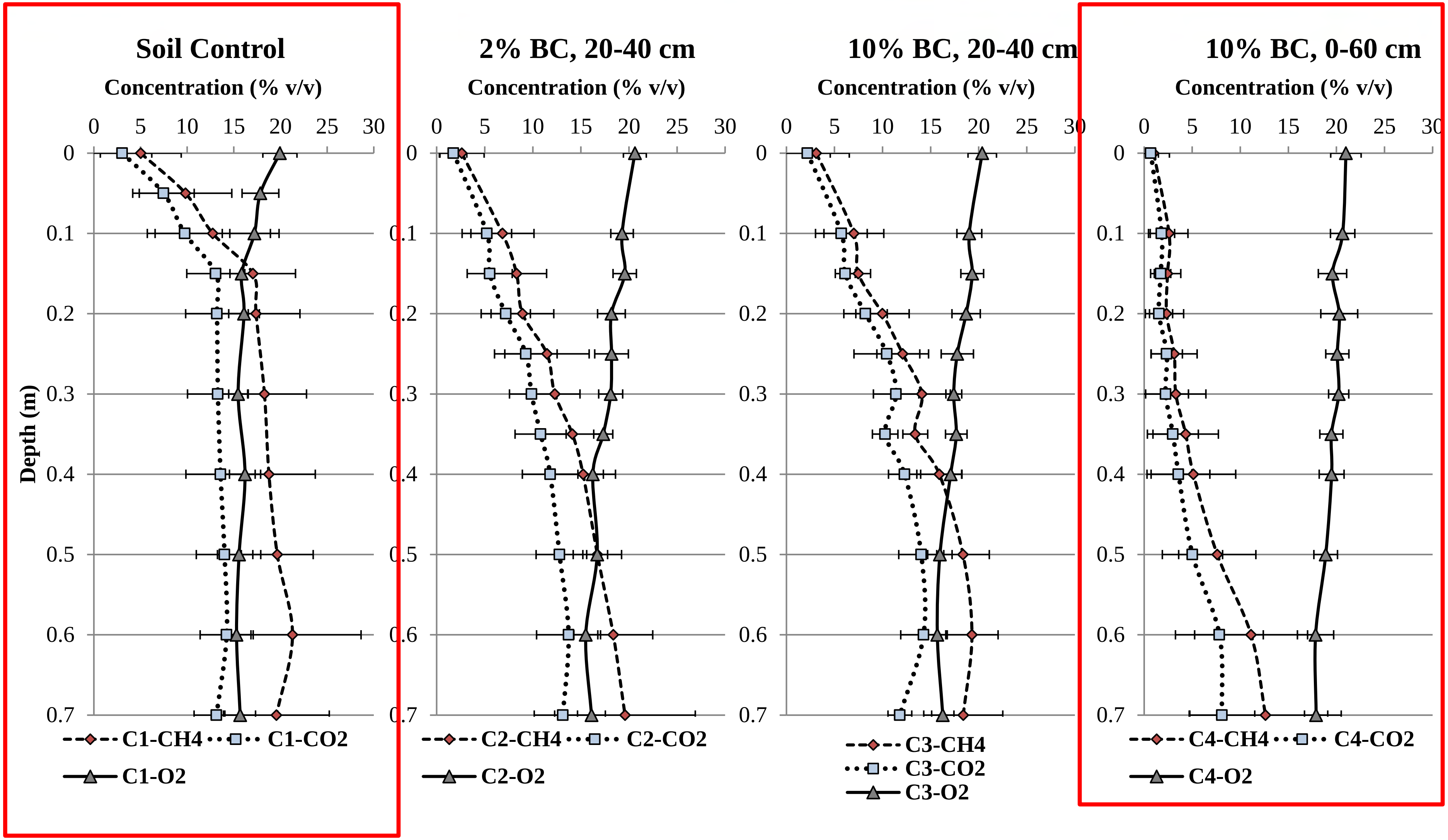




Column Tests



Biochar Amended Soil: Methane Oxidation



Steady State Gas Profiles

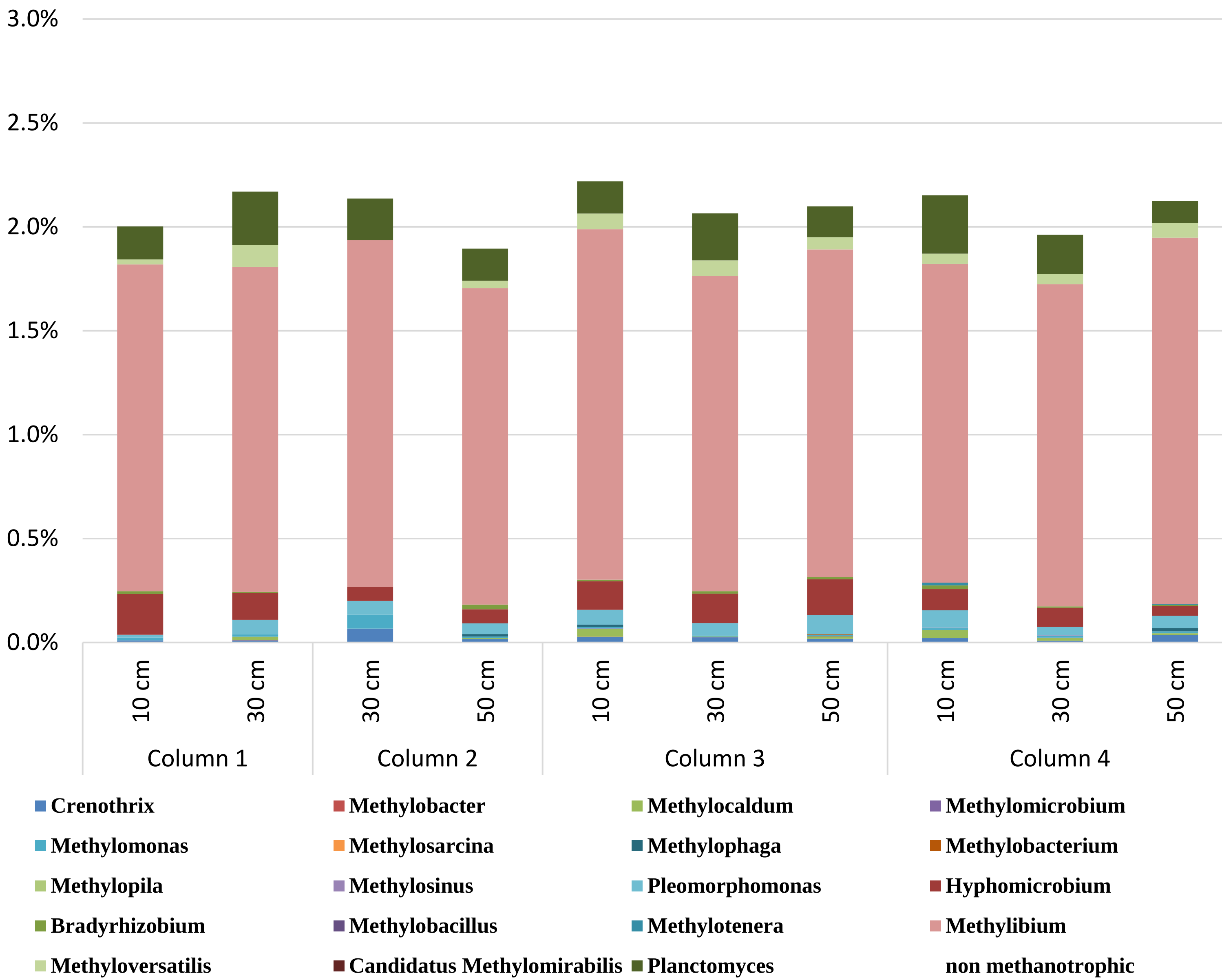
Microbial Characterization

DNA Extraction and Purification → qPCR amplification of 16SrRNA gene → Next-generation sequencing

↓

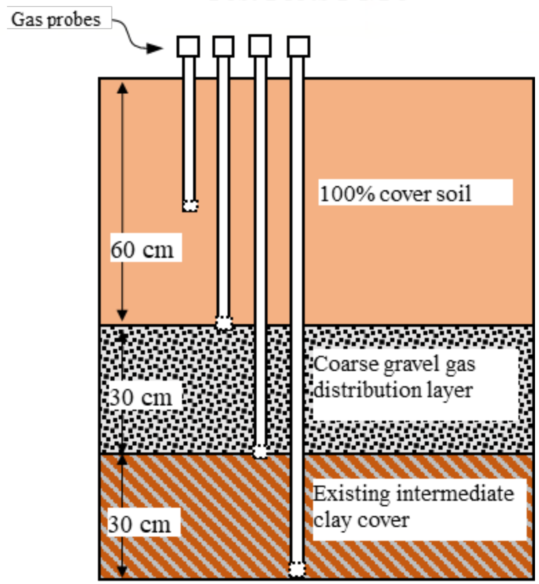
Comparison of relative abundance and types of MOB present ← Taxonomic classification of sequence data ← Trimming and quality check of DNA sequences

Microbial Community

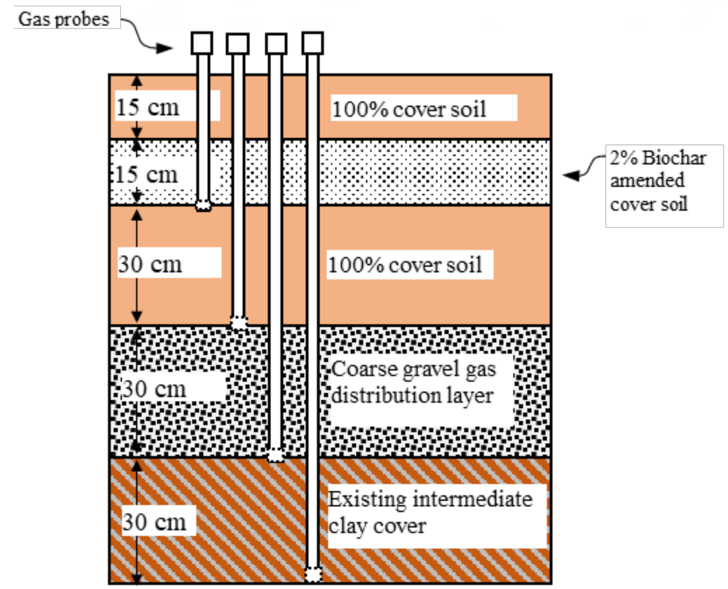


Field Test Plots

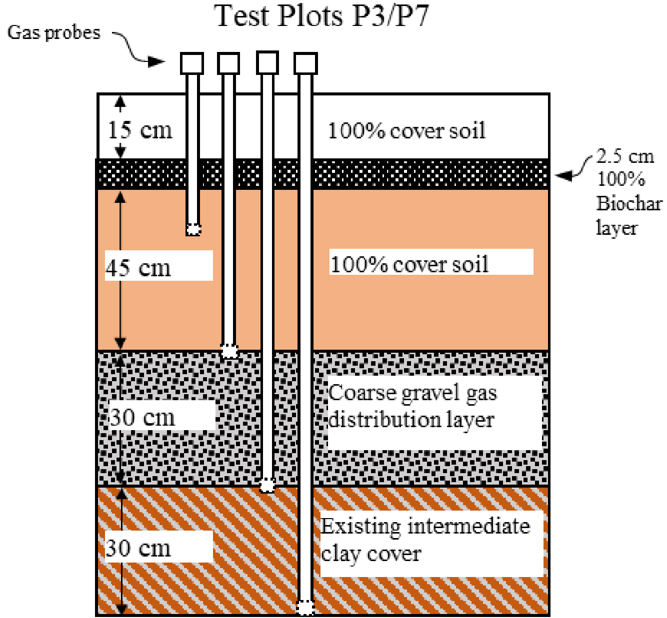
Test Plots P1/P5



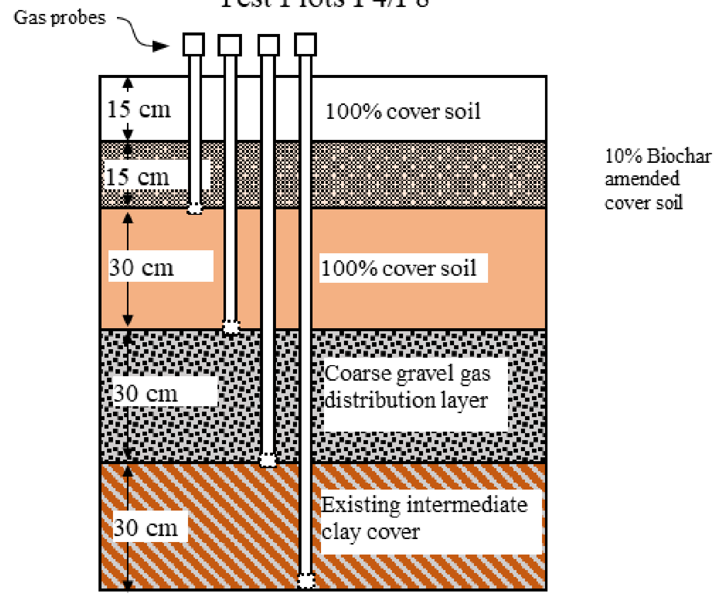
Test Plots P2/P6



Test Plots P3/P7

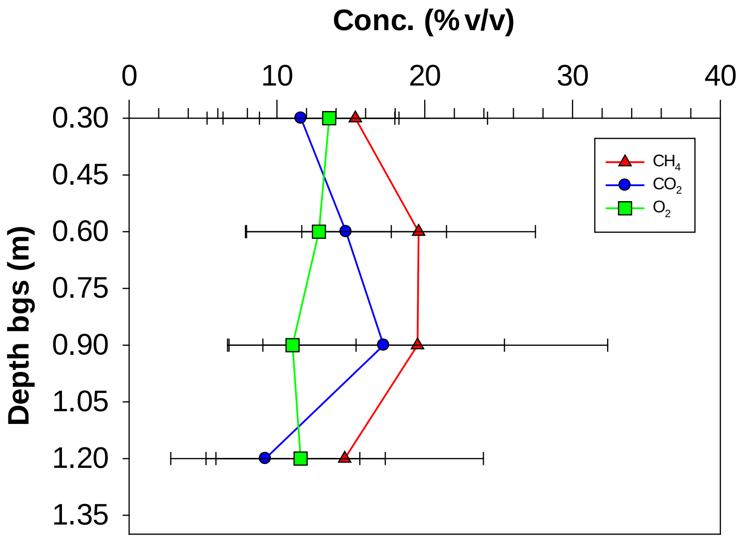


Test Plots P4/P8

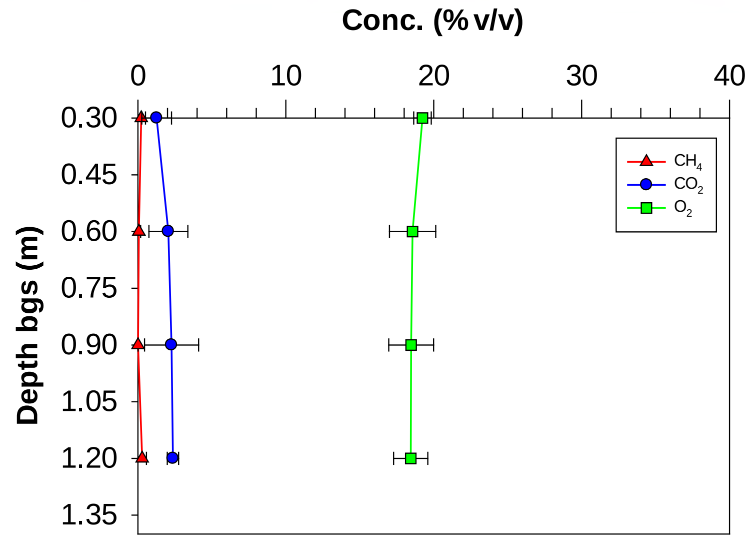


Field Pilot Tests

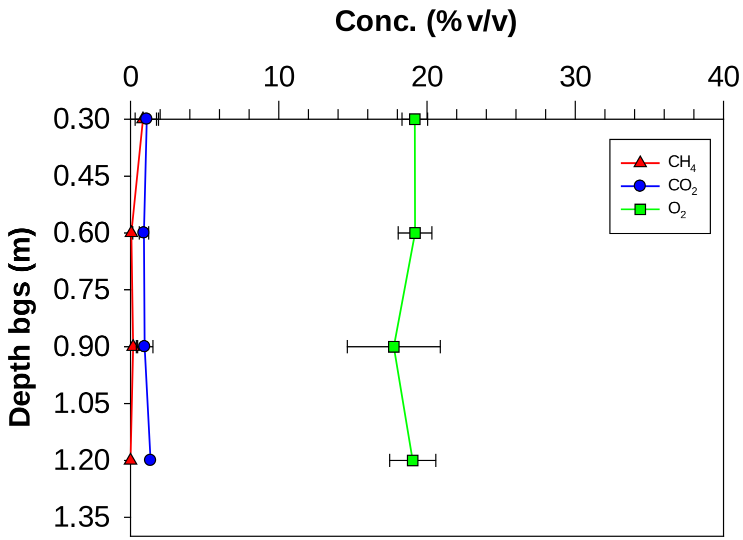
Gas Profiles Along the Depth of Test Plots



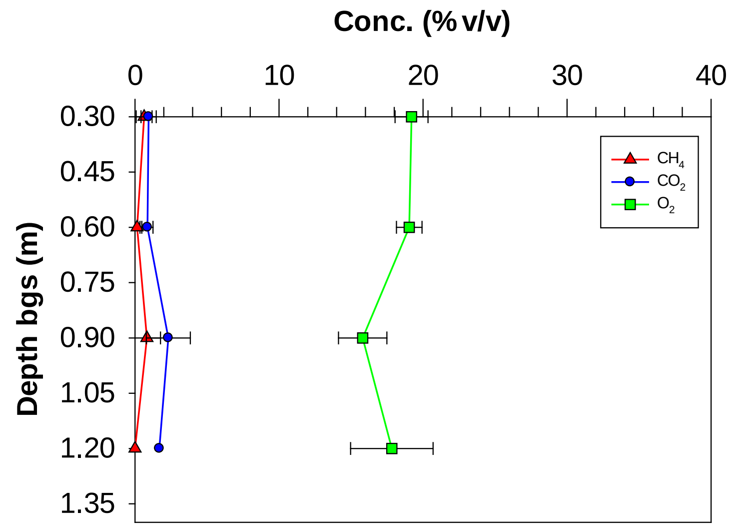
P1: Soil Control



P2: 2% Biochar Layer at 0.15 - 0.30 m

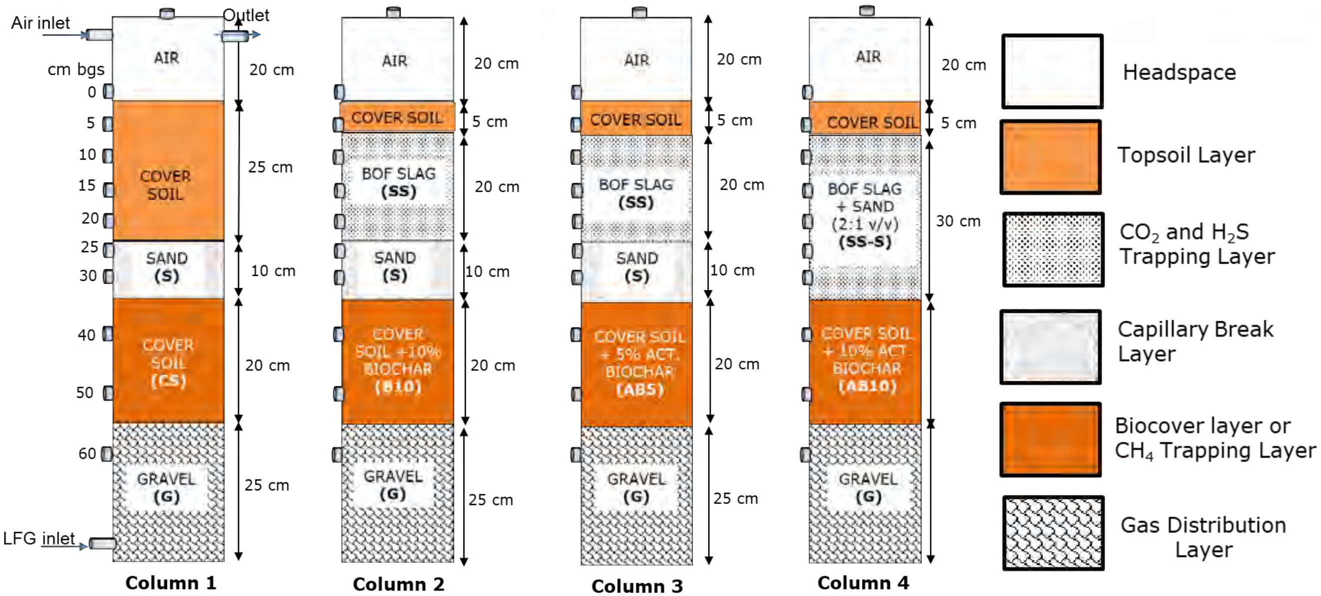


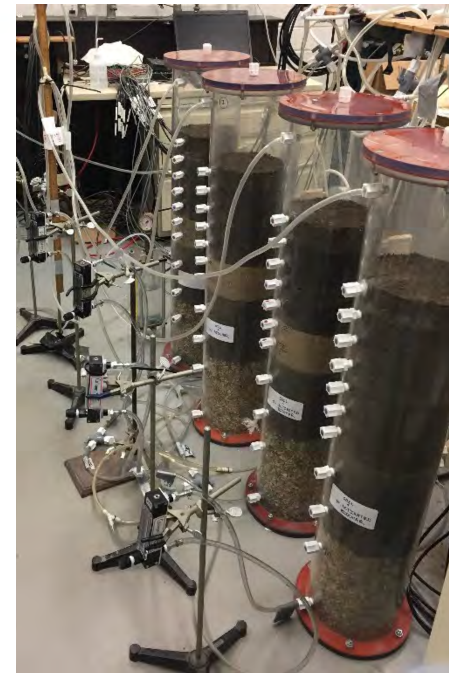
P3: 100% Biochar Layer at 0.15 - 0.18 m

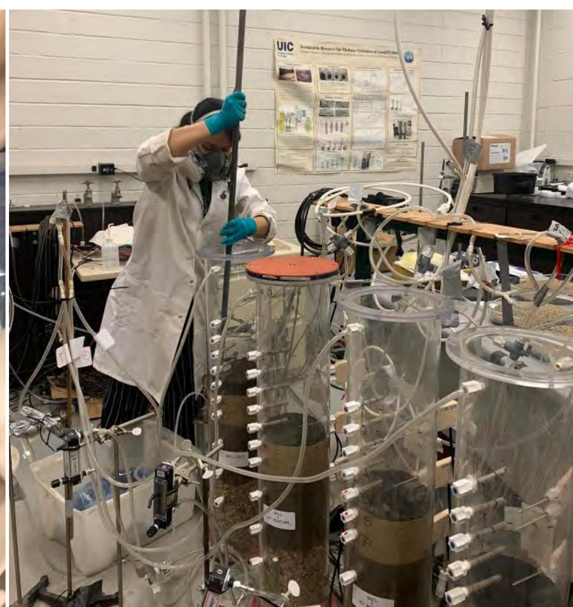


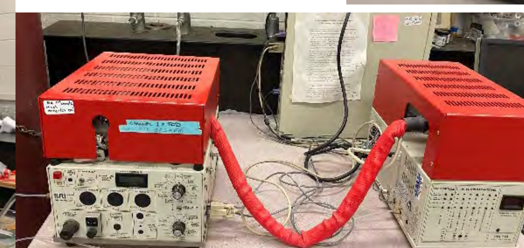
P4: 10% Biochar Layer at 0.15 - 0.30 m

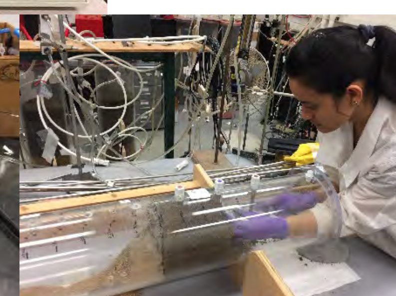
BGGC Profiles: Large Column Tests
(Addition of BOF Slag Layer)



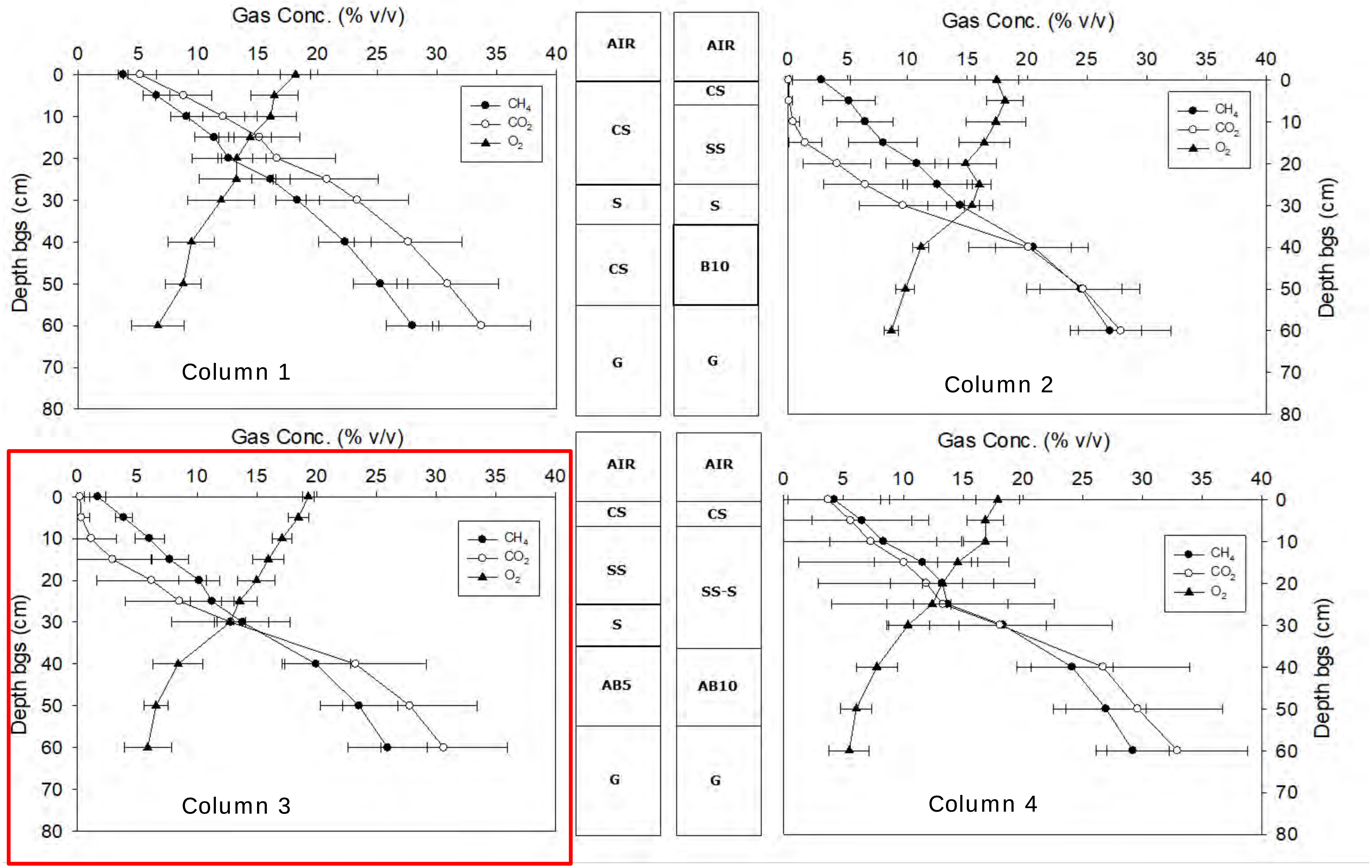




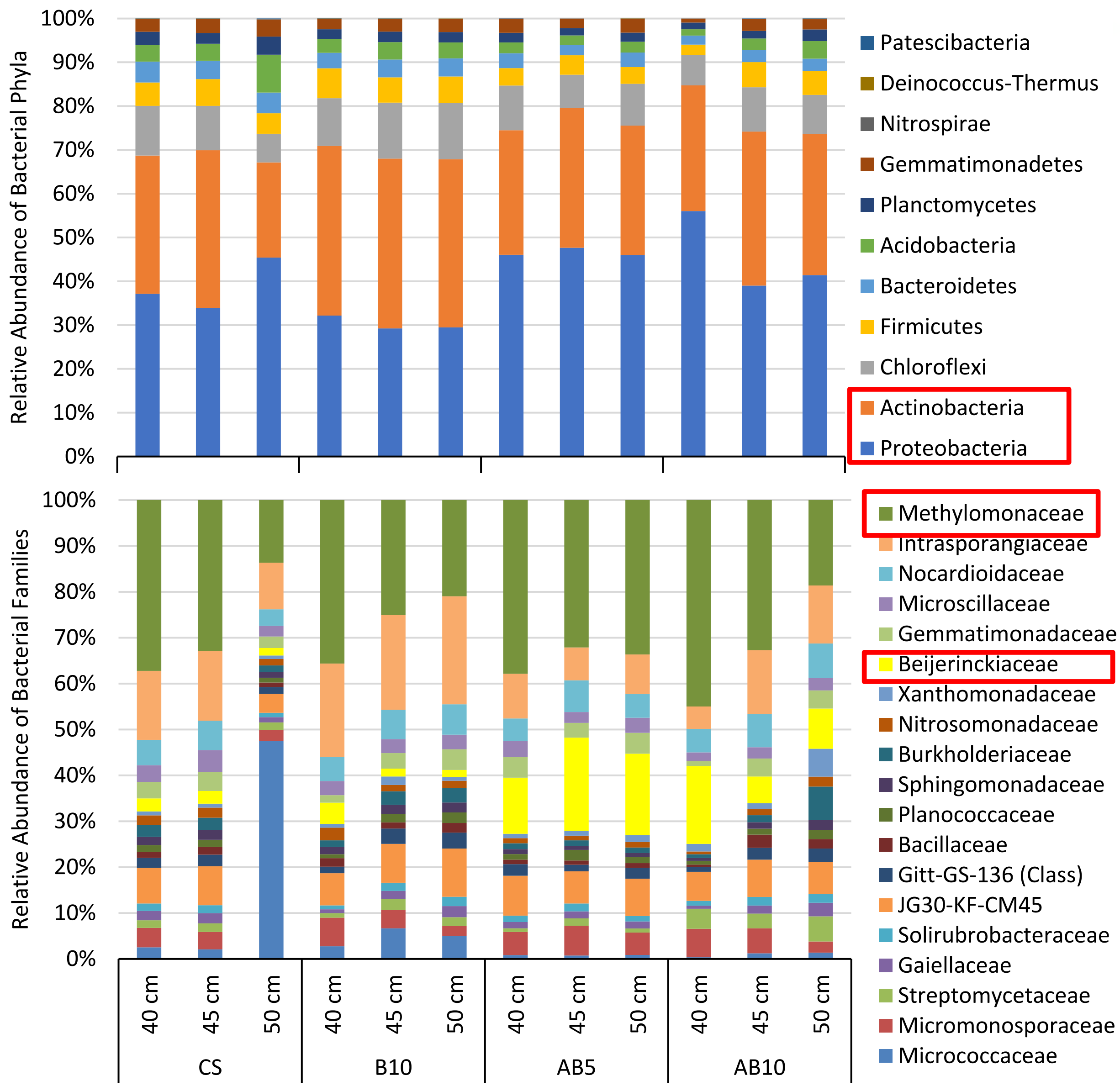




BGCC Profiles: Large Column Tests



Terminal Microbial Community Analysis

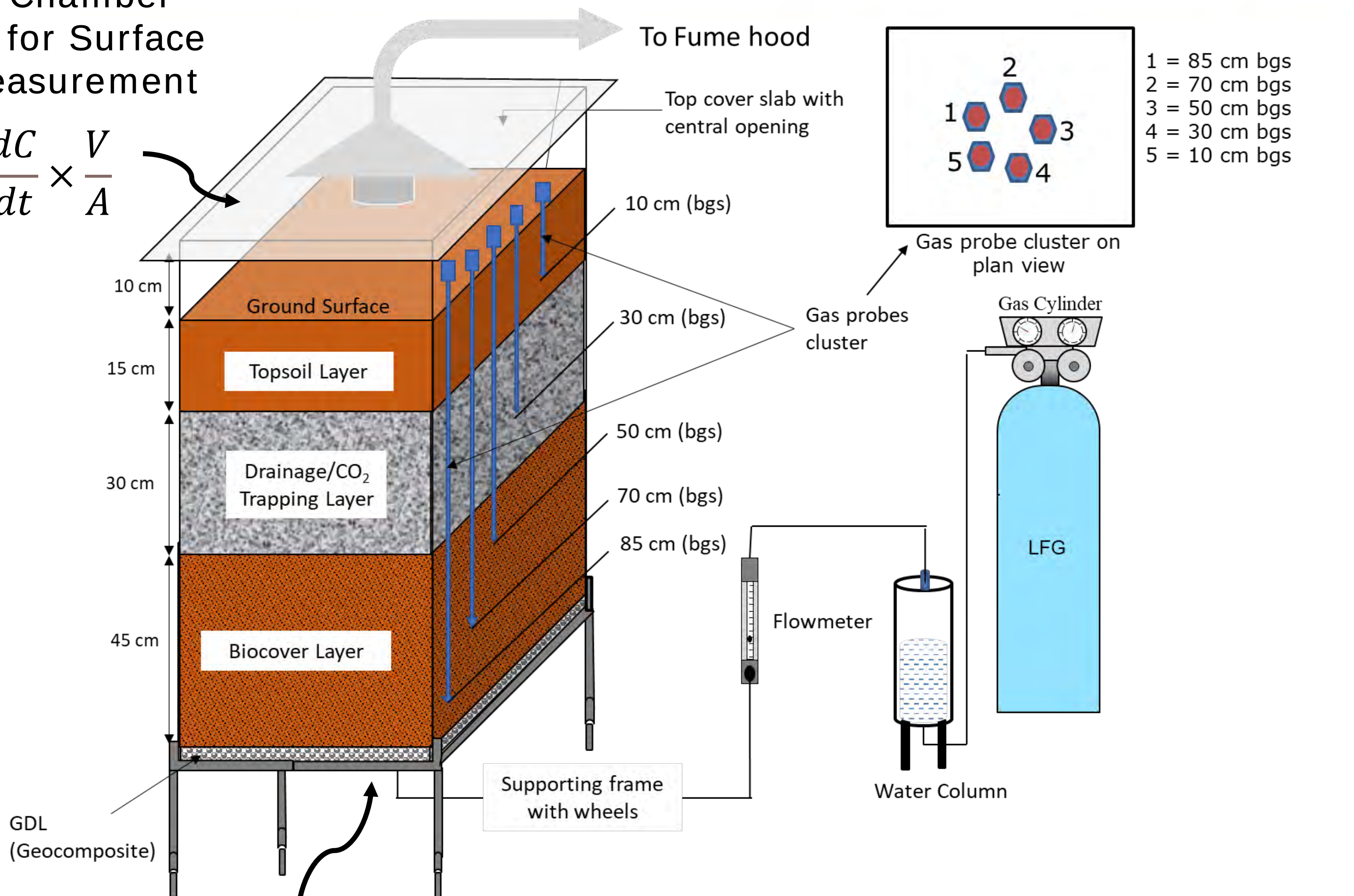


Chetri, J.K., Reddy, K.R., and Green, S.J. (2022). "**Use of methanotrophically activated biochar in novel biogeochemical cover system for carbon sequestration: Microbial characterization**." ***Science of The Total Environment***, 821, 153429 (DOI: 10.1016/j.scitotenv.2022.153429)

Near-Field Scale Tests

Static Chamber Method for Surface Flux Measurement

$$J_{out} = \frac{dC}{dt} \times \frac{V}{A}$$



$$J_{in} = \frac{Q_{in} \times C_{in}}{A}$$

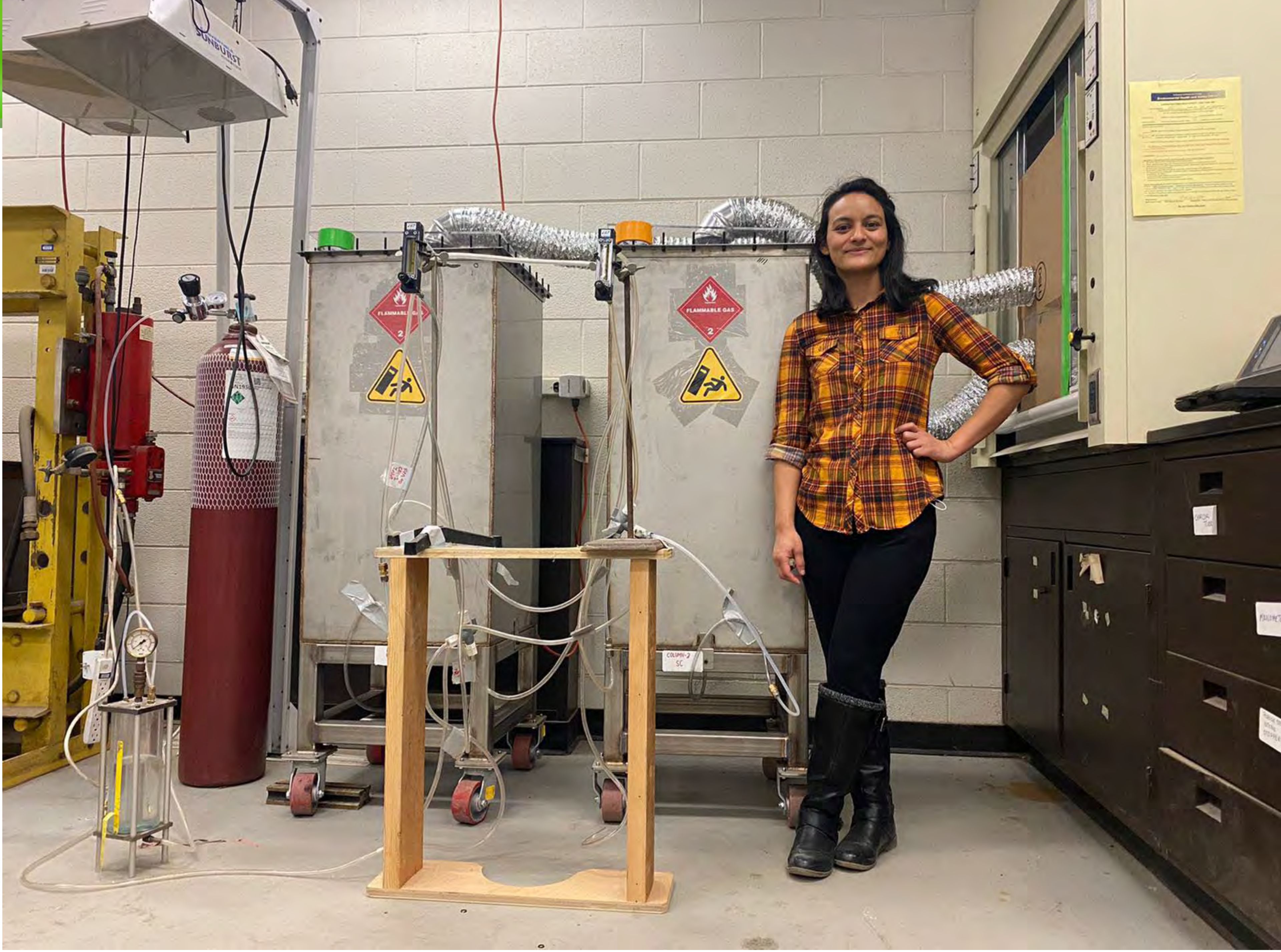
$$\textit{Gas Removal Efficiency} = \frac{J_{in} - J_{out}}{J_{in}} \times 100\%$$

Near-Field Scale Testing Set Up

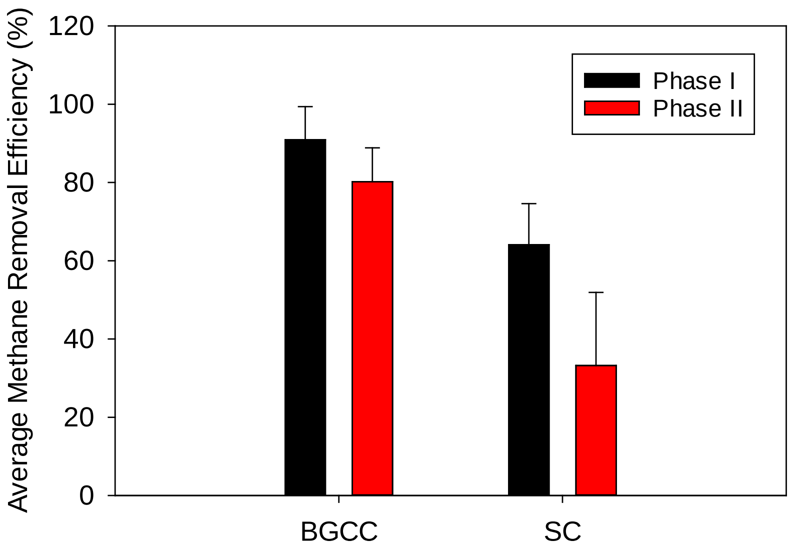






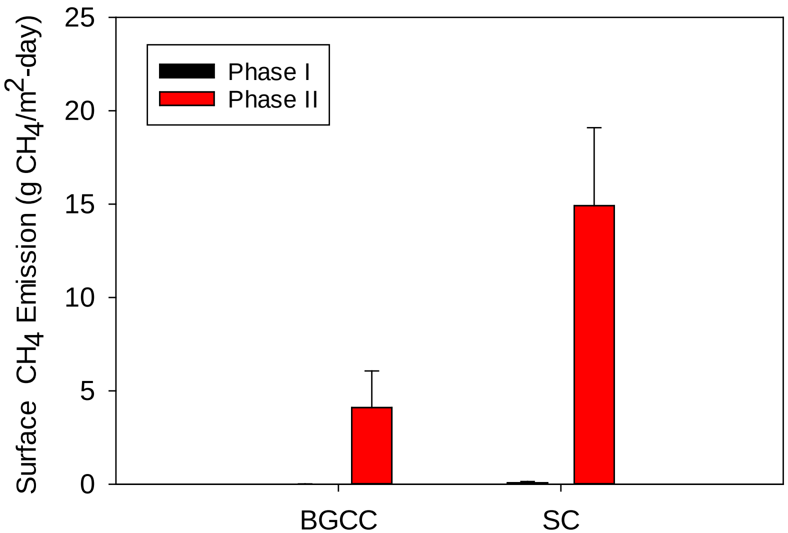


SUNBURST
FLAMMABLE GAS
2
FLAMMABLE GAS
2

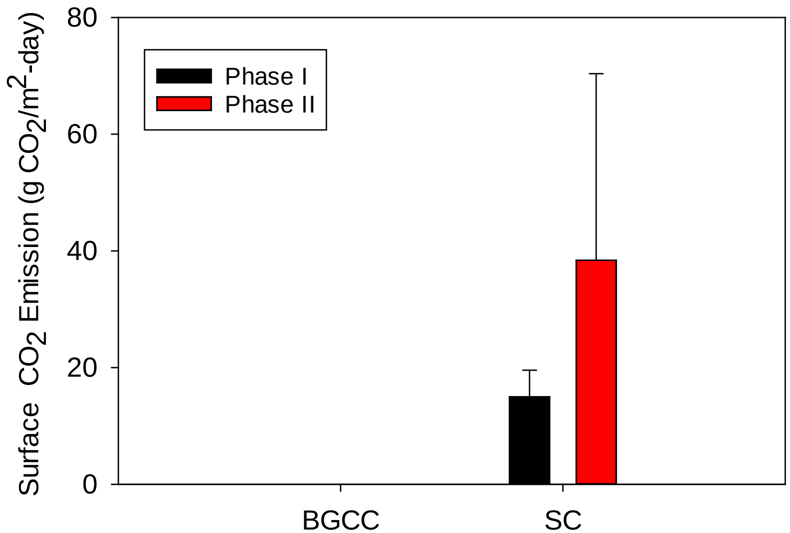
Near-Field Scale Tests: Gas Removal



Phase I = 1000 ppm CH_4 ($0.1 gCH_4/m^2$-day)

Phase II = 50% CH_4, 50% CO_2 ($20-25 gCH_4/m^2$-day)

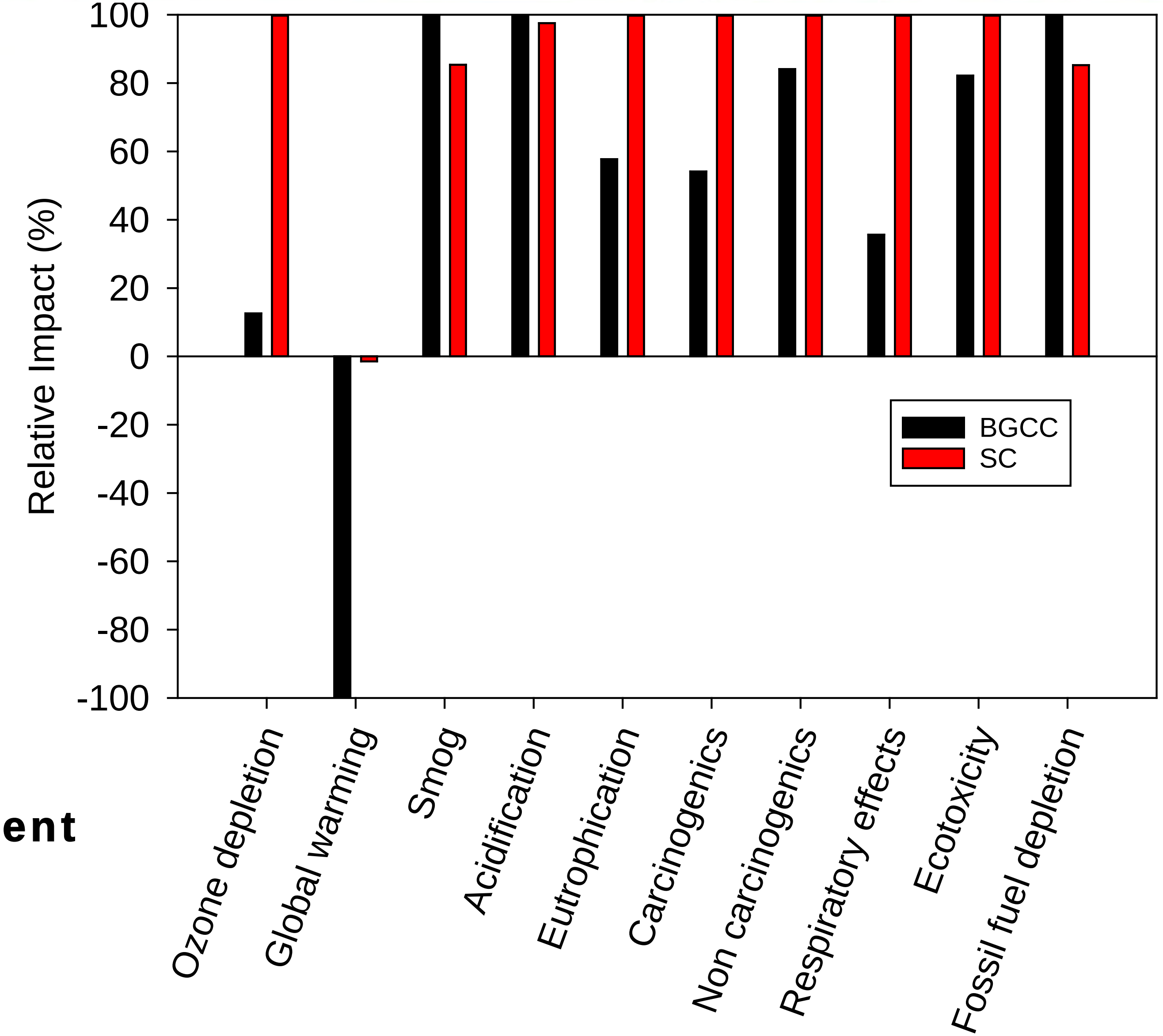




Is it Sustainable?

UIC

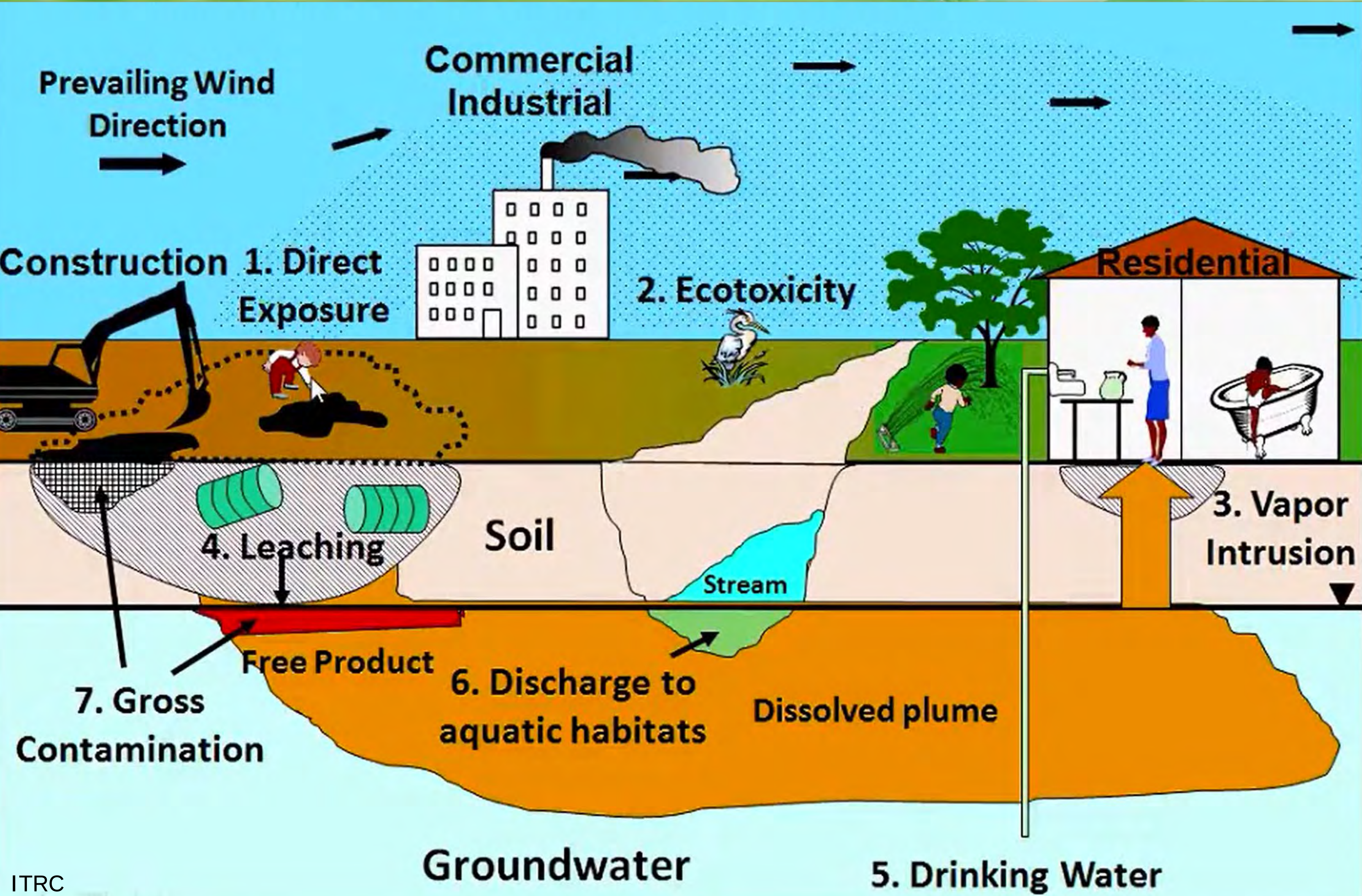
Both biochar and slag are wastes (byproducts)



Life Cycle Assessment (LCA) Results

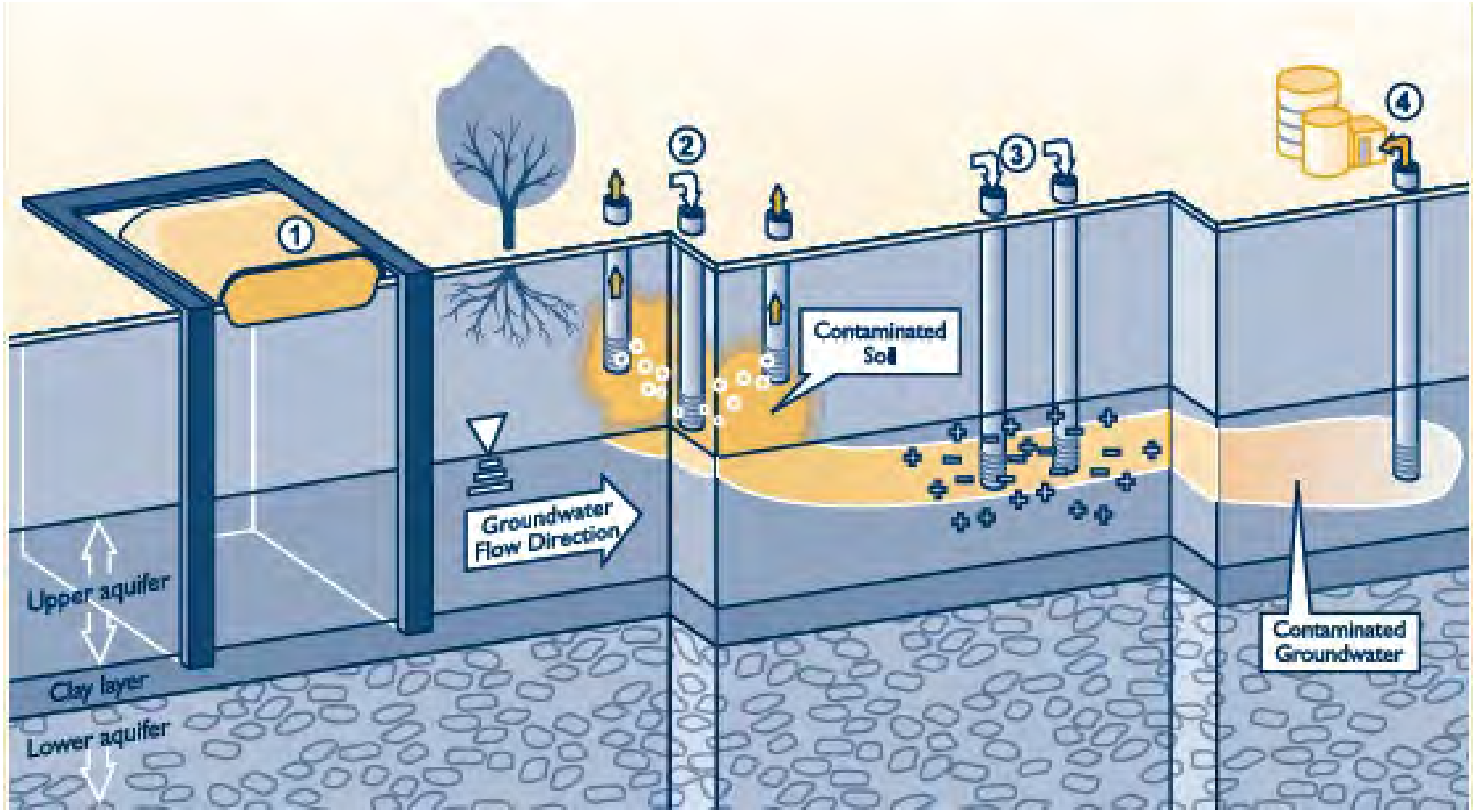
Method: TRACI 2.1 V1.01

Environmental Pollution



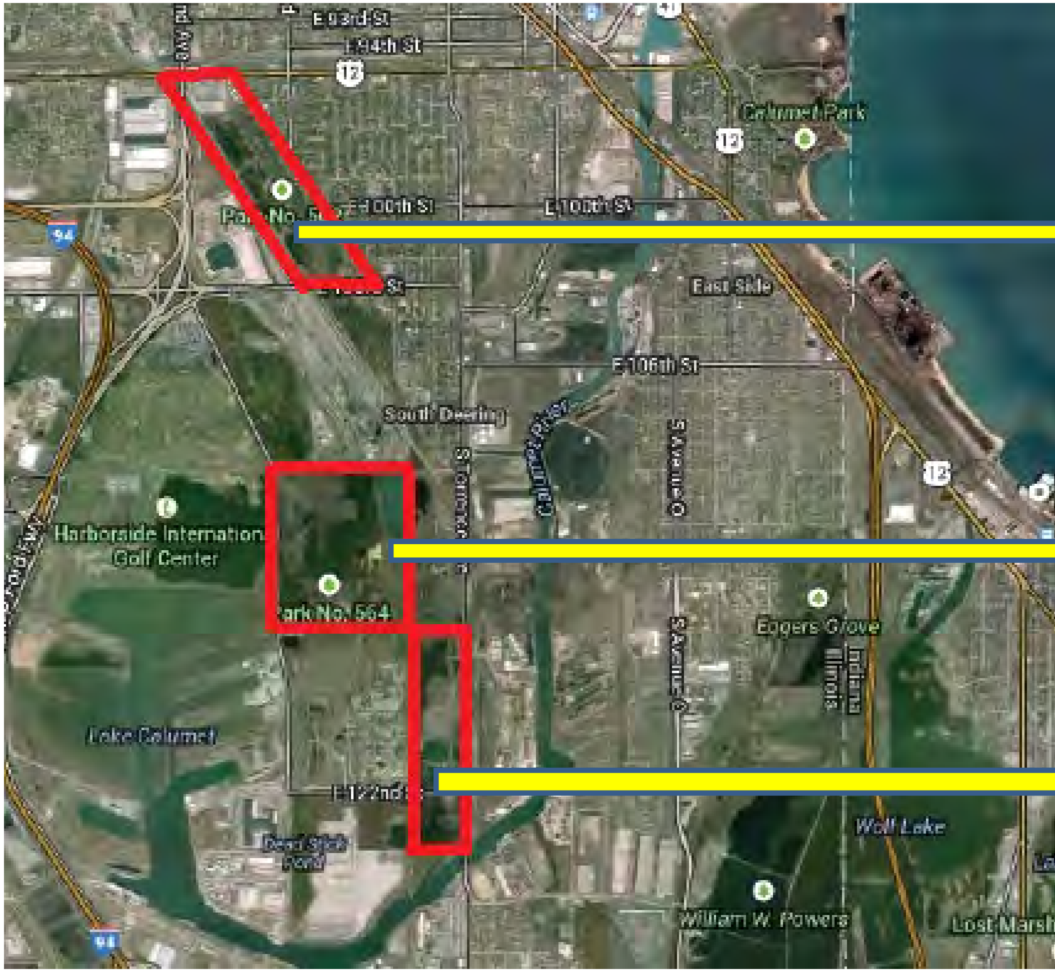
ITRC

Remedial Alternatives



1. Containment Technologies (e.g., Slurry Trench Cutoff Walls)
2. Soil (Vadose Zone) Remediation Technologies (e.g., S/S, SVE)
3. Groundwater Source Zone Remediation (e.g., PAT, ISCO)
4. Groundwater Plume Remediation (e.g., MNA, Bioremediation)

Polluted Soils



Van Vlissingen Marsh
(117 acres)

Big Marsh
(289 acres)

Indian Ridge Marsh
(100 acres)

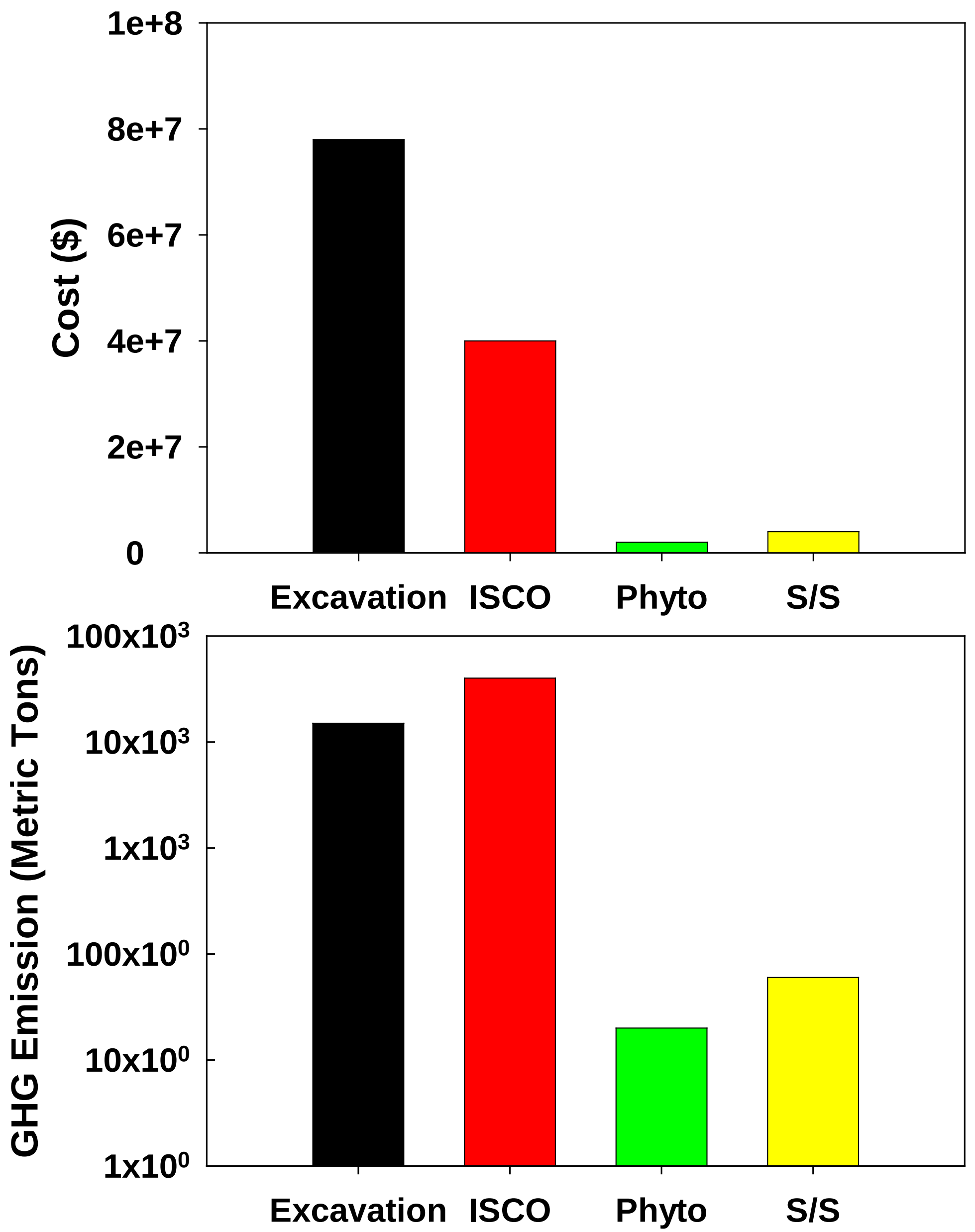
- Located about 15-20 miles from downtown Chicago (owned by the City of Chicago)!
- Large open sites, but surface soils/fill are polluted with mixed contamination (PAHs and heavy metals) due to past activities: manufacturing, UST, dredged soil disposal, illegal dumping, etc.!
- Idle! Can we remediate to use for beneficial purposes (e.g., ecological open space reserve, recreational parks)?

Sustainability Assessment

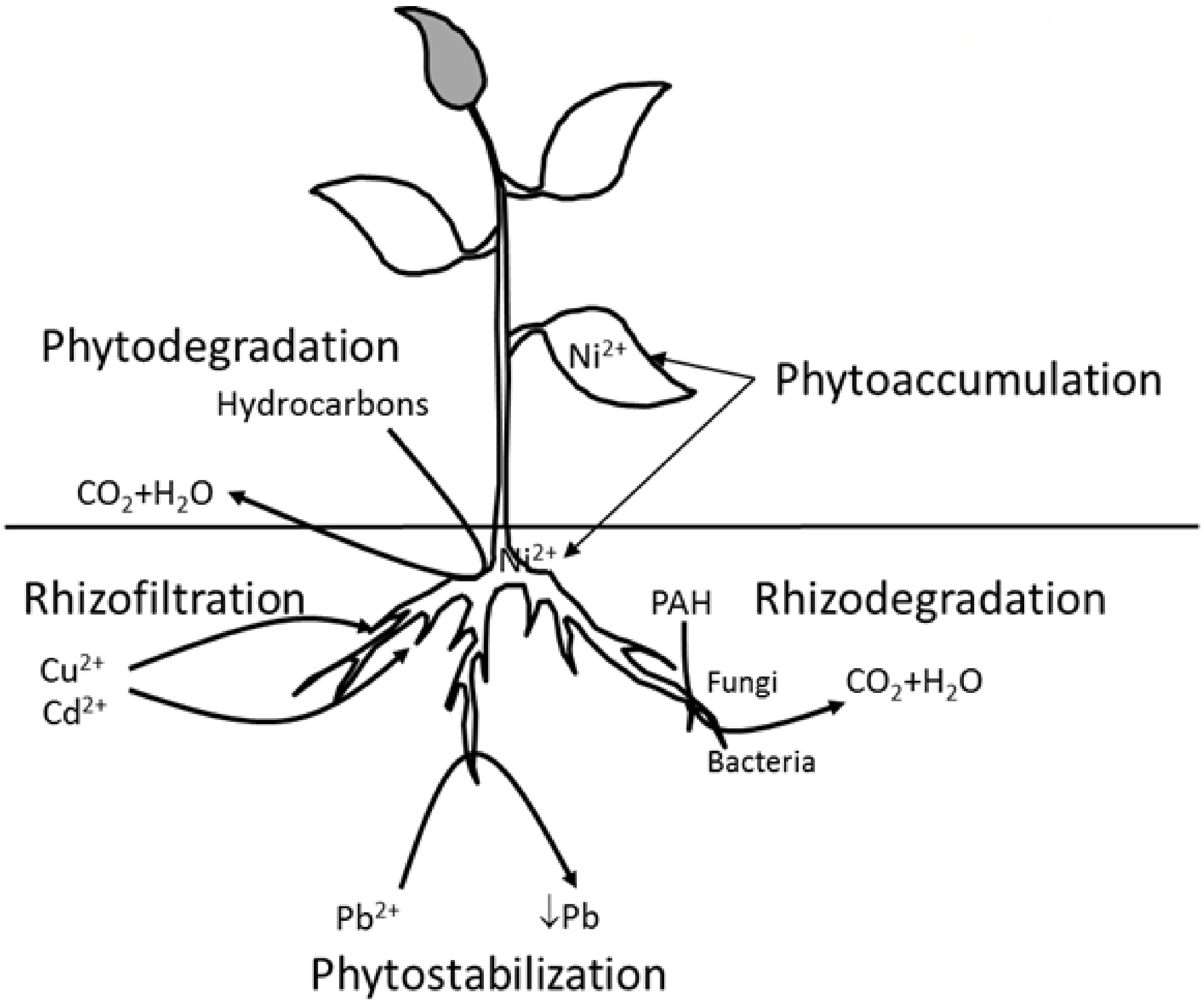
- Cost
- GHG emission
- NO_X emission
- SO_X emission
- PM_{10} emission
- Energy usage
- Water usage
- Accident/injury

Sustainable Option:
Phytoremediation?

Reddy and Chirakkara (2013)



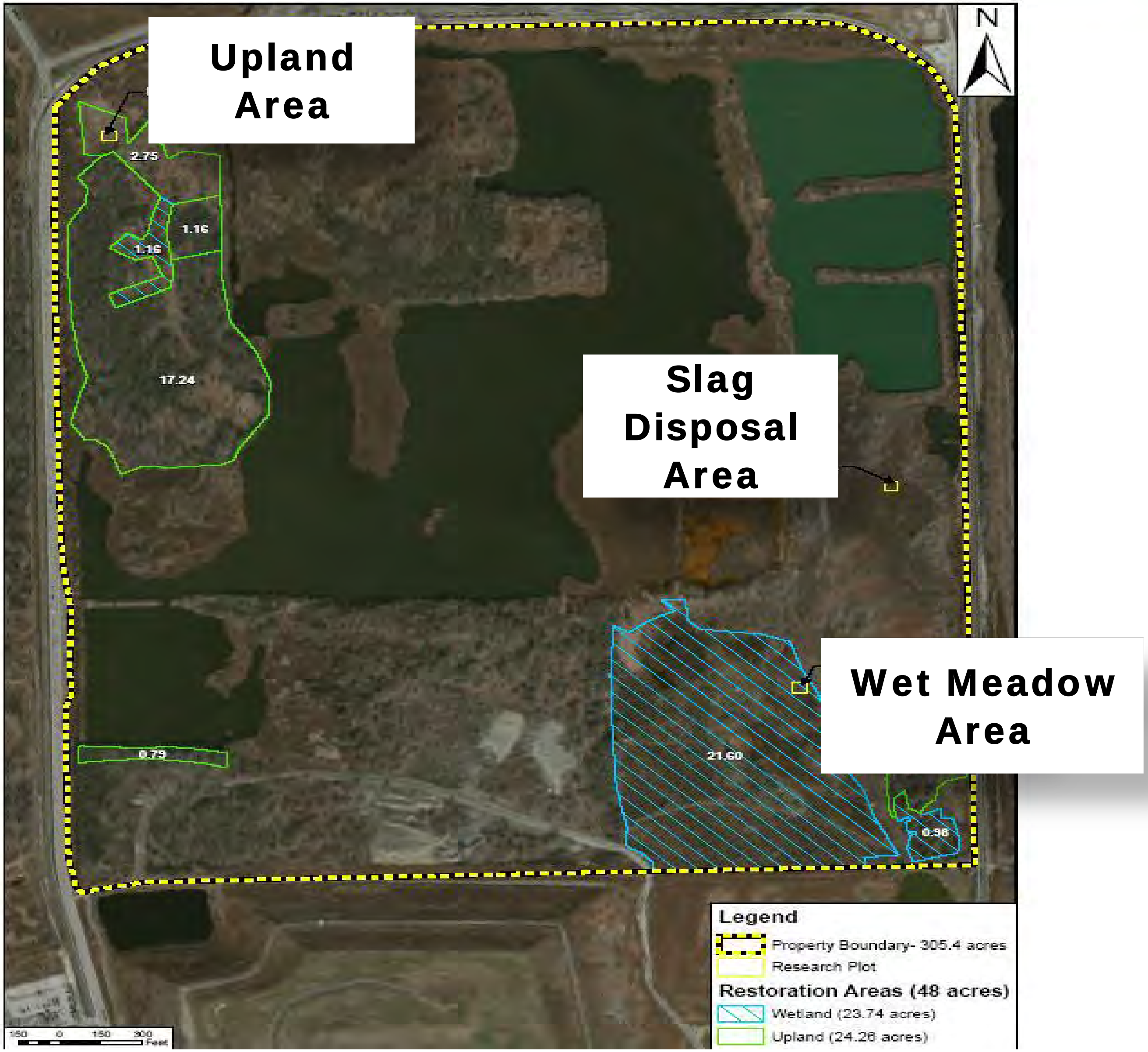
Phytoremediation?



Chirakkara, R.A., Cameselle, C., and Reddy, K.R. (2016). “Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants.” *Reviews in Environmental Science & Bio/Technologies*. 15(2), 299-326 (DOI: 10.1007/s11157-016-9391-0).

Field Investigation: Big Marsh Site

UIC



Initial Soil Characterization

Plant Selection

Area	Type	Scientific Name	Common Name	Sample ID
Slag Area and Upland Area	Grasses/Plugs (GPs)	*Andropogon scoparius*	Little bluestem	LBS
		Bouteloua curtipendula	Side oats grama	SOG
		Dalea purpurea	Purple prairie clover	PPC
		Panicum virgatum	Switch grass	SWG
		Ratibida pinnata	Yellow coneflower	YCF
	Trees (T)	*Celtis occidentalis*	Hackberry	HBY
		Quercus velutina	Black oak	BOK
	Shrubs (S)	*Cornus racemosa*	Gray dogwood	GDW
		Circis canadensis	Eastern redbud	ERB
Wet Meadow	Grasses/Plugs	*Asclepias incarnata*	Swamp milkweed	SMW
		Cassia hebecarpa	Wild Senna	WSA
		Deschampsia caespitosa	Tufted hair grass	THG
		Solidago graminifolia	Common grass-leaved goldenrod	CGG
		Spartina pectinata	Prairie cord grass	PCG
	Trees	*Acer saccharinum*	Silver maple	SMP
		Quercus bicolor	Swamp white oak	SWO
	Shrubs	*Amorpha fruticosa*	False indigo bush	FIB
		Cornus stolonifera	Red-osier dogwood	ROD

Slag Disposal Area

Switchgrass


After planting


1 month


End of the 1st season


End of the 3rd season

Gray Dogwood


After planting


1 month


End of the 1st season


End of the 3rd season

Wet Meadow Area

Grass-leaved Goldenrod


After planting


1 month


End of the 1st season


End of the 2nd season

False Indigo Bush


After planting


1 month


End of the 2nd season


End of the 3rd season

Upland Area

Little Bluestem

After planting

End of the 1st season

End of the 2nd season

End of the 3rd season

Eastem Red Bud

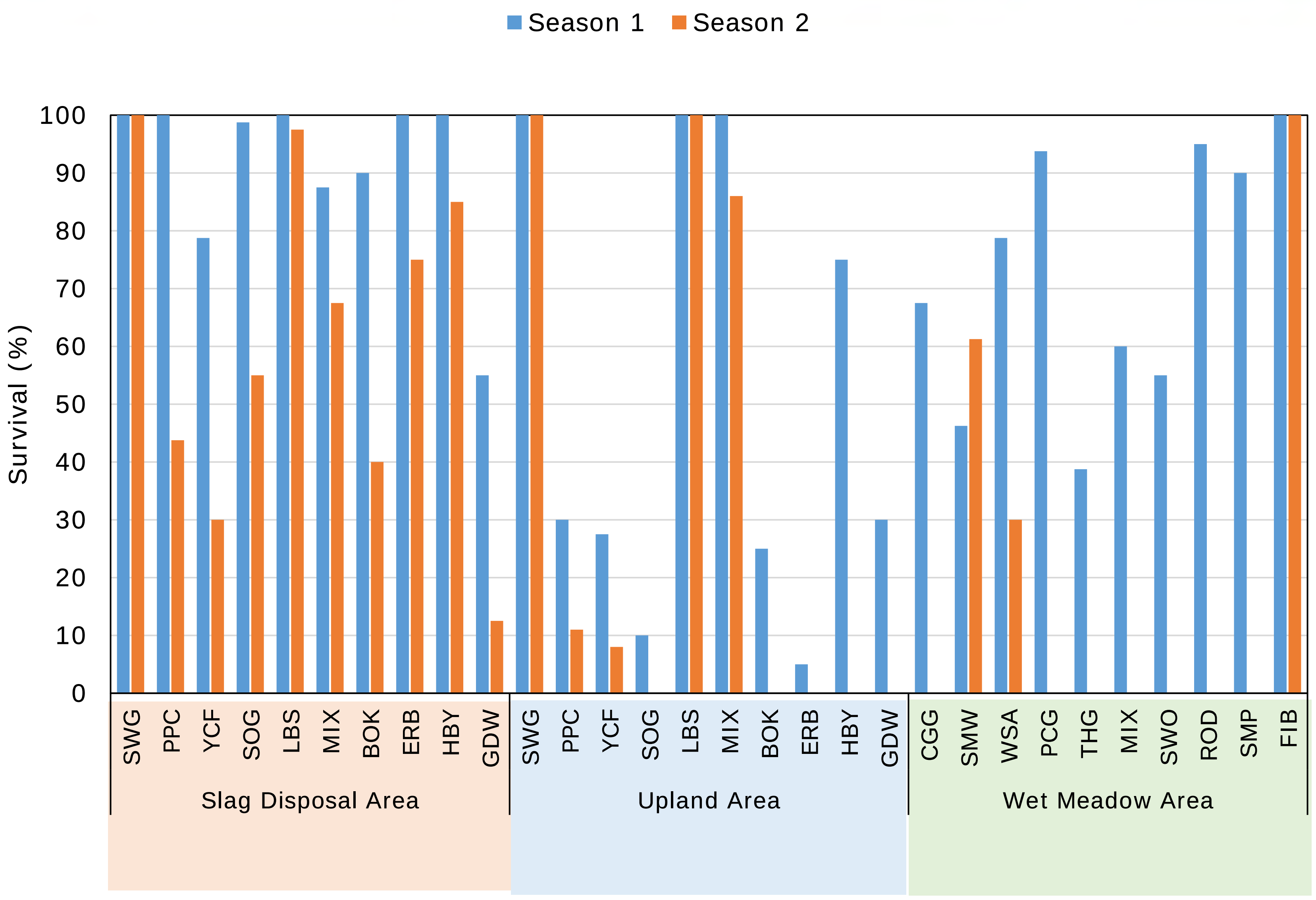
After planting

1 month

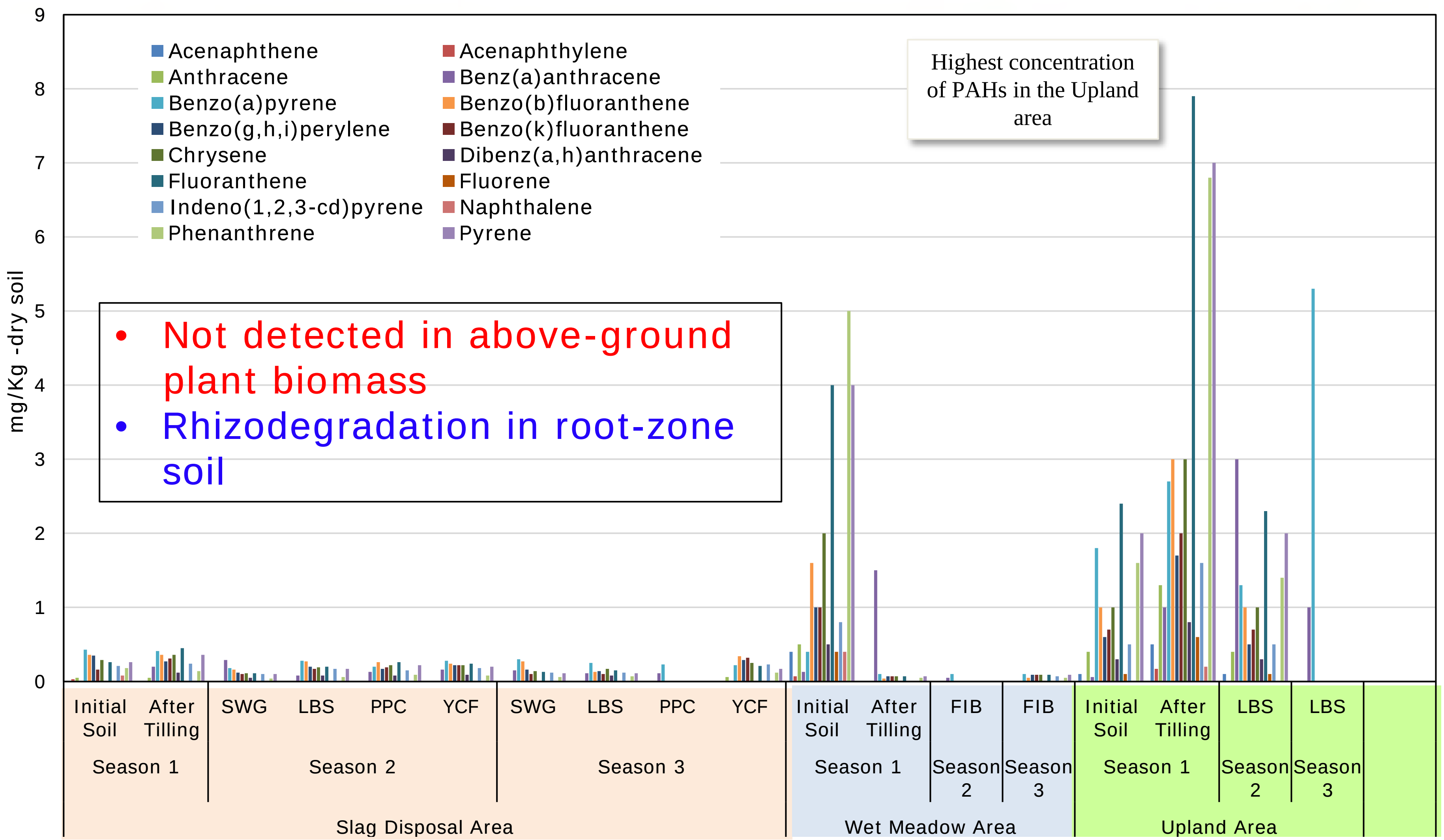
End of the 2nd season

End of the 3rd season

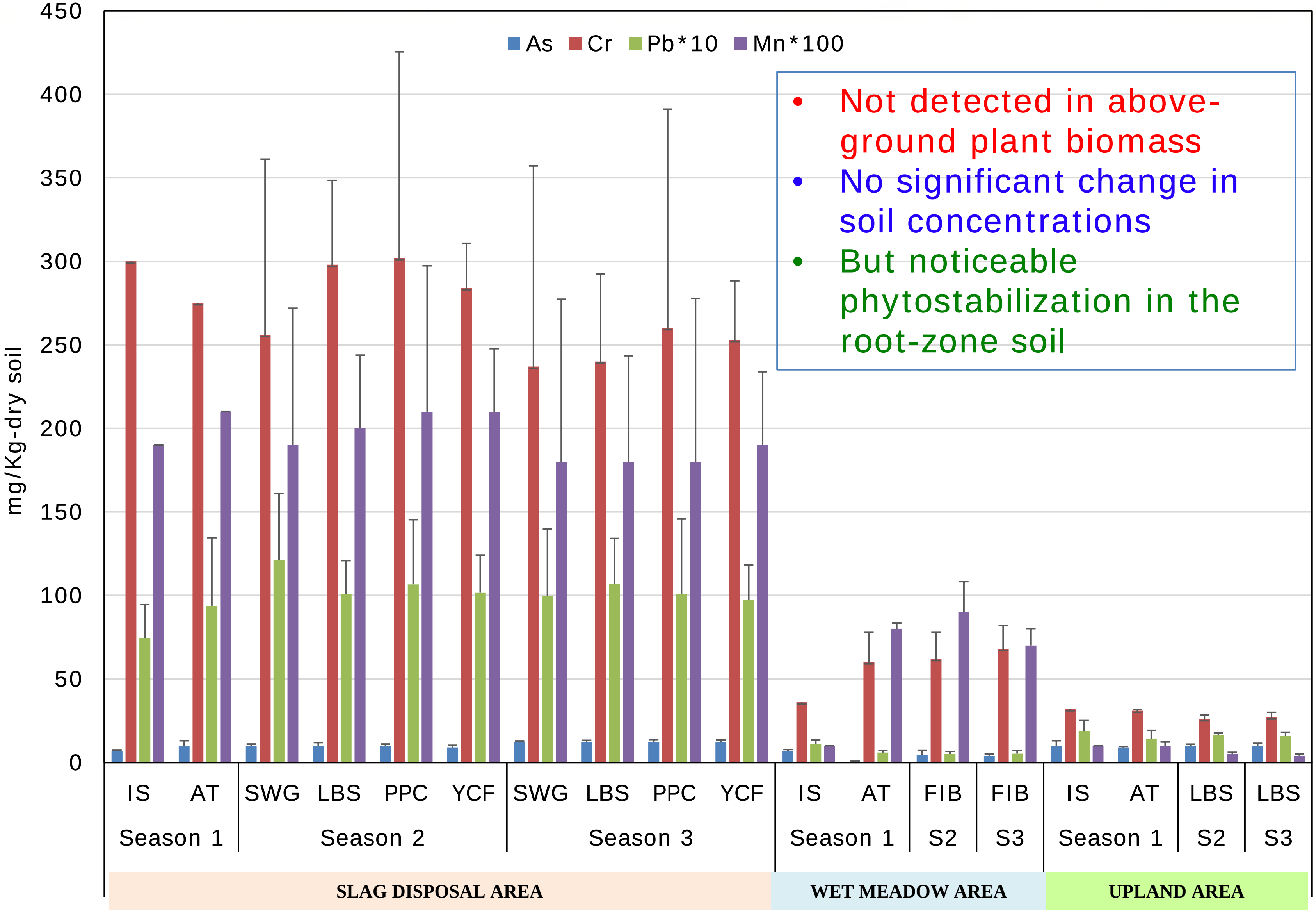
Plant Growth and Survival



PAHs in Soil

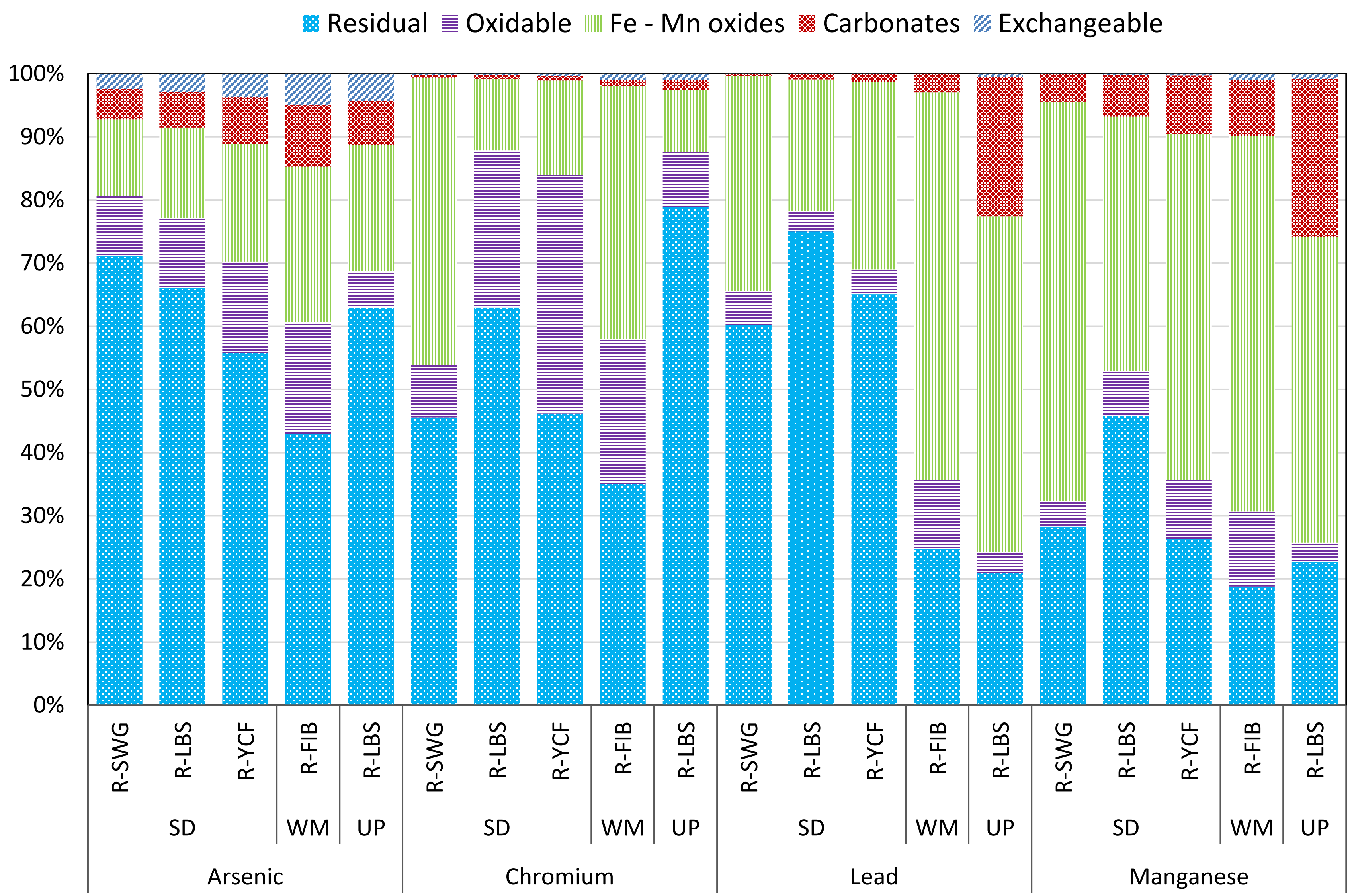

mg/Kg -dry soil
0
1
2
3
4
5
6
7
8
9
Acenaphthene
Acenaphthylene
Anthracene
Benz(a)anthracene
Benzo(a)pyrene
Benzo(b)fluoranthene
Benzo(g,h,i)perylene
Benzo(k)fluoranthene
Chrysene
Dibenz(a,h)anthracene
Fluoranthene
Fluorene
Indeno(1,2,3-cd)pyrene
Naphthalene
Phenanthrene
Pyrene
Highest concentration of PAHs in the Upland area
• Not detected in above-ground plant biomass
• Rhizodegradation in root-zone soil
Initial Soil
After Tilling
SWG
LBS
PPC
YCF
SWG
LBS
PPC
YCF
Initial Soil
After Tilling
FIB
FIB
Initial Soil
After Tilling
LBS
LBS
Season 1
Season 2
Season 3
Season 1
Season 2
Season 3
Season 1
Season 2
Season 3
Slag Disposal Area
Wet Meadow Area
Upland Area

Heavy Metals in Soils



- Not detected in above-ground plant biomass
- No significant change in soil concentrations
- But noticeable phytostabilization in the root-zone soil

Root-Zone Soil: Sequential Extraction



Good News: Big Marsh Park Opened

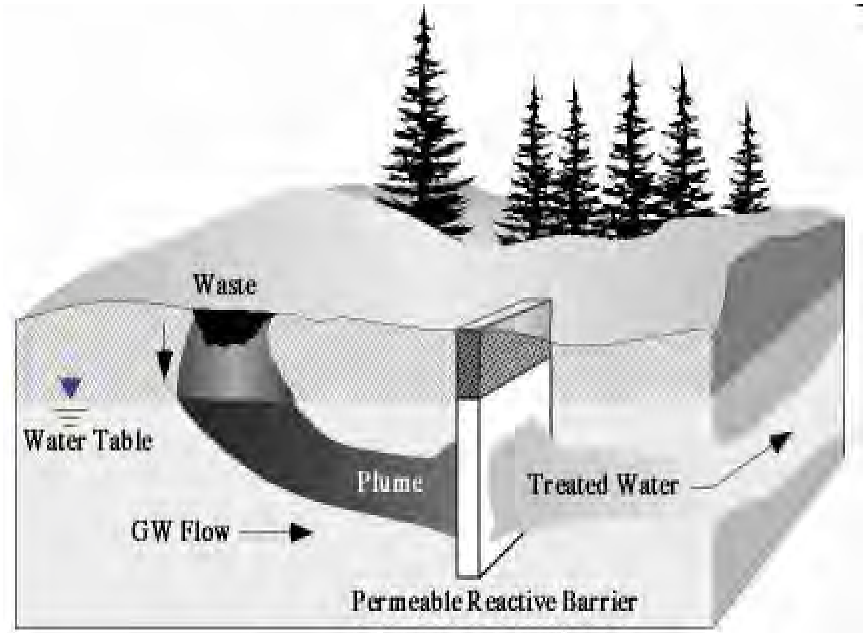
Big Marsh Park Features:

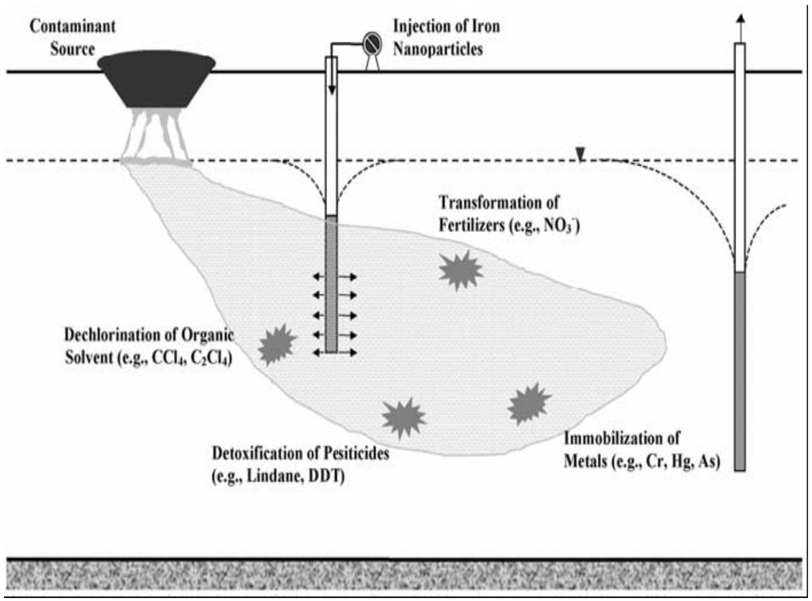
- Gravel biking and walking trails
- BMX jump lines, pump track and single-track courses
- Walking trails along the marsh
- Picnic and grilling area
- Pump Tracks
- Ford Calumet Environmental Center (FCEC)

Good News: Big Marsh Park Opened

UIC

Polluted Groundwater: Remediation





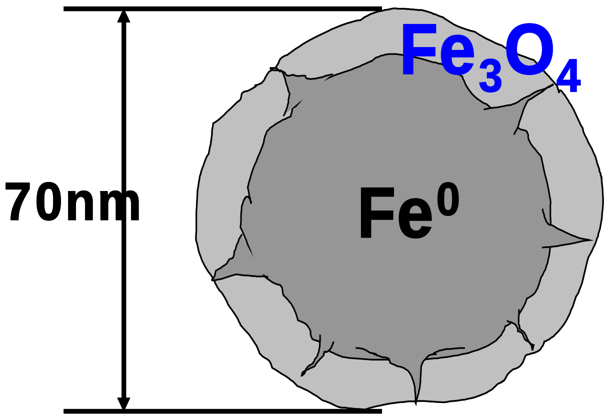
Permeable Reactive Barrier (PRB) using iron fillings

- Wait for contaminants to pass through barrier
- Longtime for remediation to occur
- Iron oxidation

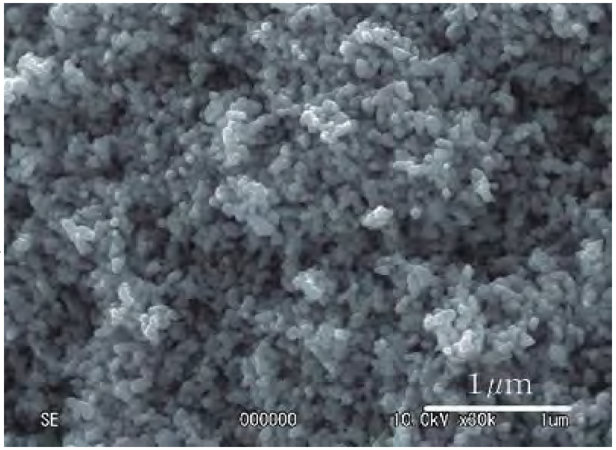
Injection of Nanoscale Iron Particles (NIP)

- Amenable to inject into subsurface
- Rapid remediation
- Can be used for different types of contaminants

Nanoscale Iron Particles (NIP)



Structure of NIP



SEM image of NIP

NIP Slurry

Properties of NIP

Property	Value
Coercive Force (Hc)	408 Oe
Mass Magnetization (ss)	149.6 emu/g
σ / σ_s (ratio of ferromagnetism and antiferromagnetism)	0.152
pH	10.7
Surface Area (BET)	37.1 m^2/g
Electrical Conductivity	2.29x10^2 mS/cm
Particle Size	50-300 nm
Aqueous Suspension	20-30 wt %
Density of Aqueous Slurry	1.2-1.3 g/mL

Chemistry

UIC

- Treatment is governed by iron corrosion reactions, lowers redox potential, generates hydrogen, friendly to subsurface biomass

- Fe(0) serves as a reducing agent. The electrons released take part in variety of reactions to transform target contaminants

- Chlorinated contaminant degradation is followed by the following mechanisms:

$$Fe(0) \rightarrow Fe^{2+} + 2e^-$$

$$2Fe0(s) + 4H^+(aq) + O_2(aq) \rightarrow 2Fe^{2+}(aq) + 2H_2O(l)$$

$$Fe0(s) + 2H_2O(aq) \rightarrow Fe^{2+}(aq) + H_2(g) + 2OH^-(aq)$$

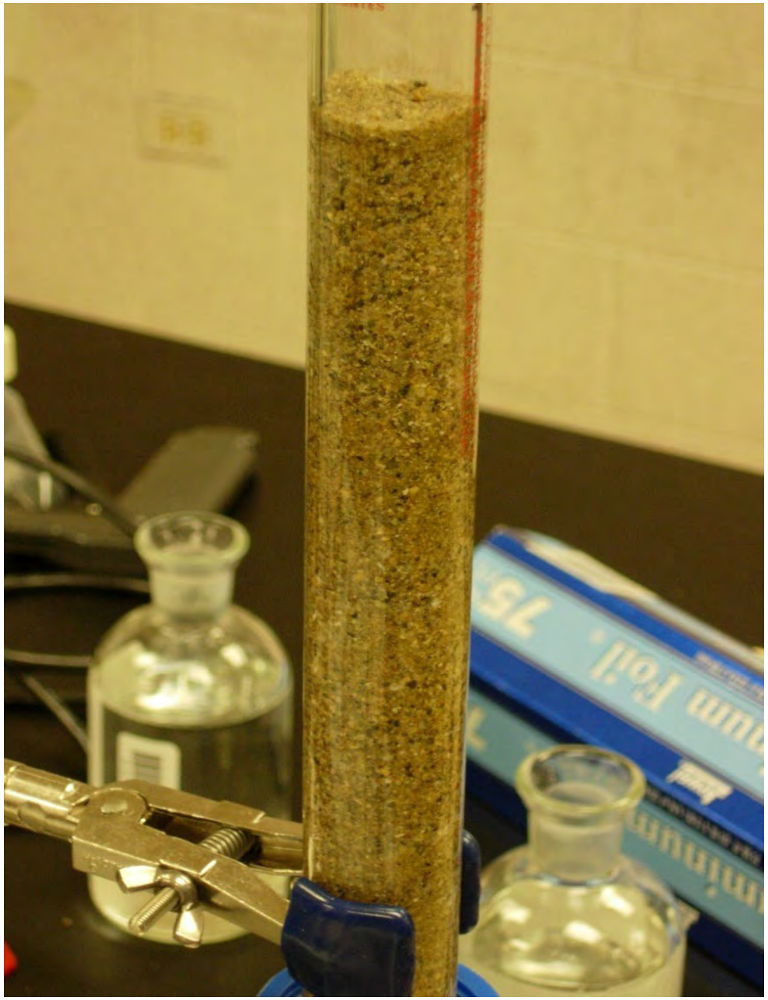
$$2H_2O \rightarrow 2H^+ + 2OH^-$$

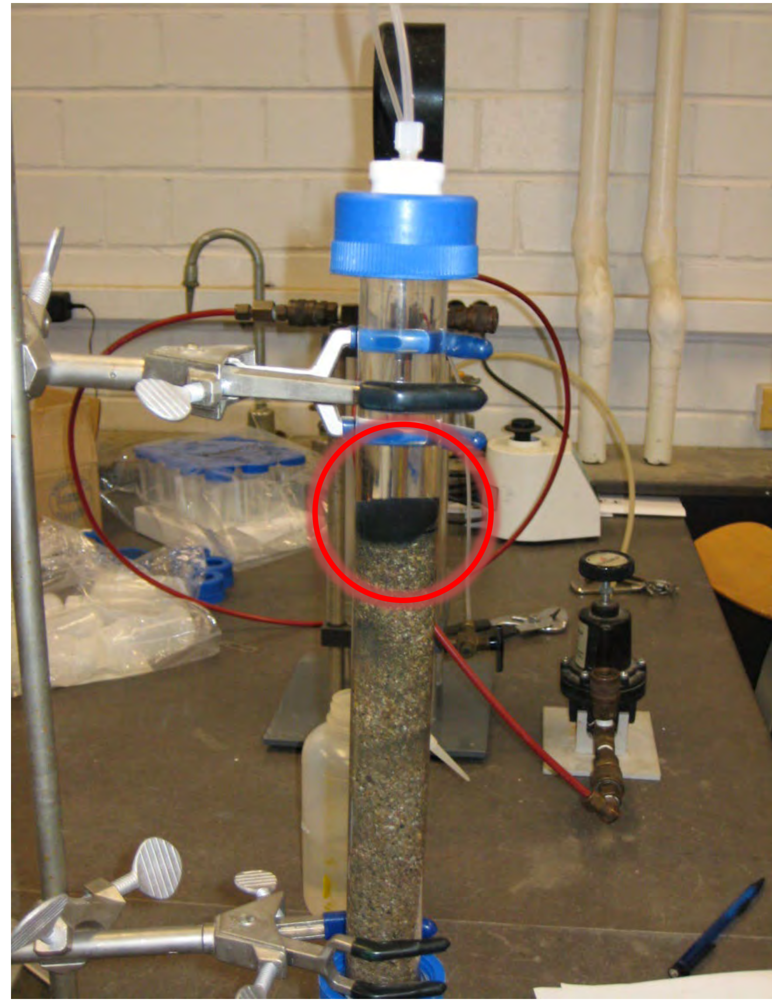
$$2H^+ + 2e^- \rightarrow H_2\,(g)$$

$$R\text{-}Cl + H^+ + 2e^- \rightarrow R\text{-}H + Cl^-$$

$$C_2HCl_3 + 3H^+ + 6e^- \rightarrow C_2H_4 + 3Cl^-$$

Transport of Bare NIP



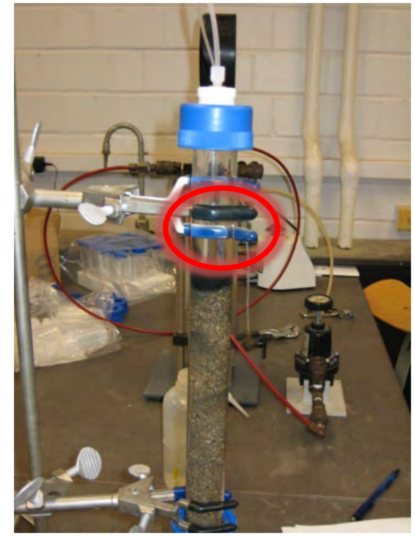


Bare NIP stack at the top of the soil column after about 20 pore volume of flushing under 30psi

Effect of AL Lactate on Delivery of NIP

Initial

After 20 pore volumes of electrolyte



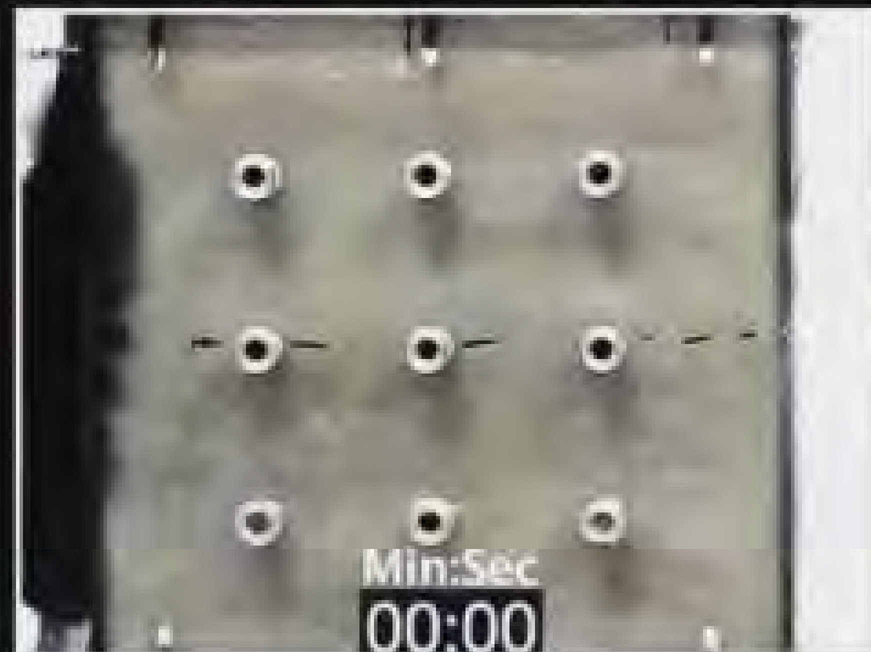
Bare NIP

6 % Al- Lactate

10 % Al-lactate

Bare NIP Transport Under Different Pressure Gradients

Bare NIP - 0.8 psi



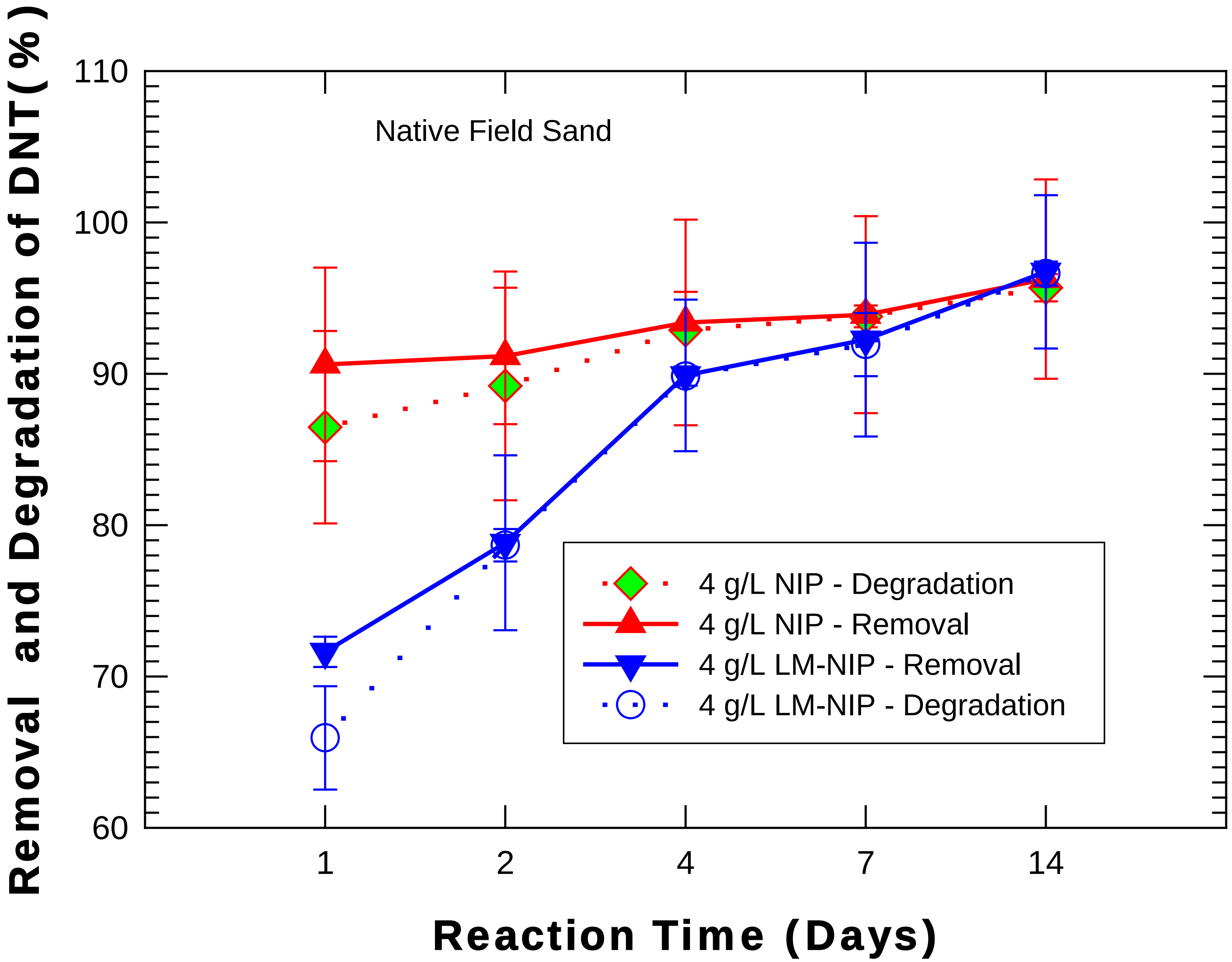
Bare NIP - 2.0 psi

LMNIP Transport Under Different Pressure Gradients

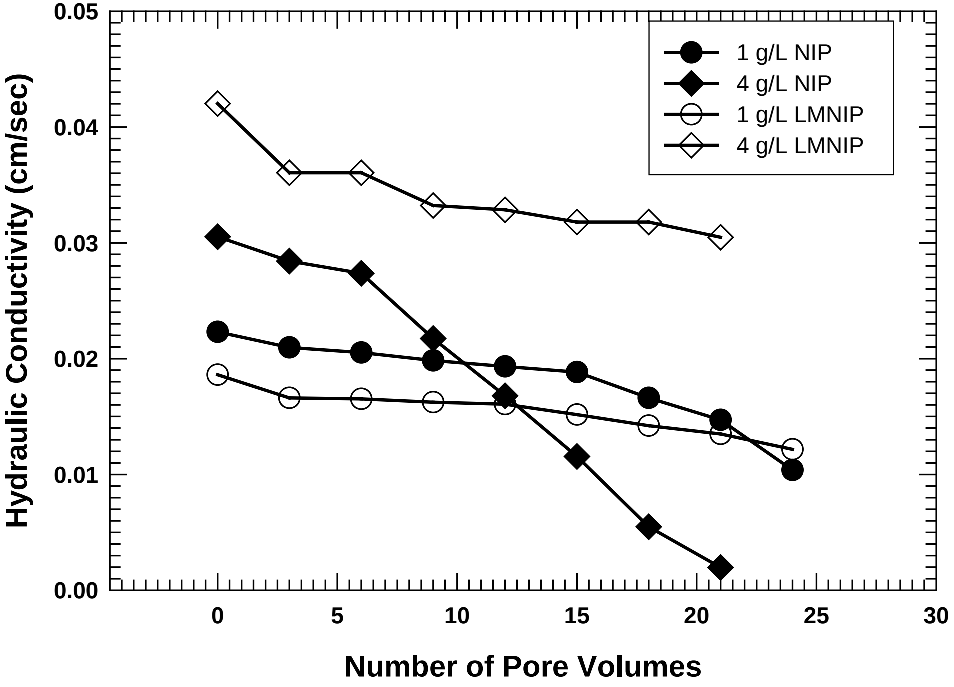
LMNIP - 0.8 psi

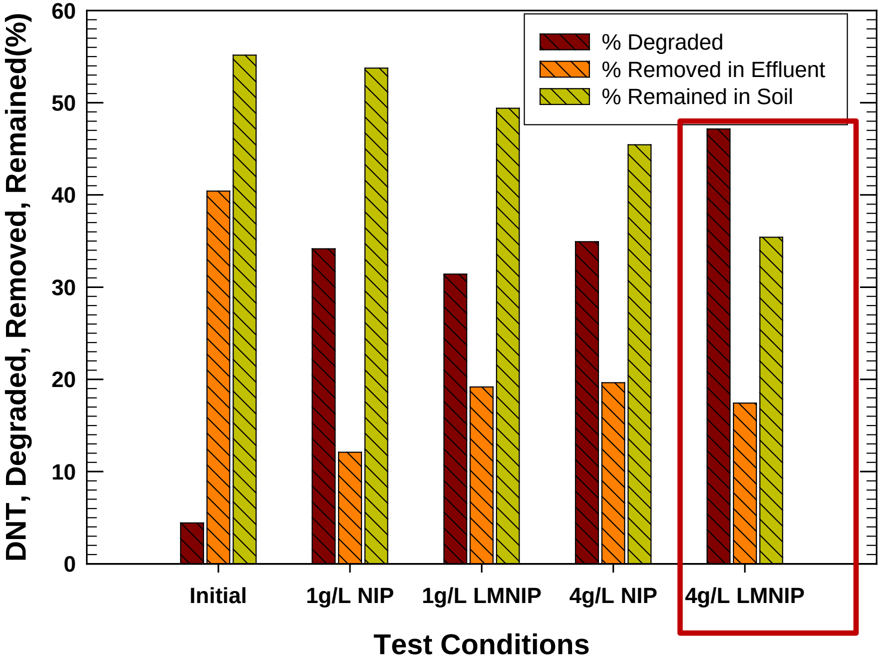
LMNIP - 2.0 psi

Batch Tests: Reactivity of DNT

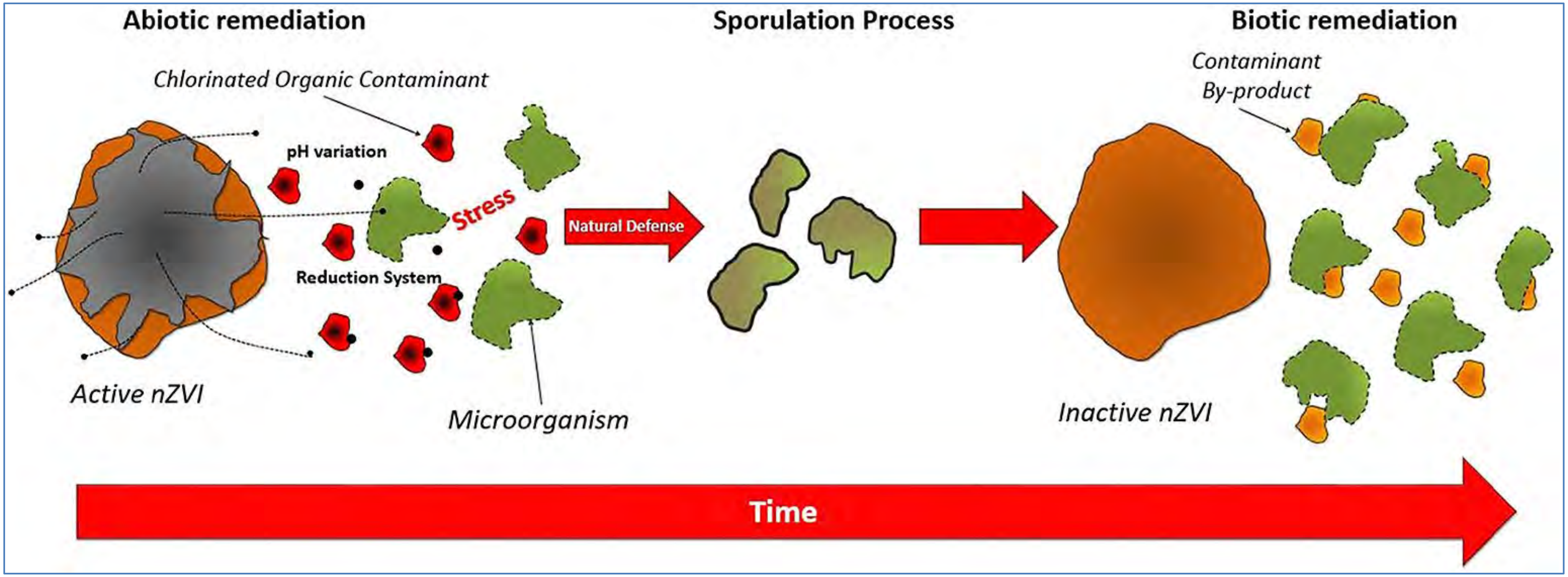


Column Tests: Transport and Reactivity





Nanobioremediation



Cecchin, I., Reddy, K.R., Thomé, A., Tessaro, E.F. and Schnaid, F. (2017). "**Nanobioremediation: Integration of nanoparticles and bioremediation for sustainable remediation of chlorinated organic contaminants in soils**." *International Biodeterioration & Biodegradation*.119, 419-428. (DOI: 10.1016/j.ibiod.2016.09.027)

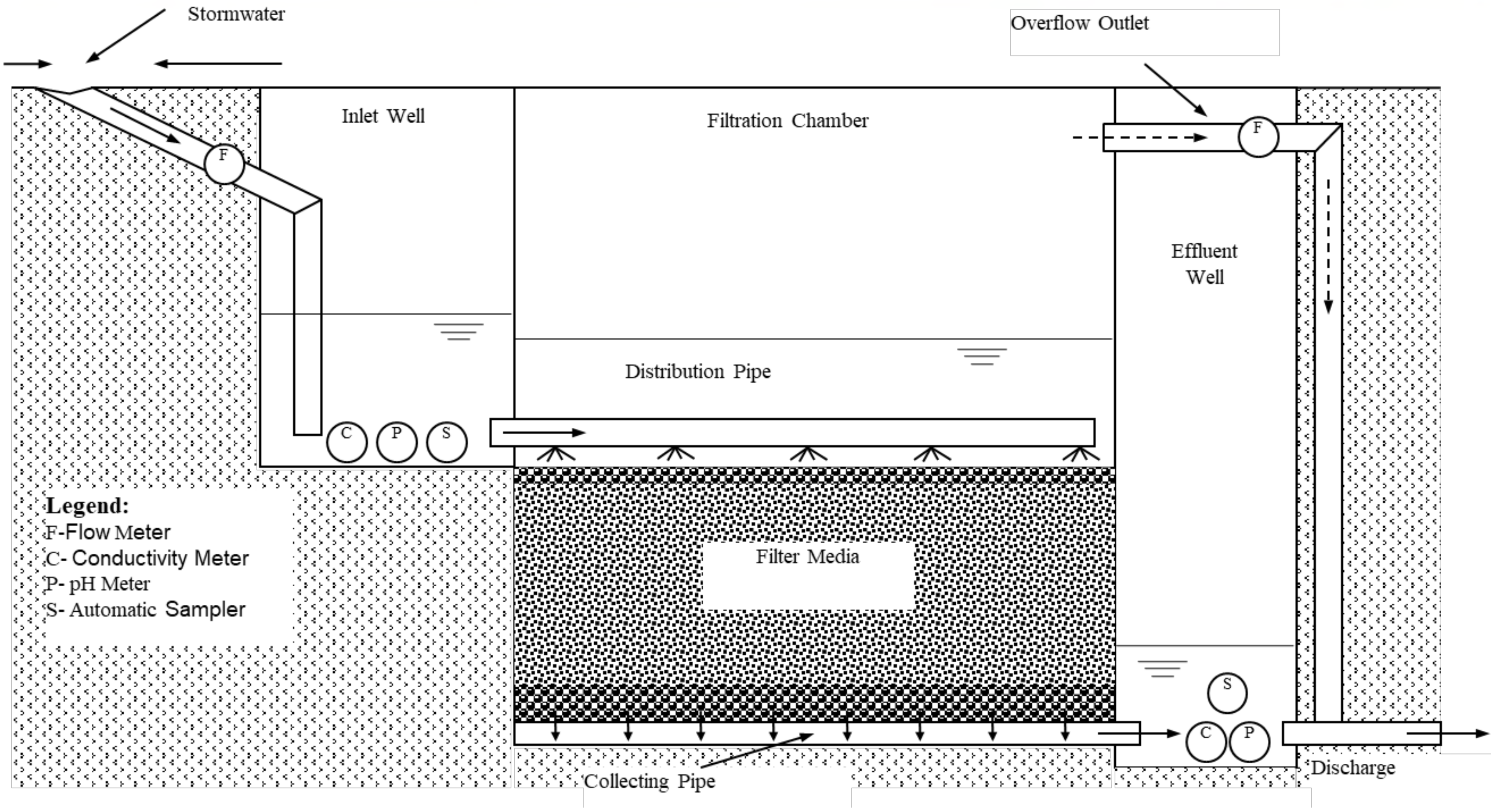
Polluted Stormwater Runoff

Most common non-point source of water pollution to rivers, lakes, estuaries, and beaches.

Beach closings are a growing concern due to the presence of pollutants in stormwater runoff.

Contaminants mainly include nutrients (nitrogen and phosphorus), heavy metals, PAHs, as well as *E. Coli.*

Proposed Permeable Reactive Filter

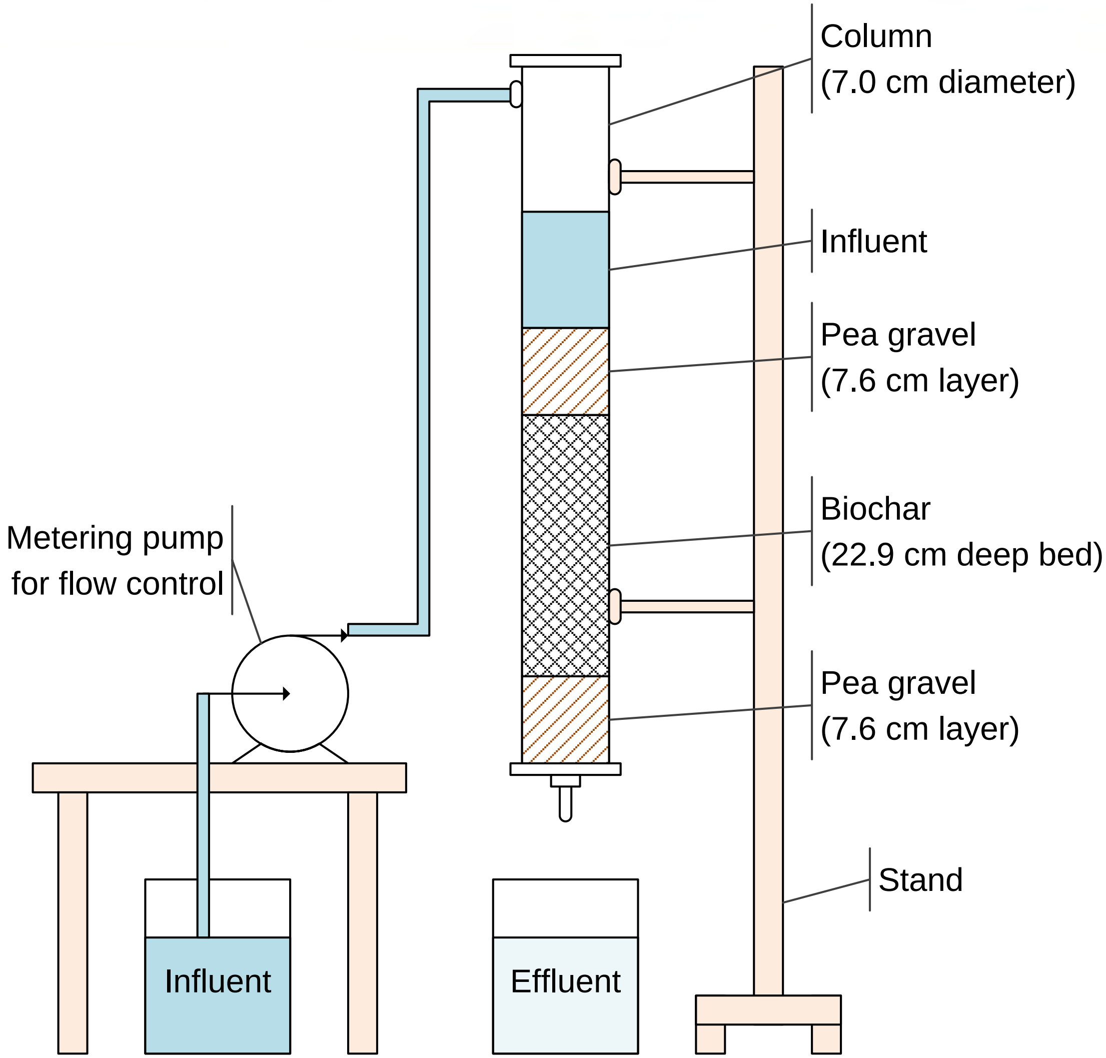


Source: Reddy (2013)

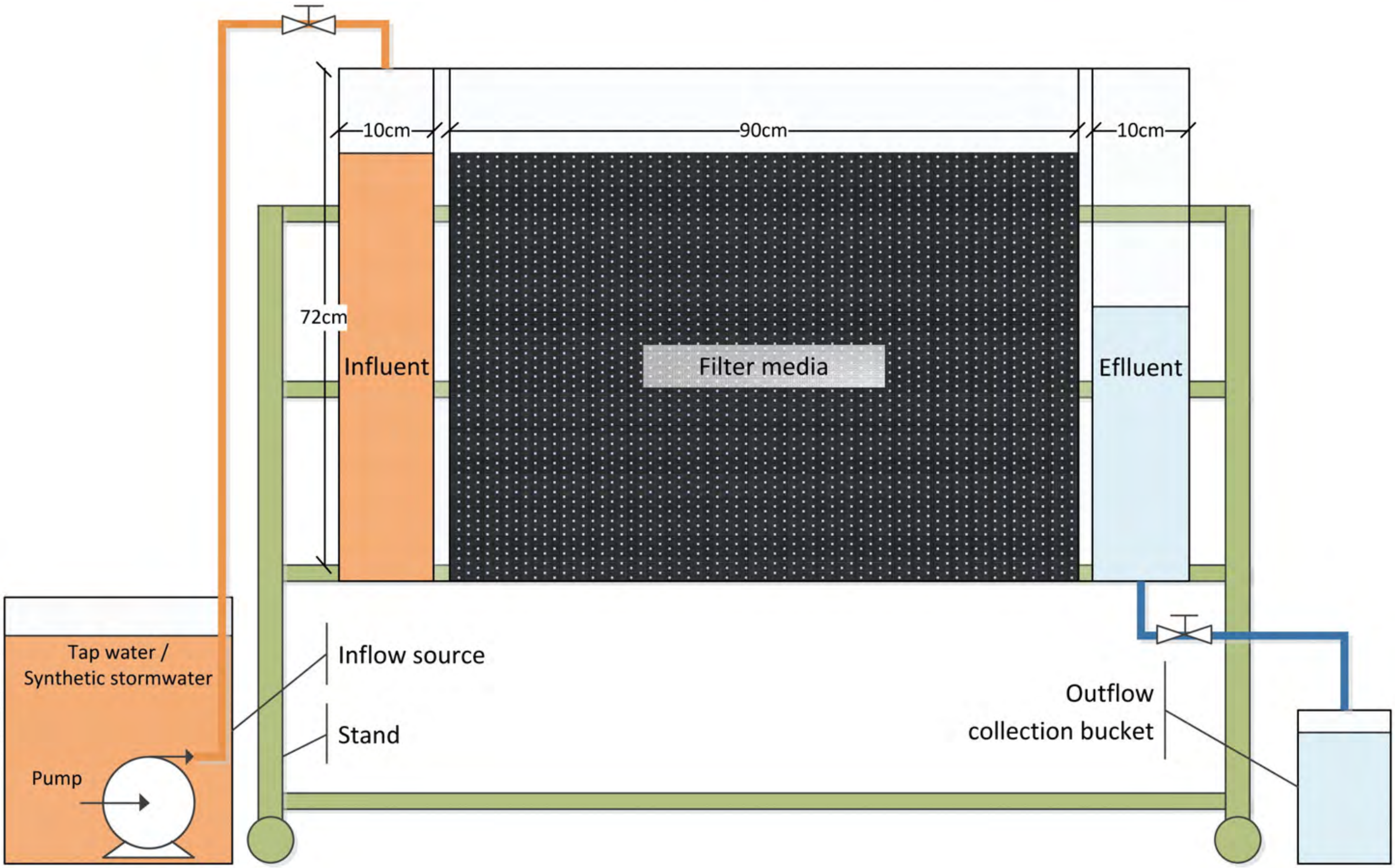
Selection of Filter Media

- Calcite
- Anthracite
- Zeolite
- Sand
- IOCS
- Iron filings
- Perlite
- Biochar

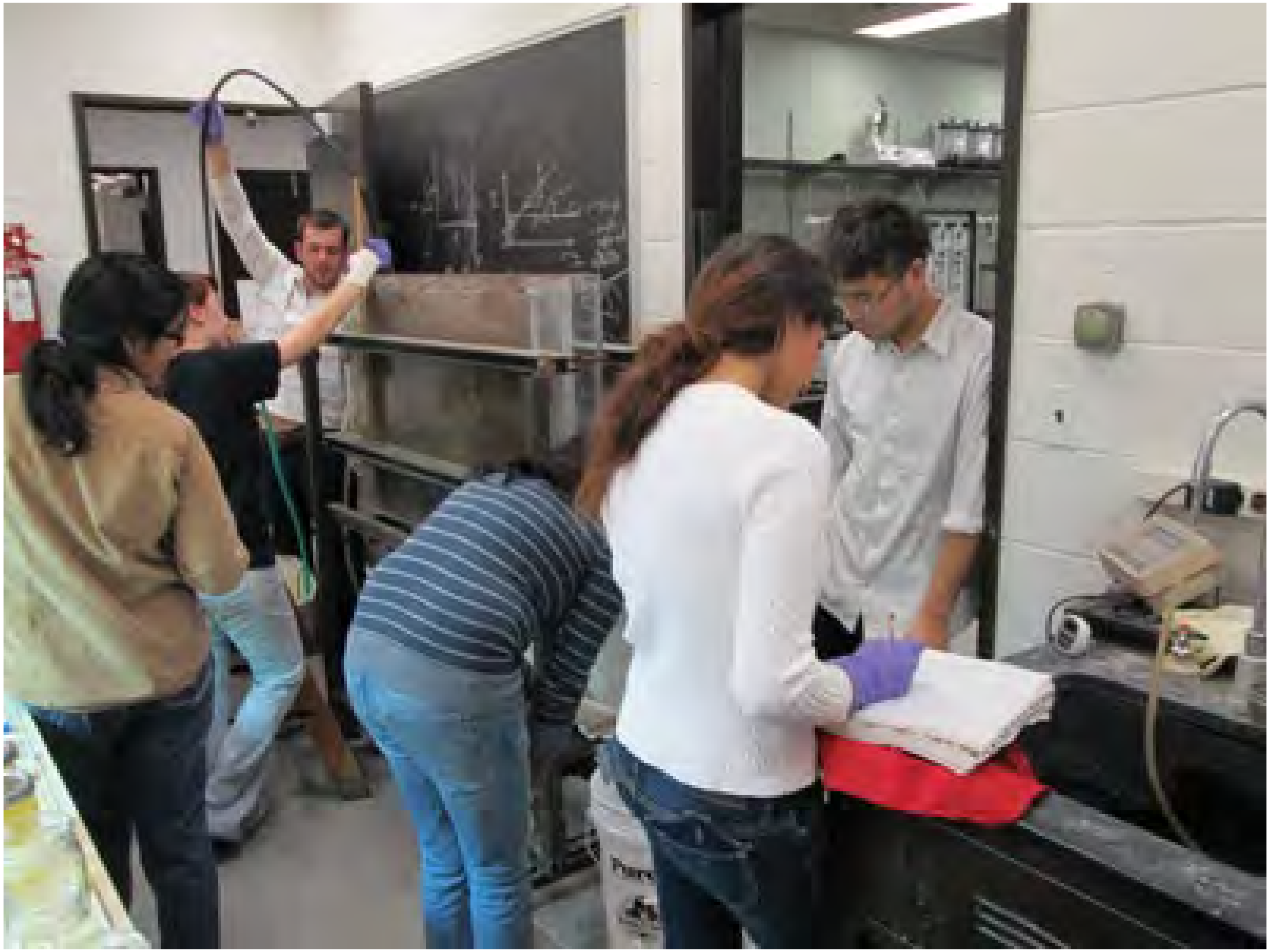
- Mixed media:
  Calcite, Sand, Iron filings and Zeolite



Large-Scale Lab Testing



Large-Scale Lab Testing



Reddy, K.R., Xie, T., and Dastgheibi, S. (2014). "**Mixed-media filter system for removal of multiple contaminants from urban stormwater: Large-scale laboratory testing**." *Journal of Hazardous, Toxic, and Radioactive Waste*, ASCE, 18(3), 04014011

Field Demo at Rainbow Beach, Chicago

Filter Installation and Monitoring

Geoenvironmental Engineering Challenges

- **Safe Disposal of Non-Hazardous and Hazardous Wastes**
  - Characterization of Wastes (e.g., MSW, Industrial Waste, Coal Ash, Mine Tailings, Nuclear Waste,…)
  - Design of Containment Systems (e.g., Landfills and Impoundments)

- **Characterization and Remediation of Polluted Sites**
  - Site Investigations (e.g., Contaminant Sensors)
  - In-Situ Barriers (e.g., Slurry Walls, Grout Curtains, Capping)
  - Soil, Sediment, Groundwater, and Stormwater Remediation Technologies (e.g., Stabilization/Solidification, Electrokinetics)

- **Enhance Environmental Sustainability and Resiliency**
  - Carbon Sequestration (e.g., Biochar, Biocovers)
  - Nature-Based Geo-Engineering (e.g., New Green Materials, Biocementation, Phytostabilization)
  - Upcycling of Waste/Recycled Materials (e.g., Scrap Tires)
  - End Use of Closed Landfills/Remediated Sites (e.g., Parks)
  - Renewable Geo-Energy (e.g., Geothermal, Landfill Gas, Biomass)

Significantly Contribute to SDGs

(including Climate Change Mitigation and Adaptation)!

Concluding Remarks

- Both resiliency and sustainability must be addressed in engineering to address global challenges (climate change, SDGs)

- Use integrated resilience and sustainability assessment frameworks and tools (e.g., TQUALICSR, Envision) that provide structured approach to develop optimal holistic solutions!

- Promote innovative, practical, sustainable and resilient engineering solutions to address persistent and emerging real-world problems!

- Numerous opportunities for fundamental and applied research in Geoenvironmental Engineering to address insidious problems:
  - Waste Management and Containment
  - Environmental Pollution Control and Remediation
  - Decarbonization/Carbon Sequestration/Climate Mitigation
  - Environmental Justice
  - SDGs

Contact / Additional Information

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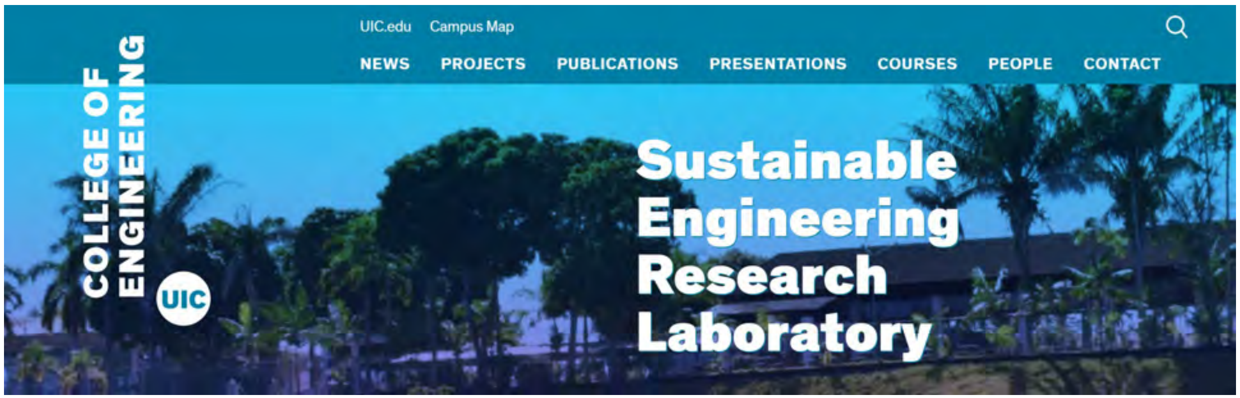

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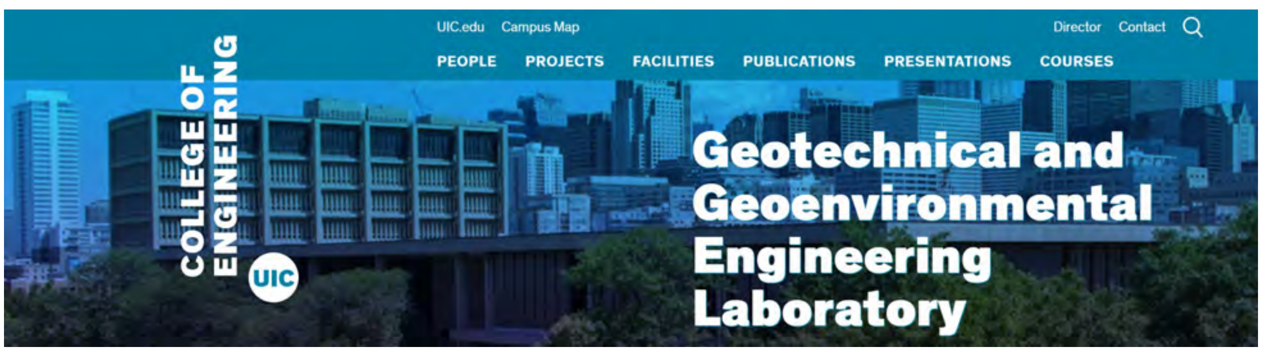

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THANK YOU