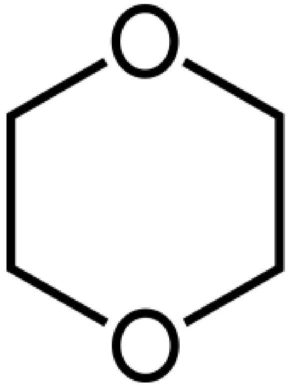
Bioaugmented Phytoremediation to Treat 1,4-Dioxane Contaminated Groundwater

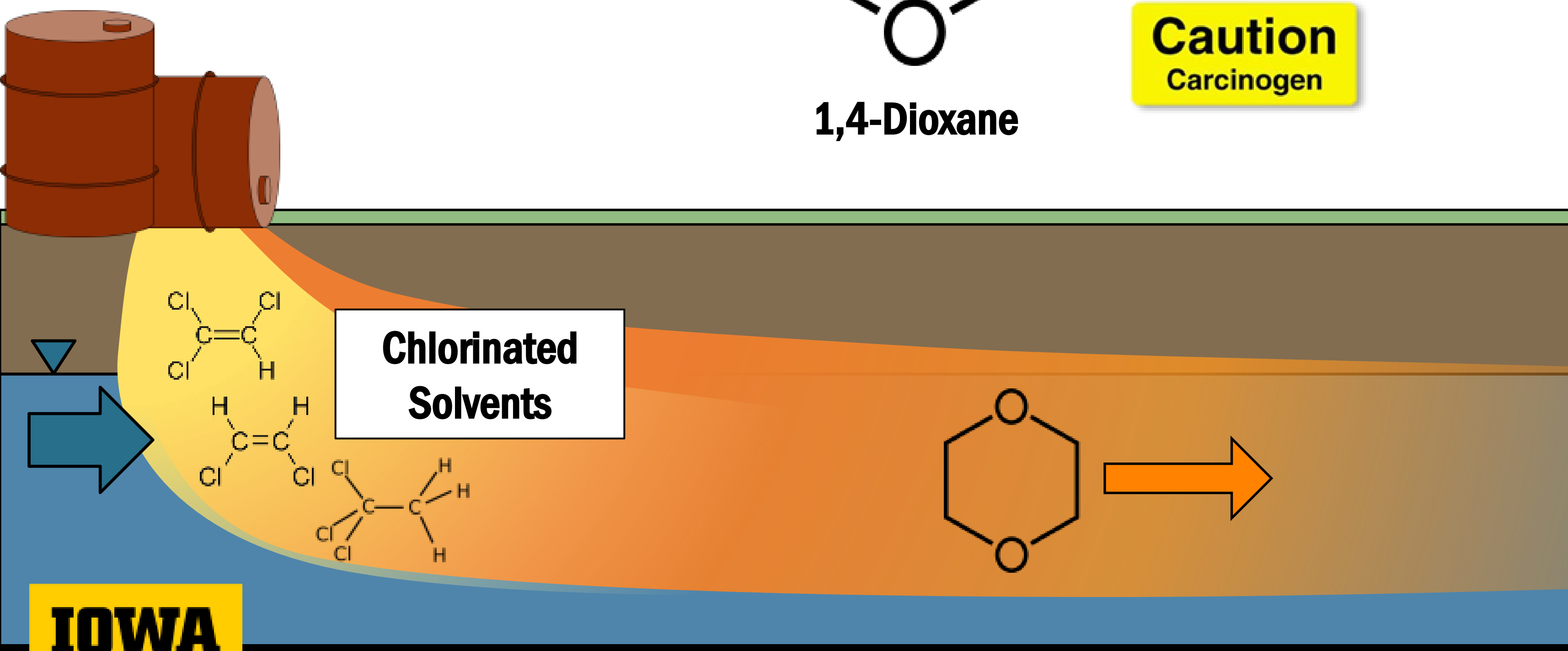
ESTCP
ER21-5096

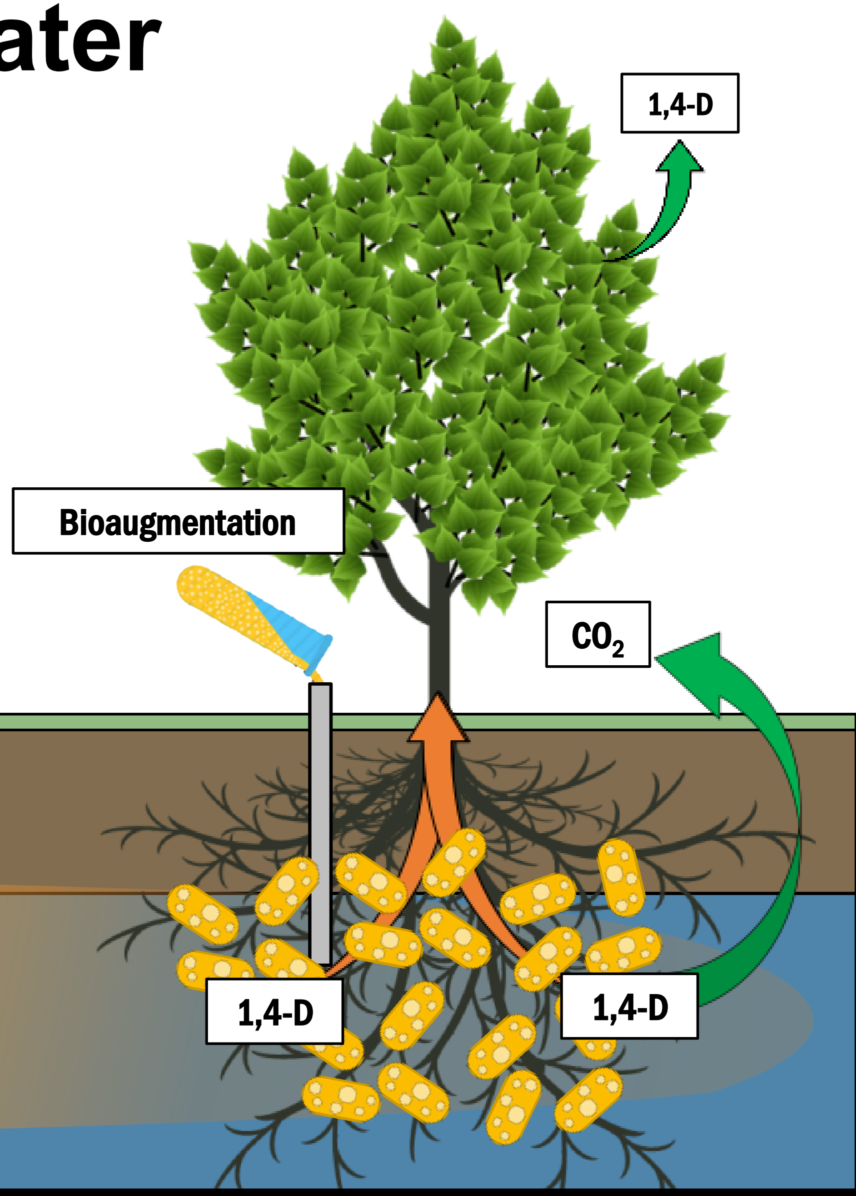
<u>Reid Simmer</u>, Phillip Dixon, Timothy Mattes, and Jerald Schnoor

May 9th, 2023



1,4-Dioxane





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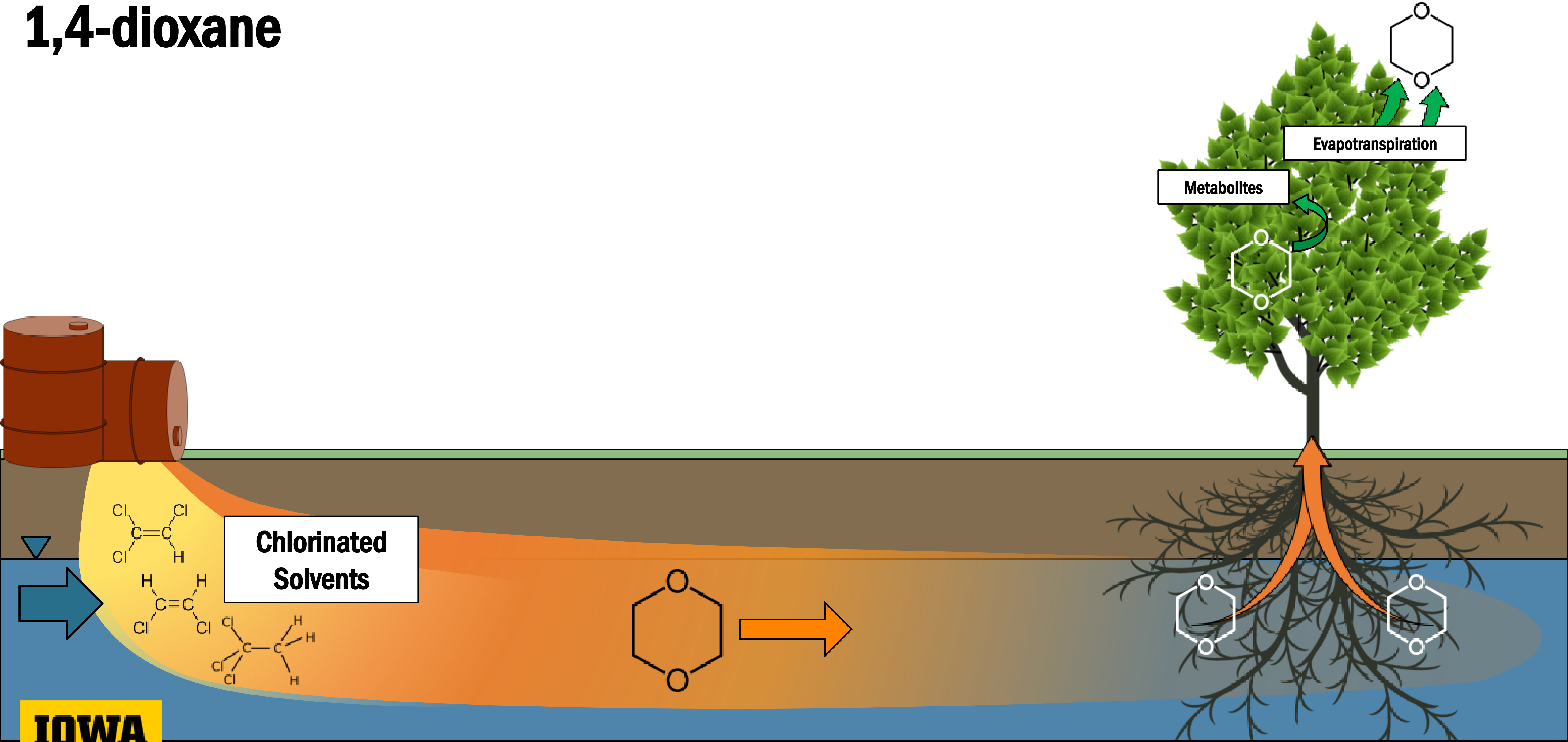
Phytoremediation is a low cost, green remediation technology for 1,4-dioxane



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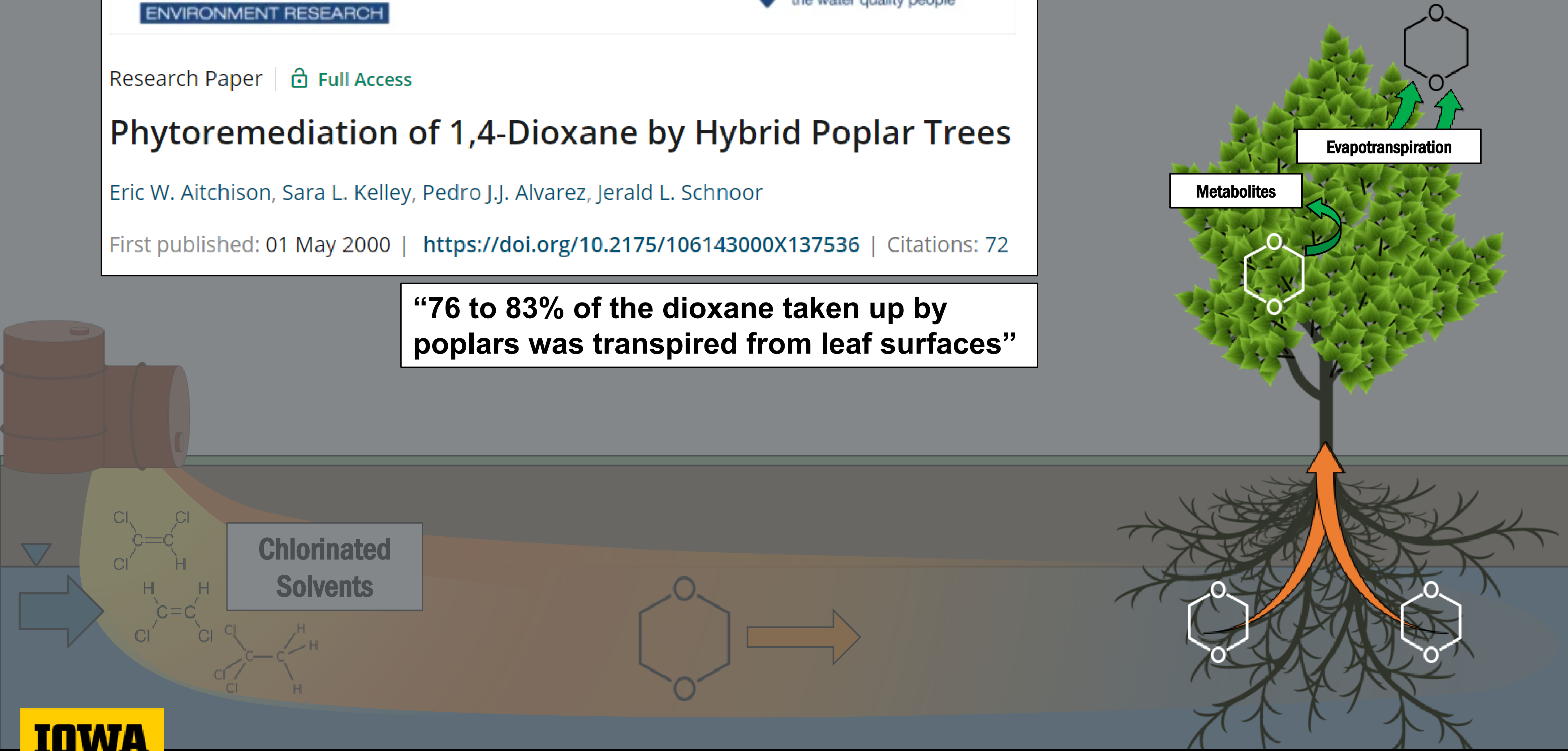
Phytoremediation of 1,4-Dioxane by Hybrid Poplar Trees

Eric W. Aitchison, Sara L. Kelley, Pedro J.J. Alvarez, Jerald L. Schnoor

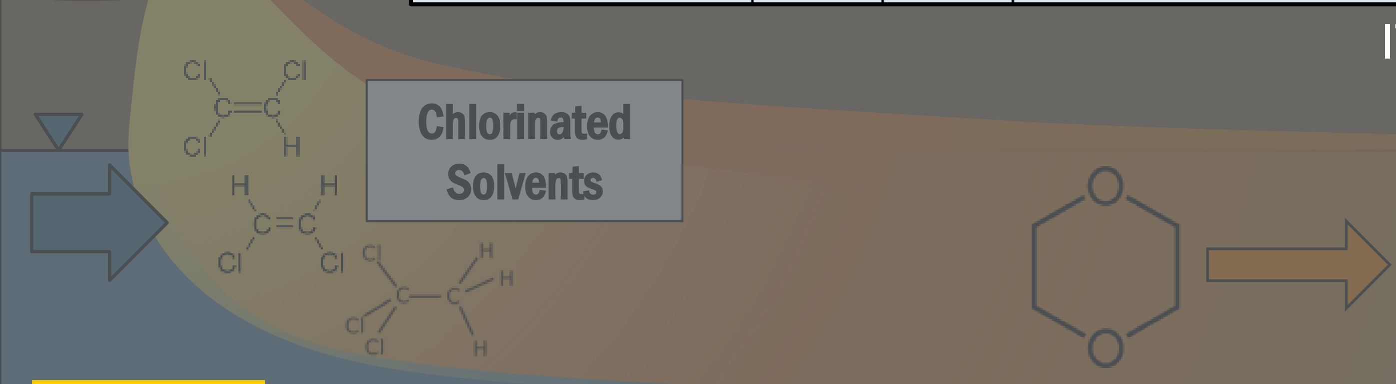
First published: 01 May 2000 | https://doi.org/10.2175/106143000X137536 | Citations: 72

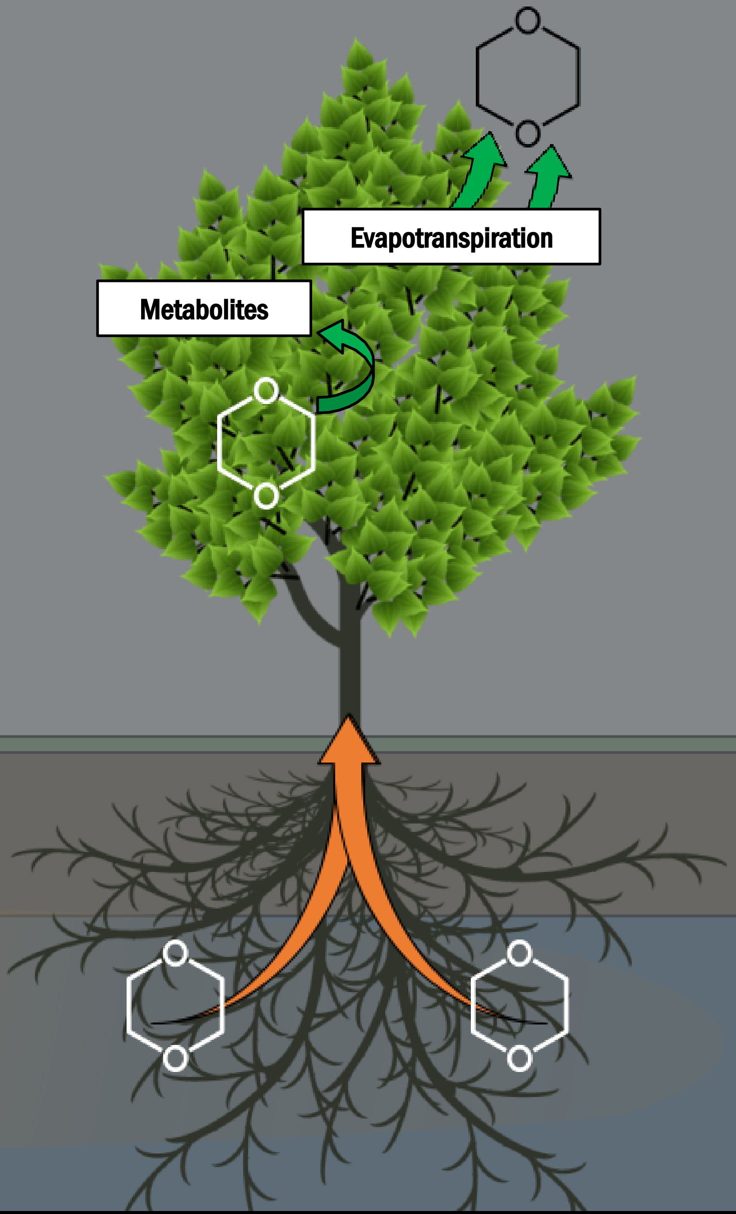
“76 to 83% of the dioxane taken up by poplars was transpired from leaf surfaces”



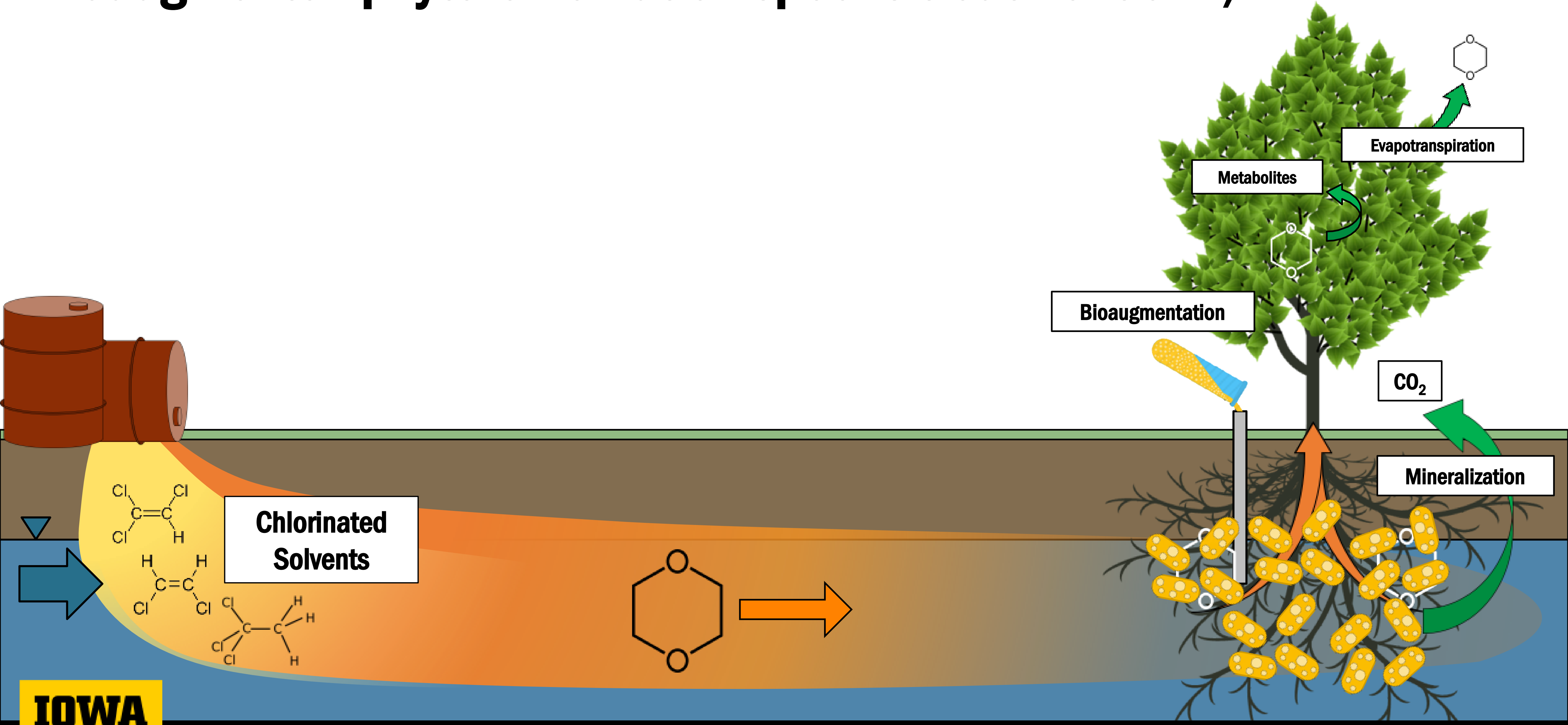
Remediation/ Treatment Technology	Development status		Effectiveness
	GW	VZS	
Monitored natural attenuation (includes physical, chemical, and biological mechanisms)	**E**	**NA**	May be effective at reducing 1,4-D at lower starting concentrations (e.g., <500 µg/L), depending on the time available and relevant attenuation mechanisms
Phytoremediation	**F**	**F**	Effective for a range of starting concentrations (up to >2,500 µg/L)
In situ chemical oxidation: Sodium persulfate/ potassium persulfate	**F**	**E**	Effective at oxidizing 1,4-D to <1 µg/L for high starting concentrations (500 to >2,500 µg/L), depending on proper design and implementation

ITRC, 2021





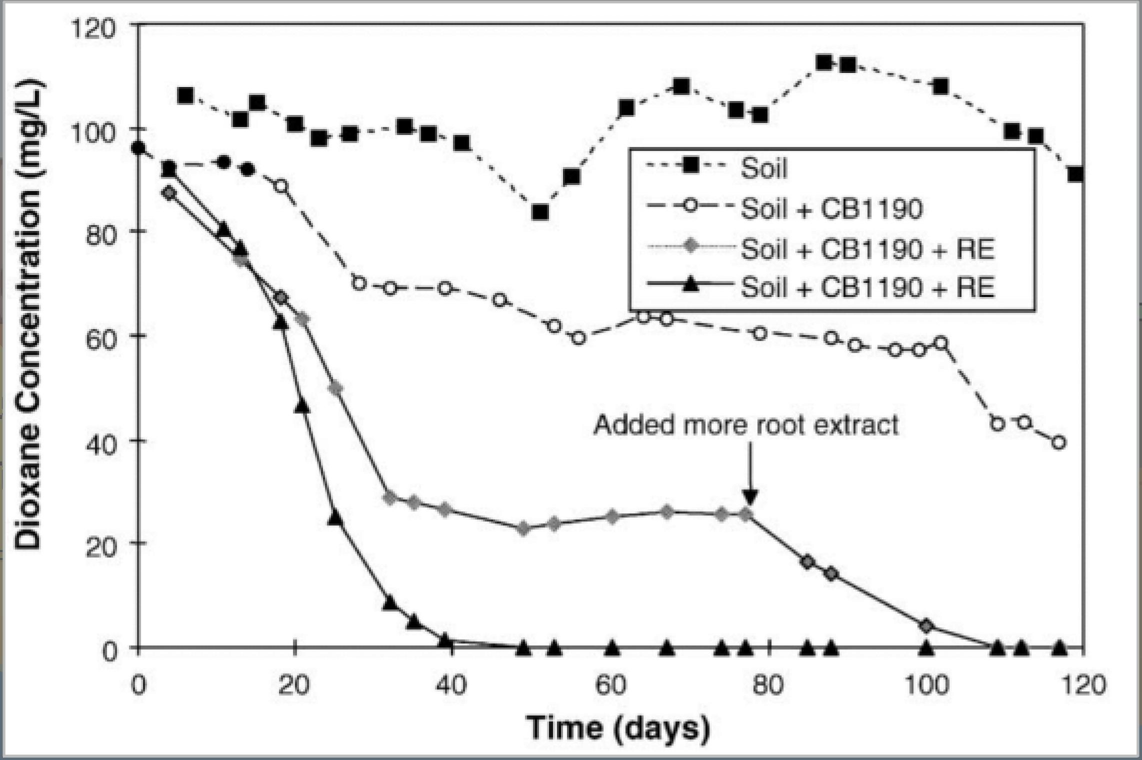
Bioaugmented phytoremediation speeds treatment of 1,4-D

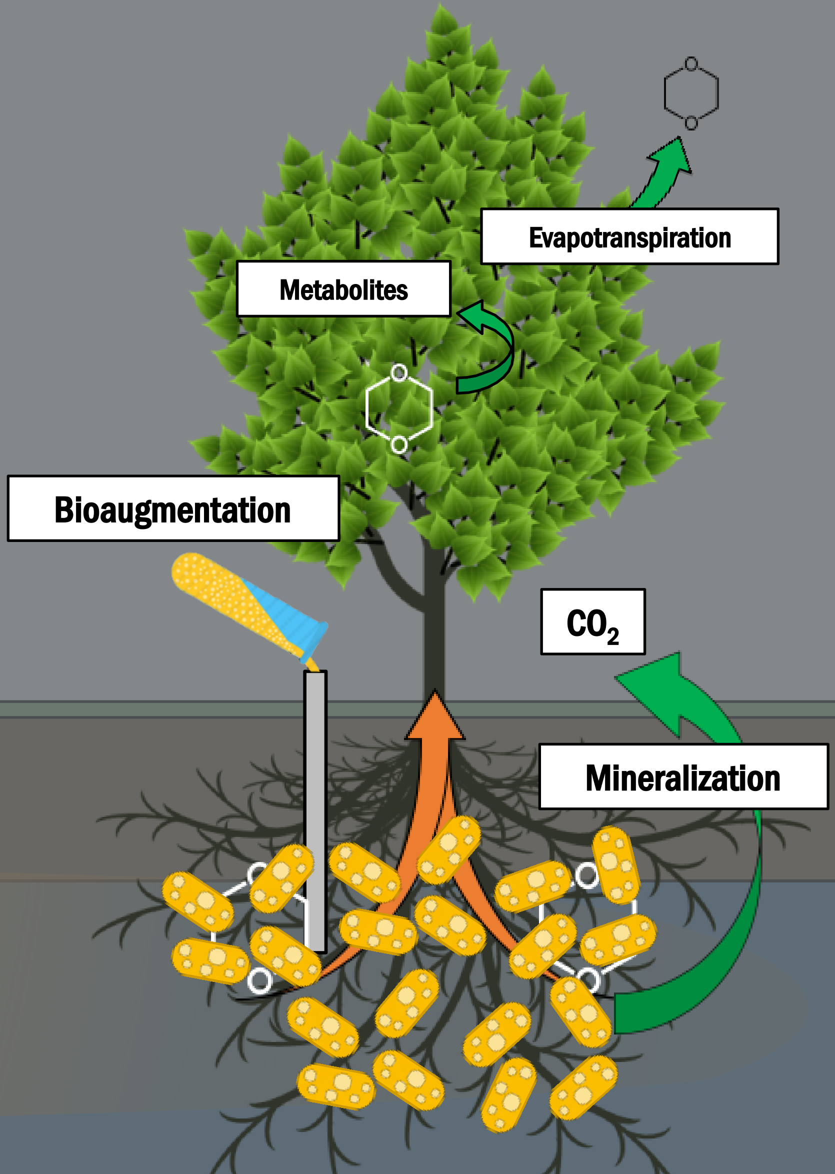


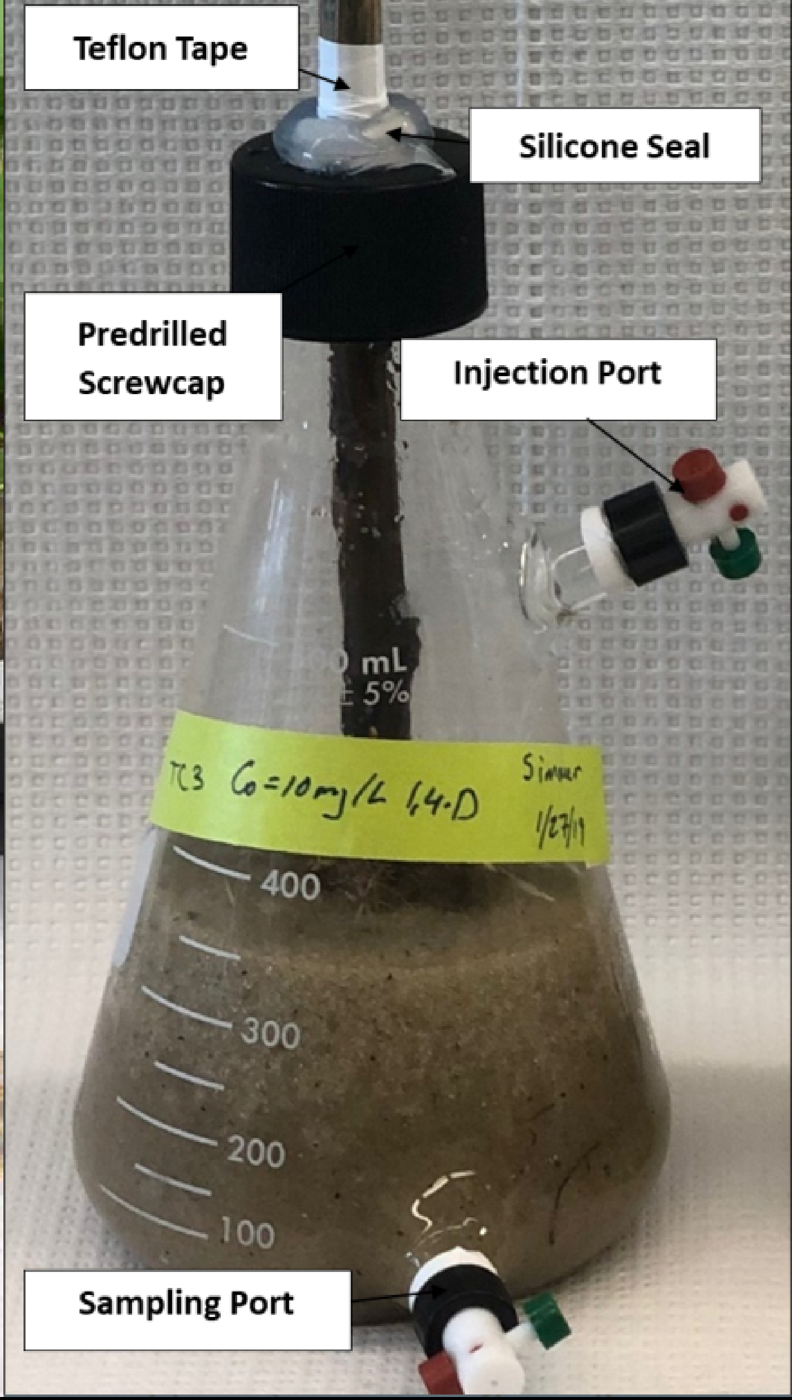
Water Research
Volume 35, Issue 16, November 2001, Pages 3791-3800

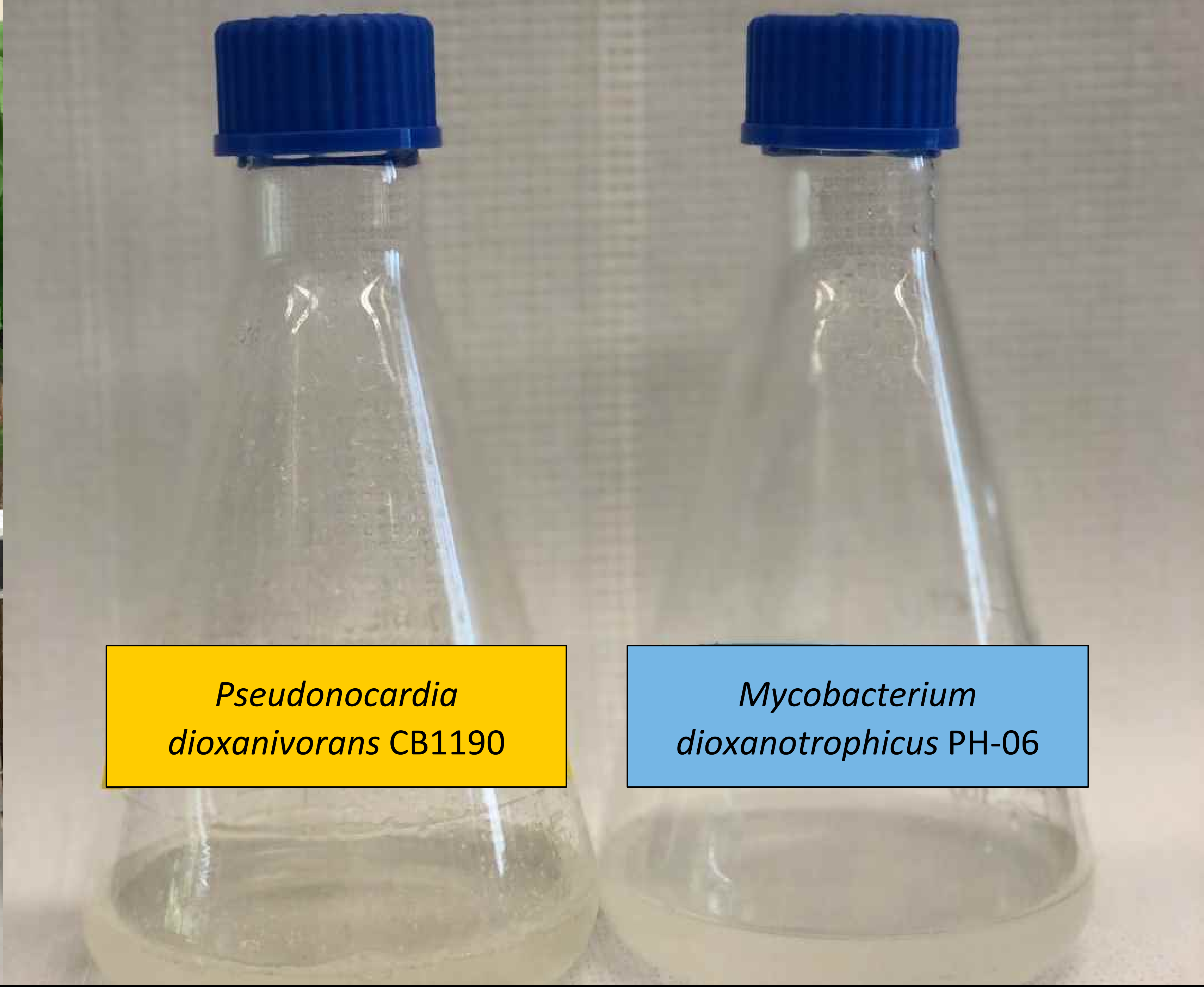
Biodegradation of 1,4-dioxane in planted and unplanted soil: effect of bioaugmentation with *amycolata* sp. CB1190

Sara L. Kelley [1], Eric W. Aitchison [1], Milind Deshpande [2], Jerald L. Schnoor [1], Pedro J.J. Alvarez [1]

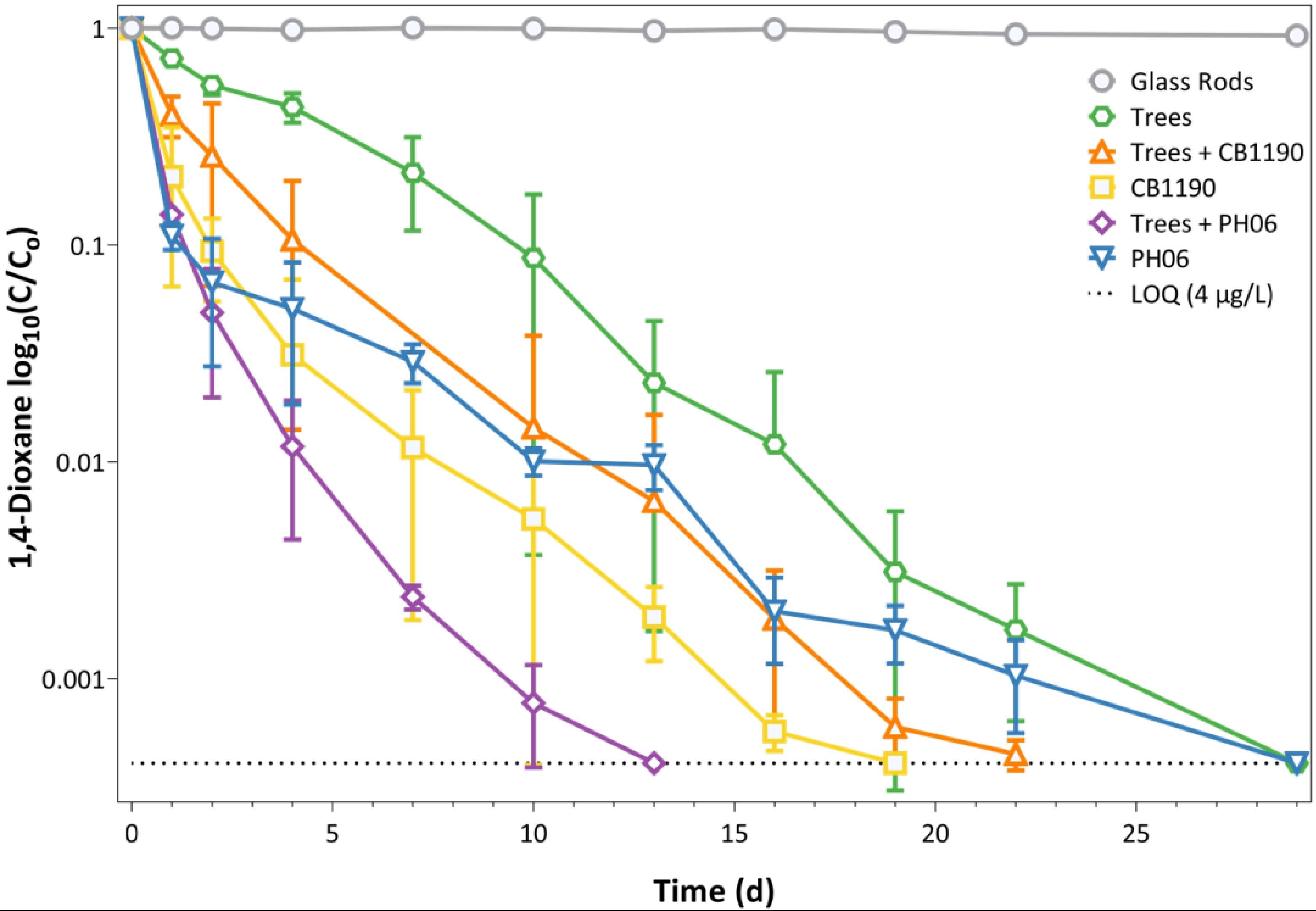





Teflon Tape
Silicone Seal
Predrilled Screwcap
Injection Port
Sampling Port
400
300
200
100


Pseudonocardia dioxanivorans CB1190
Mycobacterium dioxanotrophicus PH-06

Trees bioaugmented with *Mycobacterium sp.* PH-06 sped treatment of 1,4-D to ~4 ug/L



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Bioaugmenting the poplar rhizosphere to enhance treatment of 1,4-dioxane

Check for updates

Reid Simmer[a,*], Jacques Mathieu[b], Marcio L.B. da Silva[b], Philip Lashmit[c], Sridhar Gopishetty[c], Pedro J.J. Alvarez[b], Jerald L. Schnoor[a]

[a] Department of Civil and Environmental Engineering, College of Engineering, The University of Iowa, Iowa City, IA, USA
[b] Department of Civil and Environmental Engineering, College of Engineering, Rice University, Houston, TX, USA
[c] Center for Biocatalysis and Bioprocessing, Office for the Vice President for Research and Economic Development, University of Iowa Research Park, The University of Iowa, Coralville, IA, USA

SCAN ME

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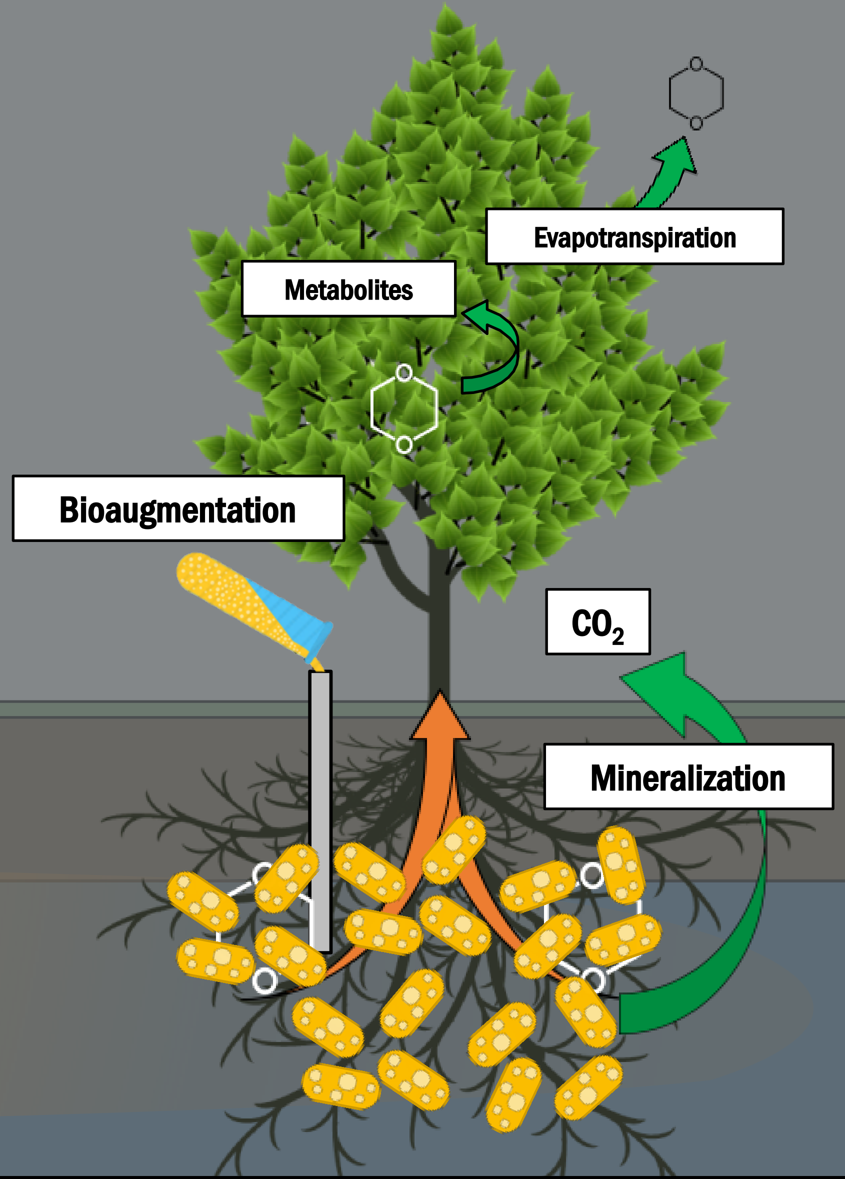
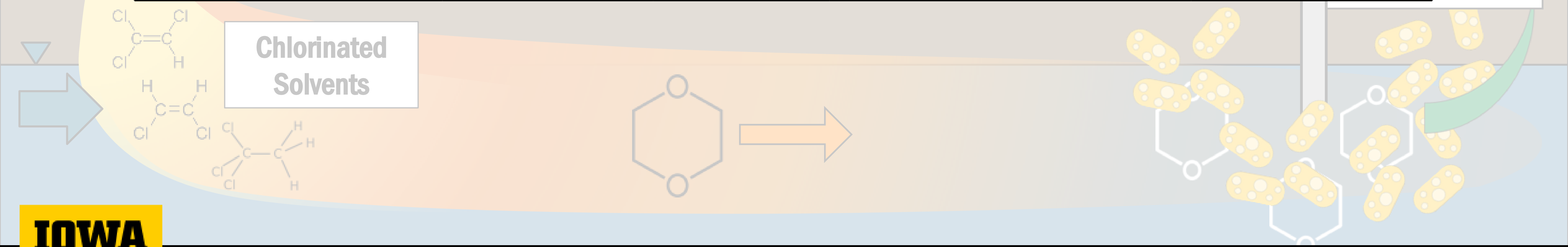


However, metabolic degraders have significant kinetic limitations

Strain	q_{max} (mg 1,4-dioxane/mg protein/day)	K_s (mg 1,4-dioxane /L)	Yield (mg protein/ mg dioxane)	S_{min} (μg 1,4-dioxane /L)	Reference
Pseudonocardia dioxanivorans CB1190	1.65 ± 0.05	**6.32 ± 0.22**	0.45 ± 0.09	**487.14 ± 173.45[a]**	Barajas-Rodriguez et al. (2018)
Mycobacterium dioxanotrophicus PH-06	Not reported	**78.00 ± 10.00**	0.16	Not reported	He et al. (2018)



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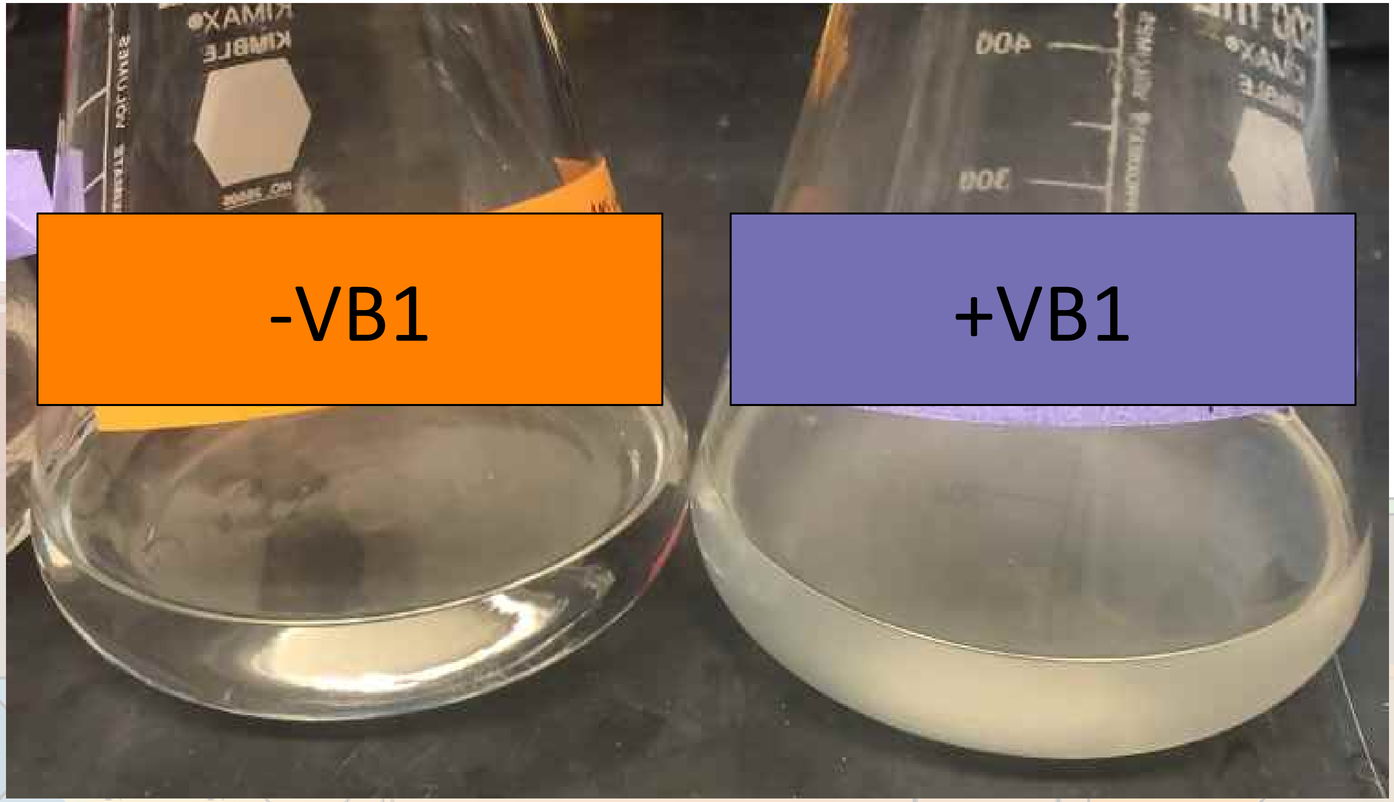
Vitamin B1 (thiamine) supplements accelerate growth in *Rhodococcus ruber* 219



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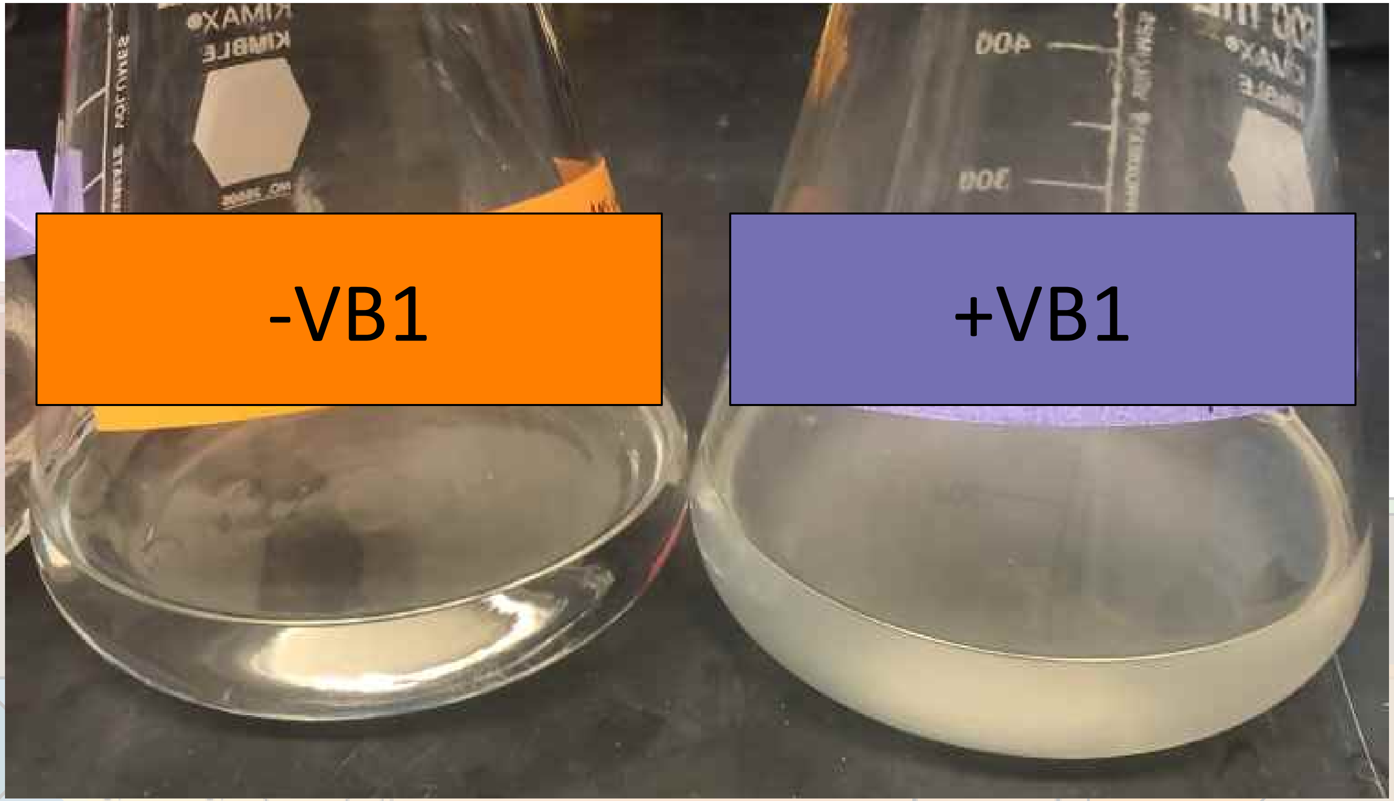

Rhodococcus ruber **219**, when supplemented with Vitamin B1, has the **lowest K_s and S_{min}** reported for dioxane-metabolizing bacteria to date, **degrading 100 µg/L dioxane to below 0.1 µg/L.**

Strain	q_{max} (mg 1,4-dioxane/mg protein/day)	K_s (mg 1,4-dioxane /L)	Yield (mg protein/ mg dioxane)	S_{min} (µg 1,4-dioxane /L)	Reference
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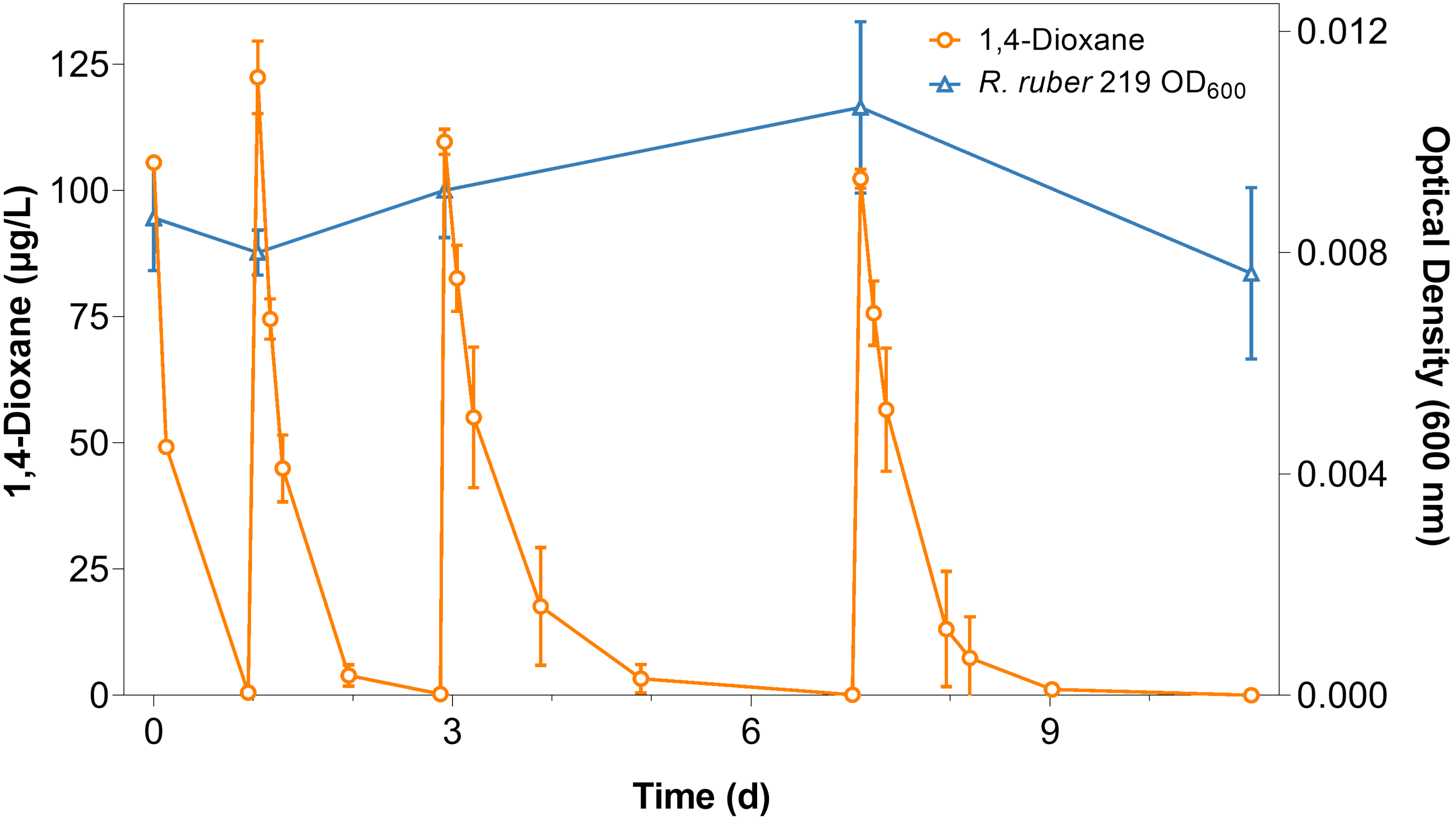
***Rhodococcus ruber* 219**	**5.00 ± 0.24**	**0.015 ± 0.03**	**0.24 ± 0.02**	**0.49 ± 1.16**	**Simmer et al. (2021)**

R. ruber 219 repeatedly degraded ~100 µg/L dioxane to <0.35 µg/L



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Environmental Science & Technology LETTERS

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Letter

Rapid Metabolism of 1,4-Dioxane to below Health Advisory Levels by Thiamine-Amended *Rhodococcus ruber* Strain 219

Reid A. Simmer,* Patrick M. Richards, Jessica M. Ewald, Cory Schwarz, Marcio L. B. da Silva, Jacques Mathieu, Pedro J. J. Alvarez, and Jerald L. Schnoor

Cite This: *Environ. Sci. Technol. Lett.* 2021, 8, 975−980

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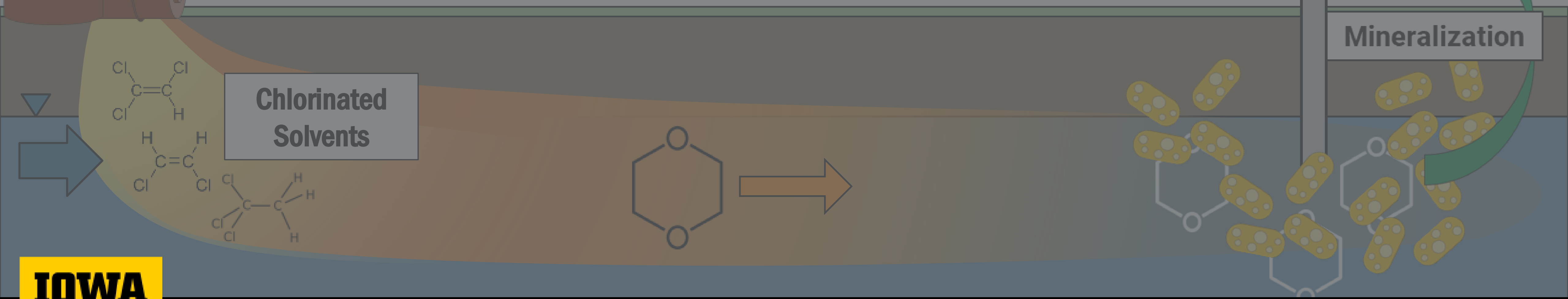

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Current Work

- Does bioaugmented phytoremediation with *R. ruber* 219 accelerate treatment of 1,4-D to <1 µg/L?

- Can treatment of 1,4-D be sustained in long term flow-through experiments?

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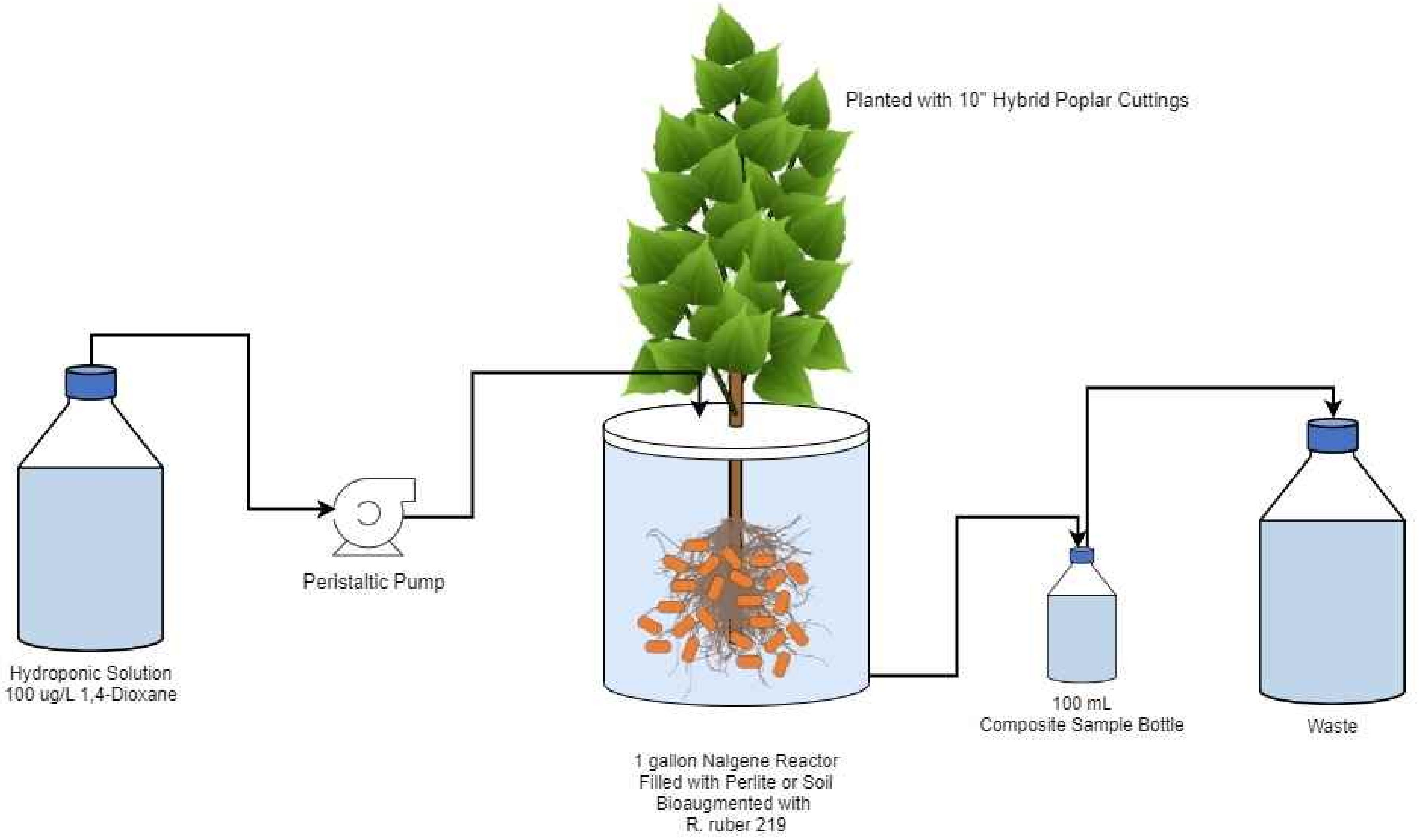
Flow-through experiments were used to emulate environmentally relevant field-scale conditions



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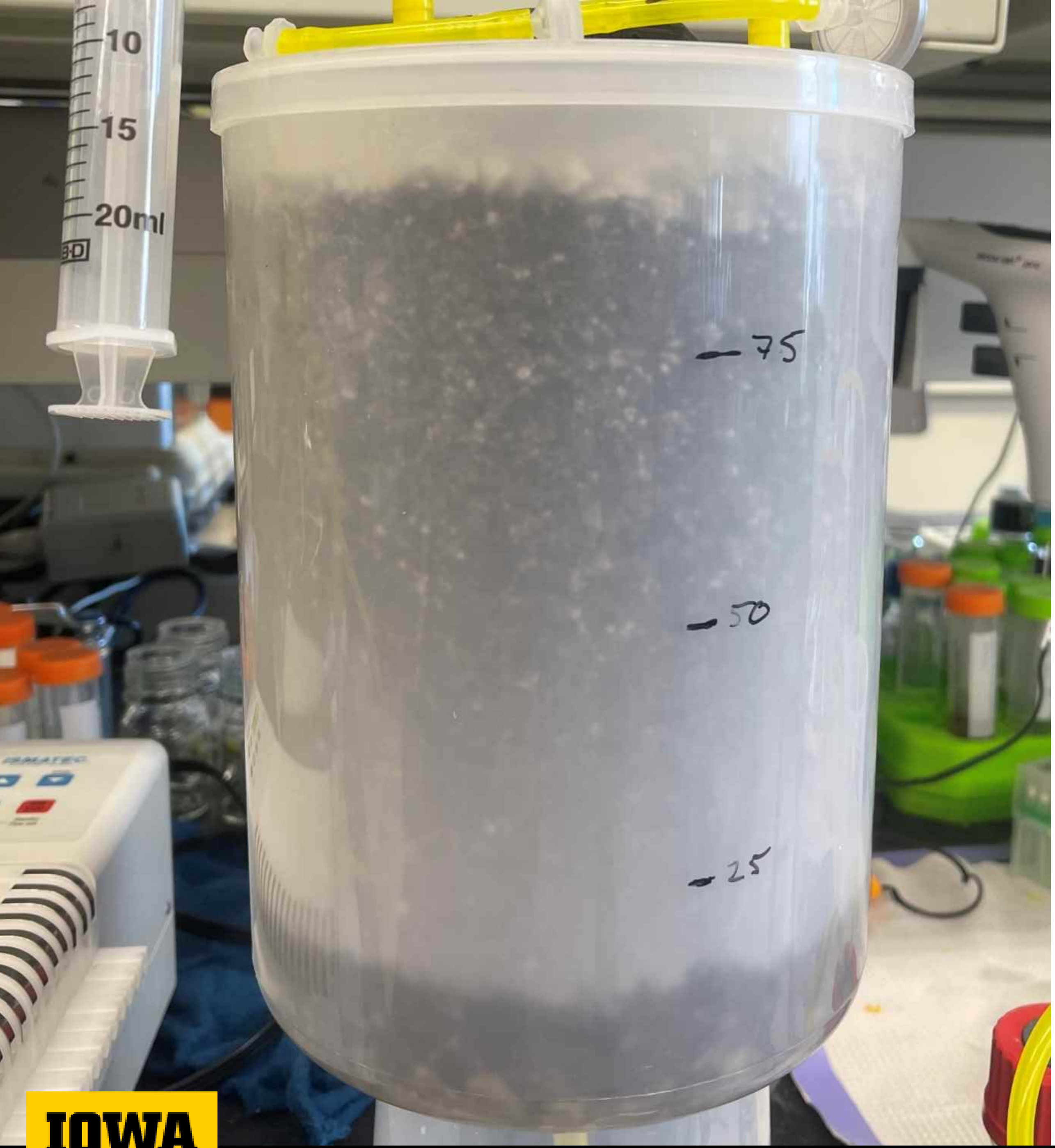

Treatment	Soil Substrate	Replicates
Glass Rod Control	Perlite	1
Tree Only	Perlite	2
R. ruber 219 only	Perlite	2
Tree + *R. ruber* 219	Perlite	3
Glass Rod Control	Soil	1
Tree Only	Soil	2
R. ruber 219 only	Soil	2
Tree + *R. ruber* 219	Soil	3
		Total: 16

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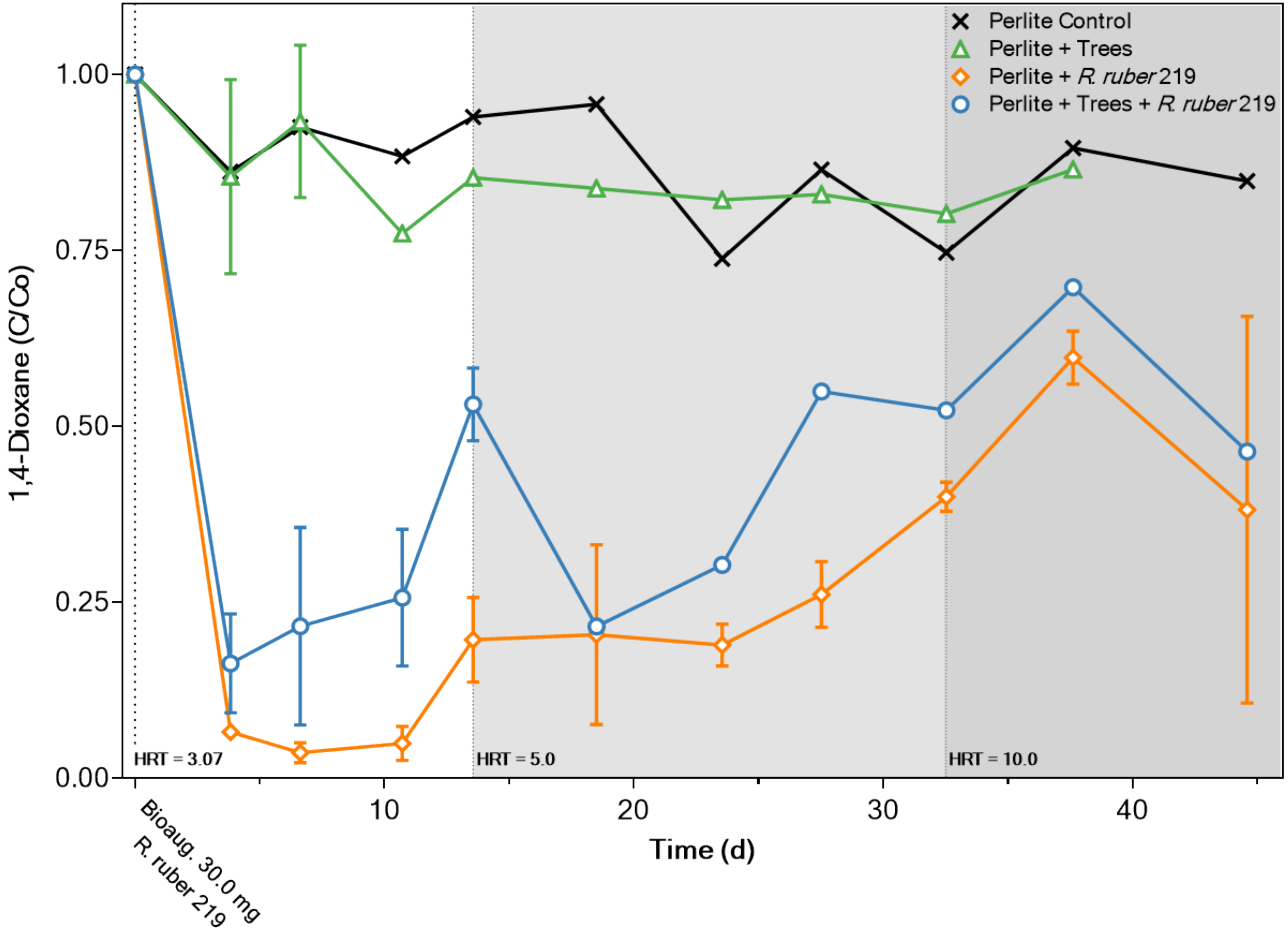
-75
-50
-25

1000 mL
900
800
700
600
500
400
300
200
100


10 20 30 40 50 60 ml

Perlite reactors bioaugmented with *R. ruber* achieved the lowest effluent concentrations



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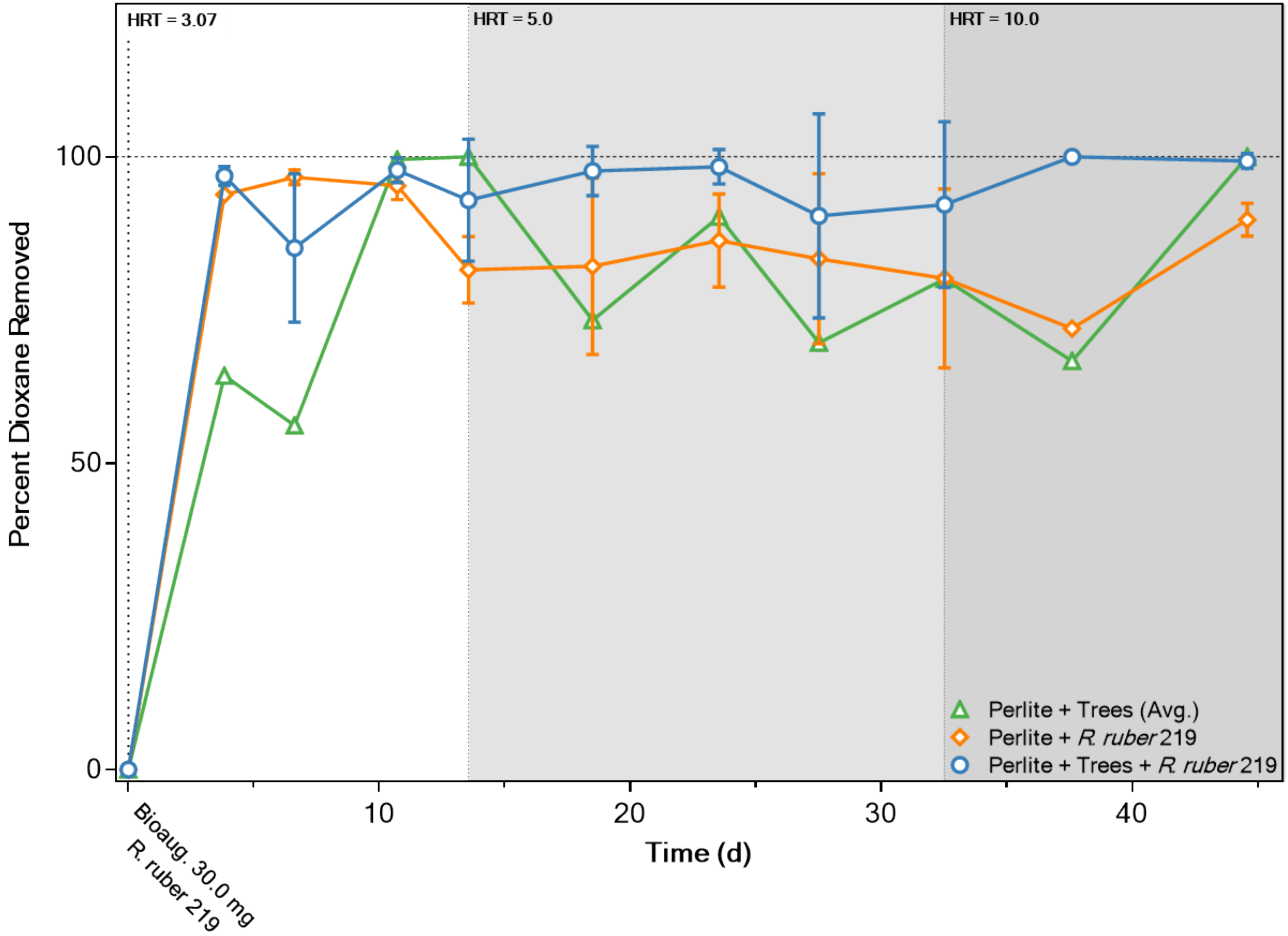
However, trees with *R. ruber* 219 was best on a mass removal basis (biodegradation + phytoextraction/evapotranspiration)



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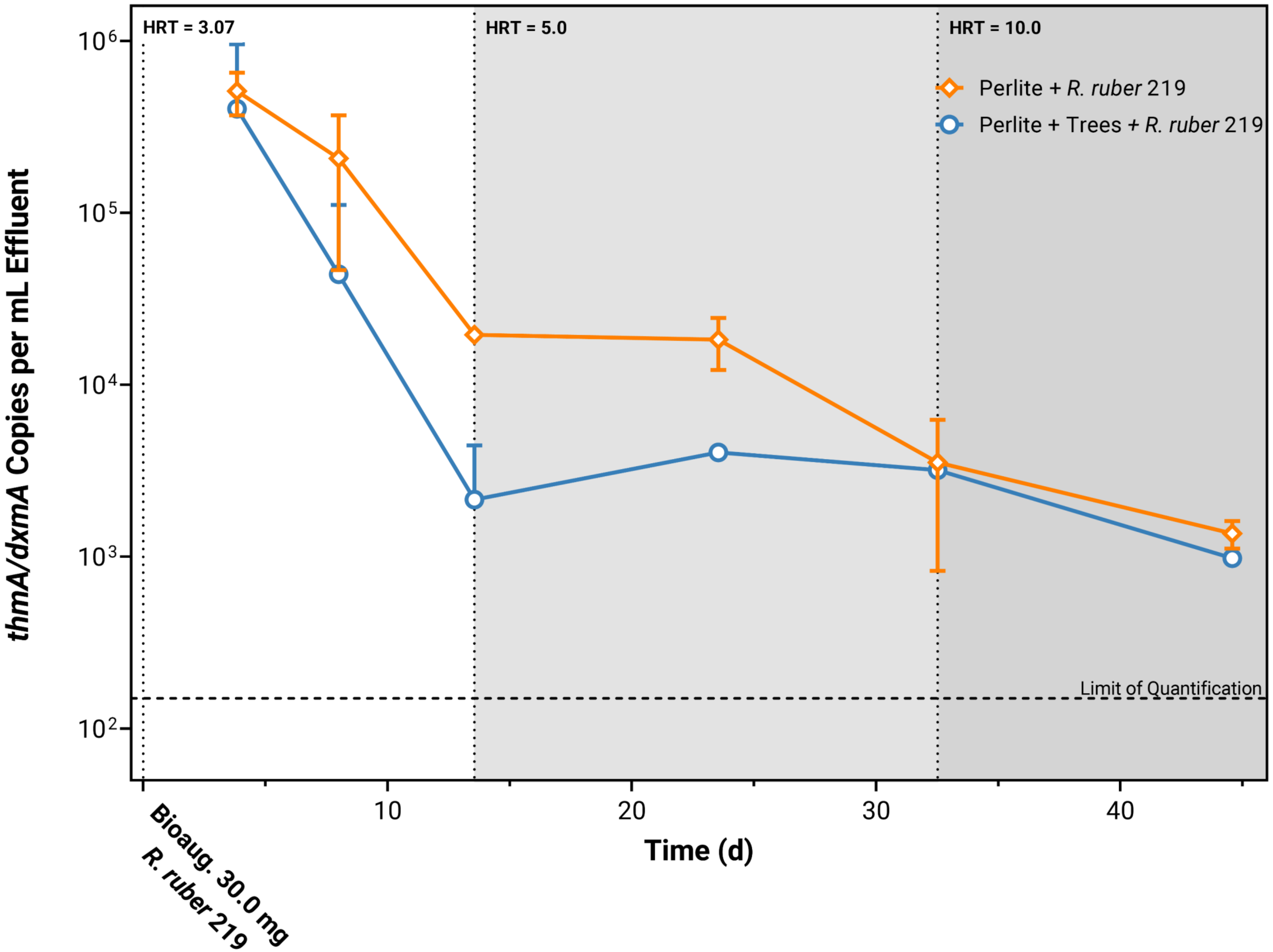
qPCR Results Show Reduced Washout of *R. ruber* 219 Gene Copies in Planted Reactors



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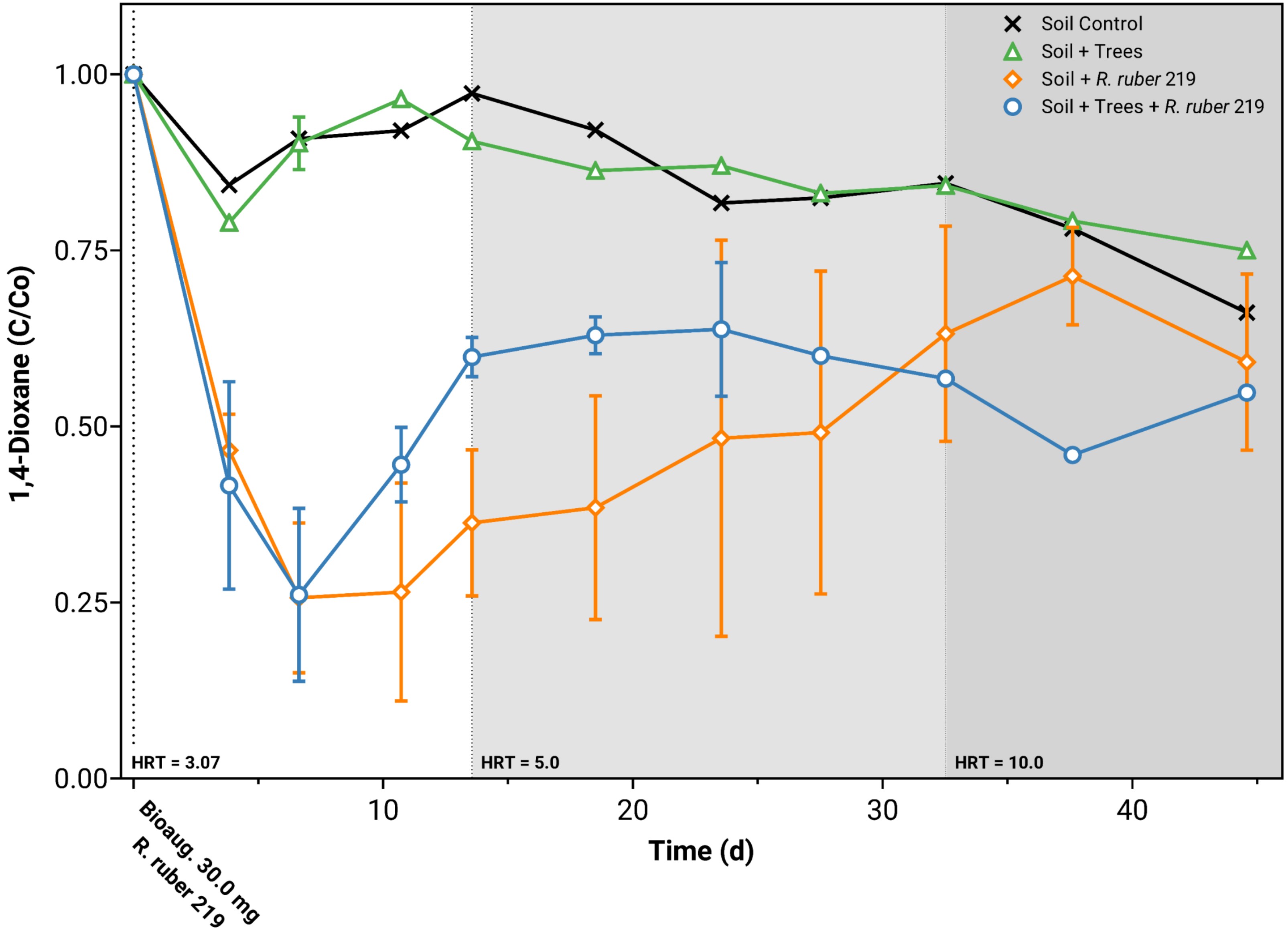
Dioxane effluent concentrations were somewhat higher in soil compared to perlite media



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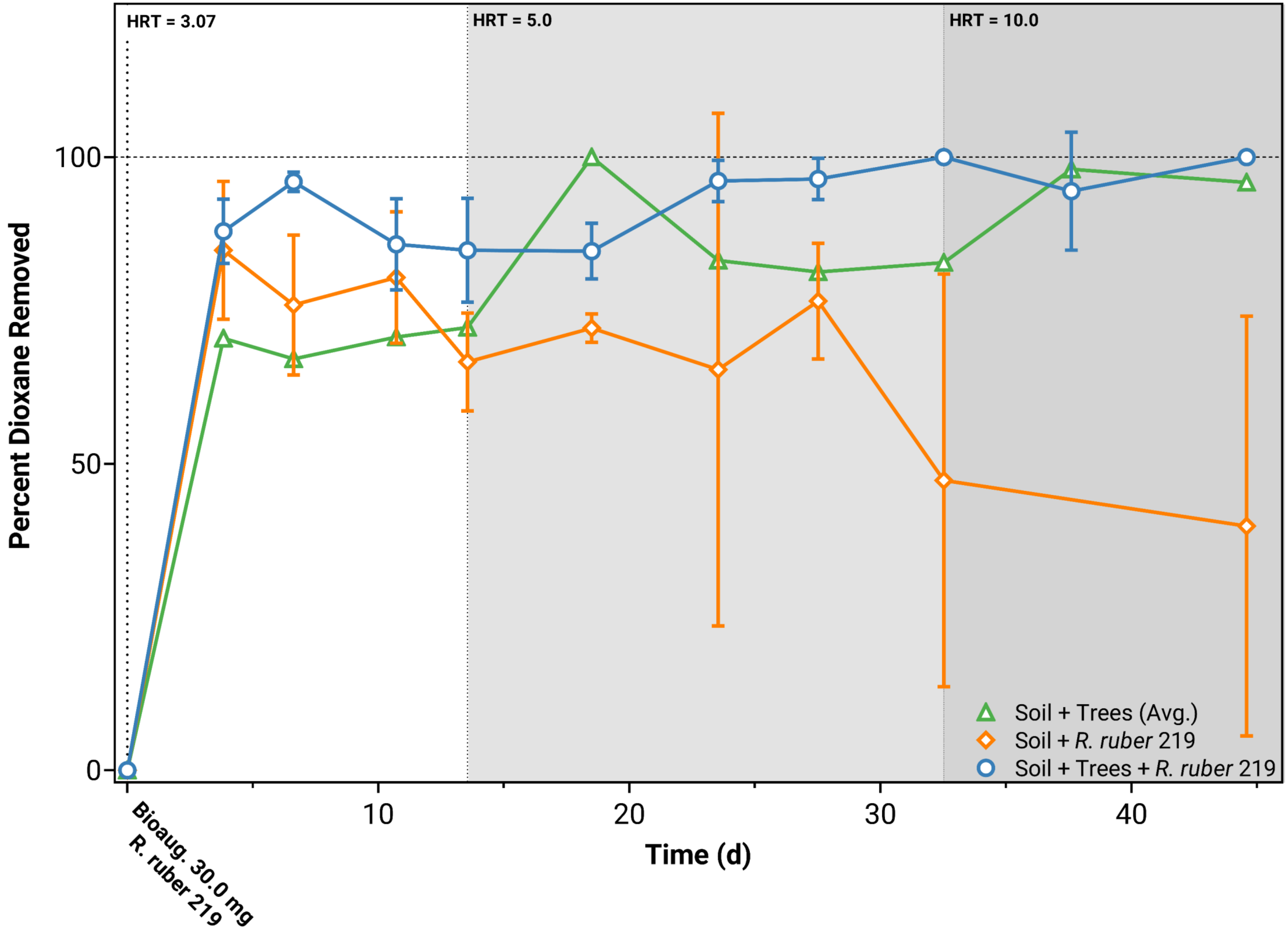
Mass removal by trees with *R. ruber* 219 in soil was significantly higher than bio alone



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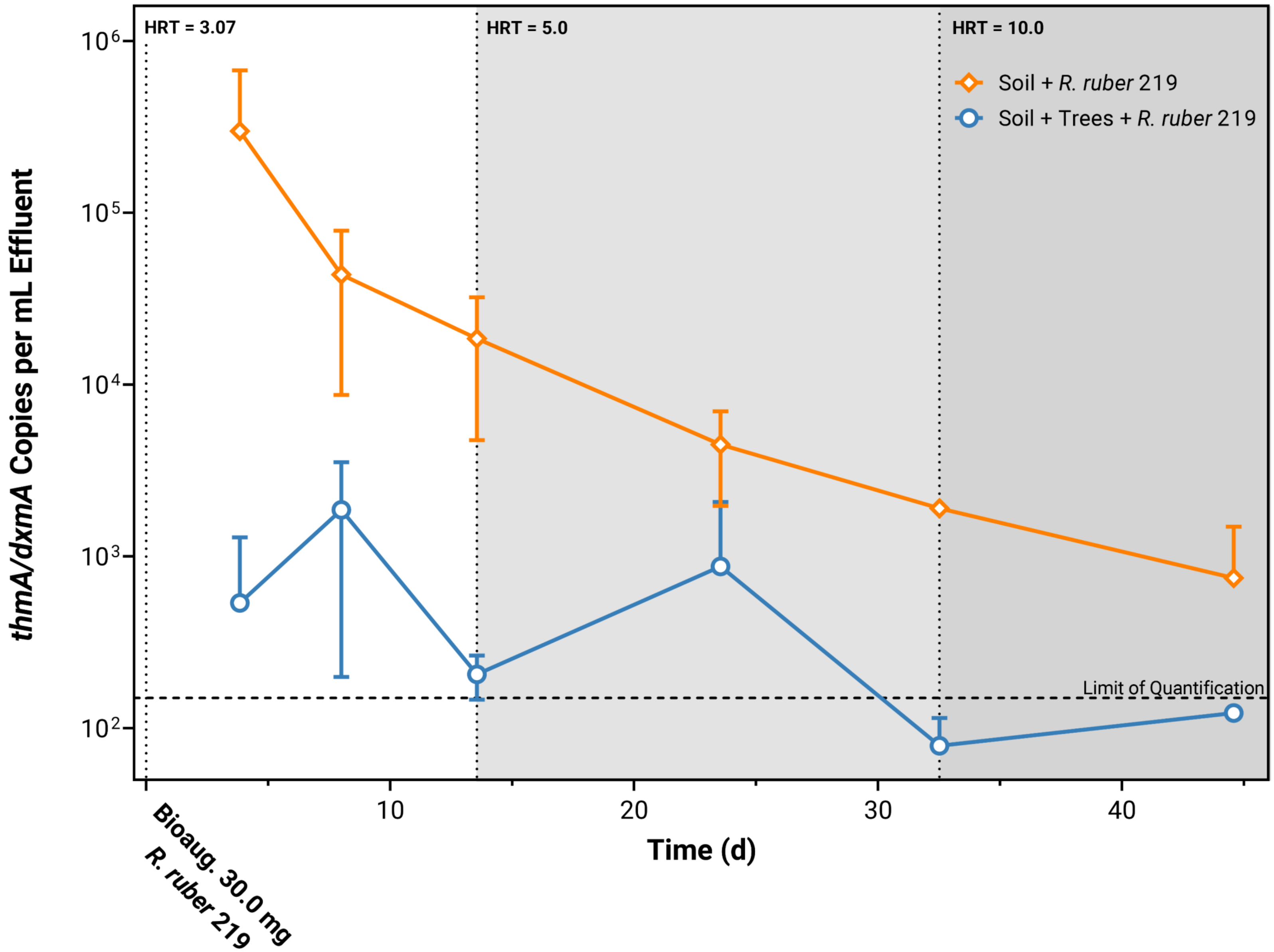
Significantly lower washout of *R. ruber* 219 gene copies in Planted Soil Reactors vs. Unplanted (tree roots help)



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Major Takeaways

✓Bioaugmented phytoremediation with *R. ruber* 219 accelerates treatment of 100 µg/L influent dioxane concentrations to near 1 µg/L

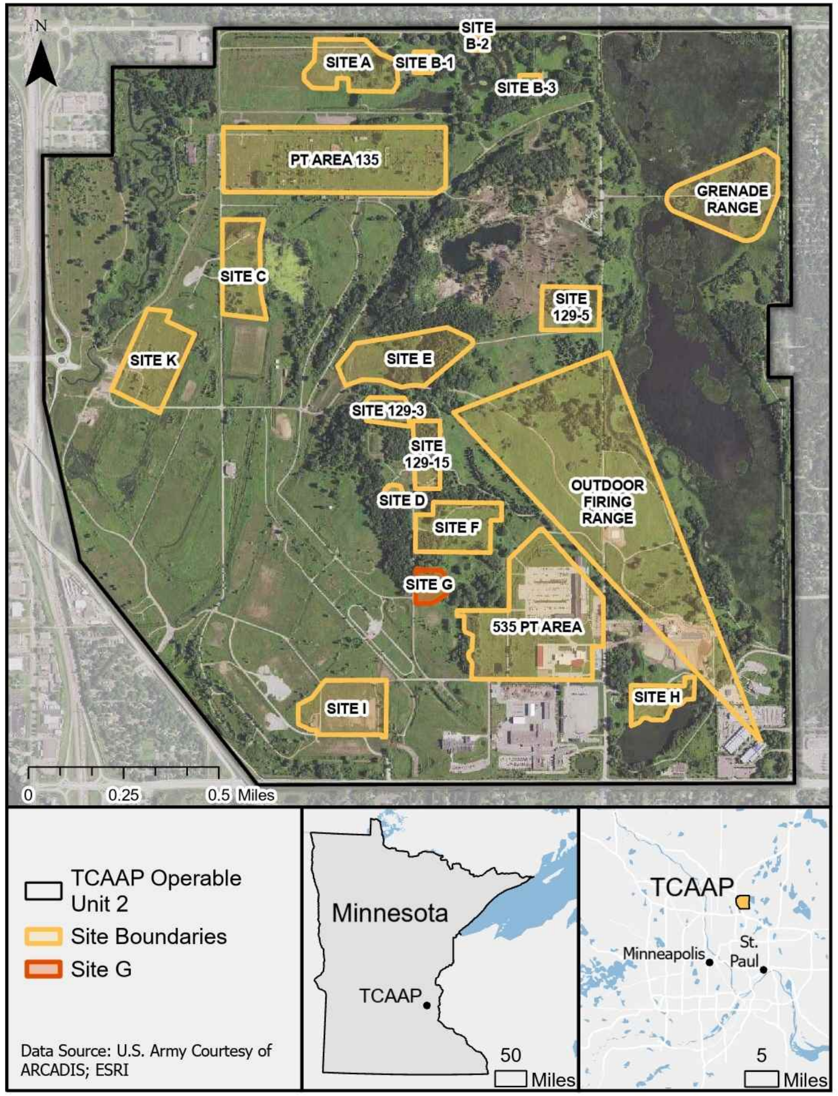
✓Sustained treatment ($\geq$50% degradation) for 44 days

Other observations

- Trees reduce washout of bioaugmented organisms
- Extended HRT improves bioremediation
- Trees capable of complete transpiration (zero discharge)
- Alternative treatment schemes may improve treatment (in-series)
- Repeated bioaugmentation may be necessary

Bioaugmented phytoremediation offers a green solution

ESTCP Demonstration at former Twin Cities Army Ammunition Plant, 2023-2025



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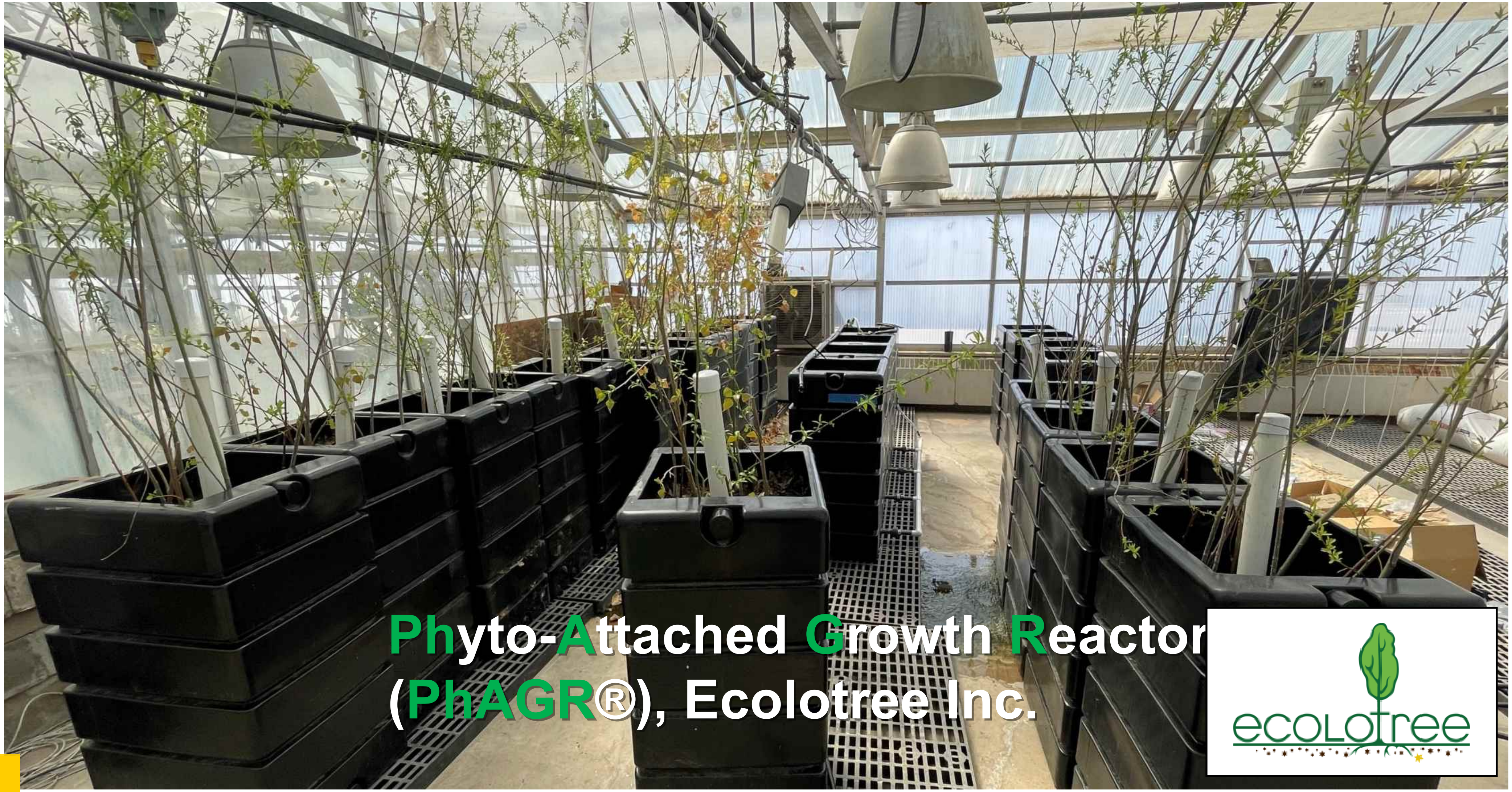

Phyto-Attached Growth Reactor (PhAGR®), Ecolotree Inc.

Acknowledgements

- Emily Jansen, Kyle Patterson, Chris Knutson (UIowa)
- Lou Licht – Ecolotree, Inc.
- Joel Burken – MS&T
- Linda Albrecht – USAEC
- Pedro Alvarez, Jacques Mathieu – Rice University
- SERDP Project ER-2719
- ESTCP Project ER21-5096
- NSF Integrative Graduate Education Research Traineeship (IGERT) [Grant # 0966130]

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ESTCP

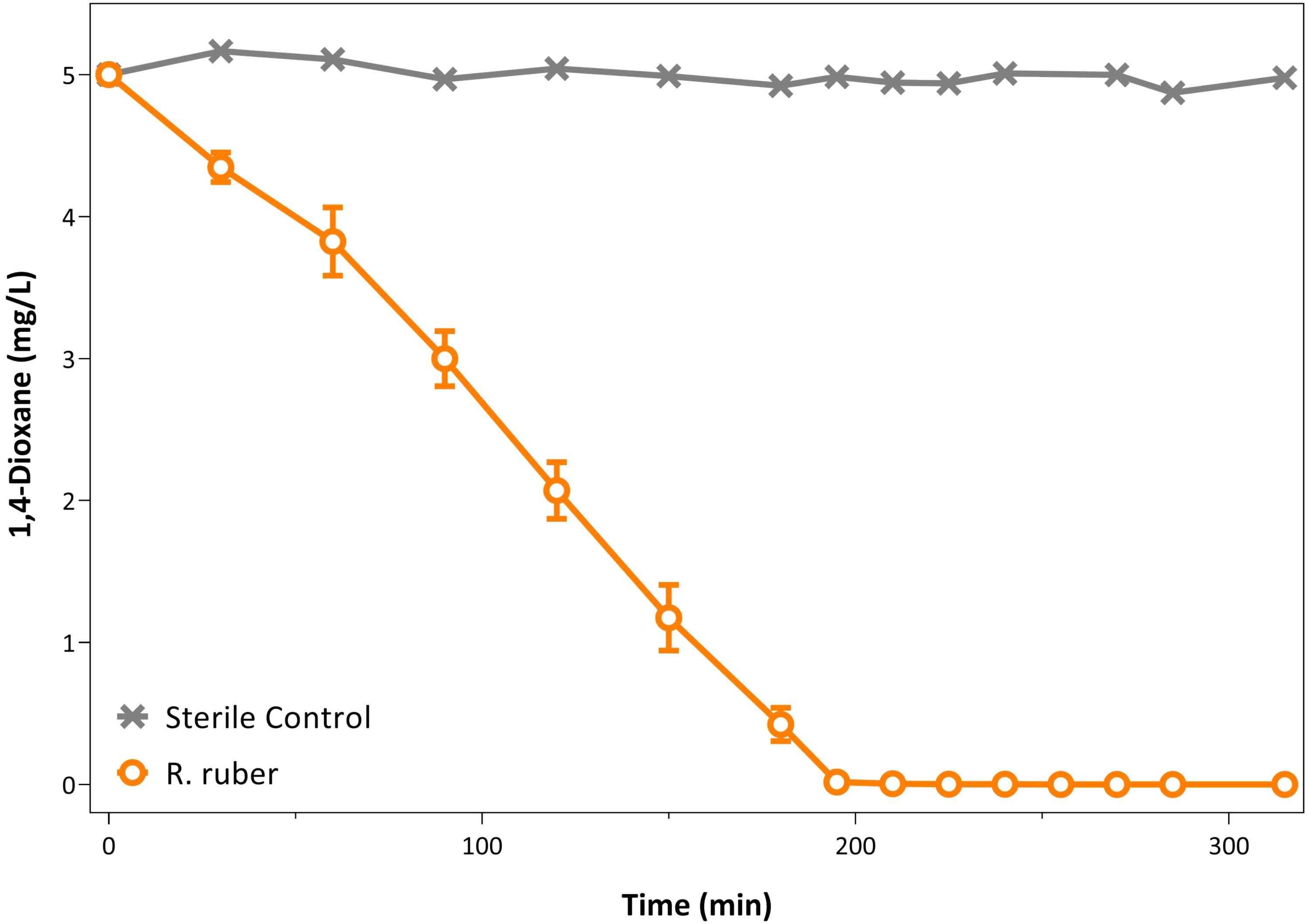
SERDP DOD ▪ EPA ▪ DOE

NSF

GEEMaP Geoinformatics for Environmental and Energy Modeling and Prediction

Backup Slides

R. ruber 219 rapidly degrades 5 mg/L dioxane to <1µg/L



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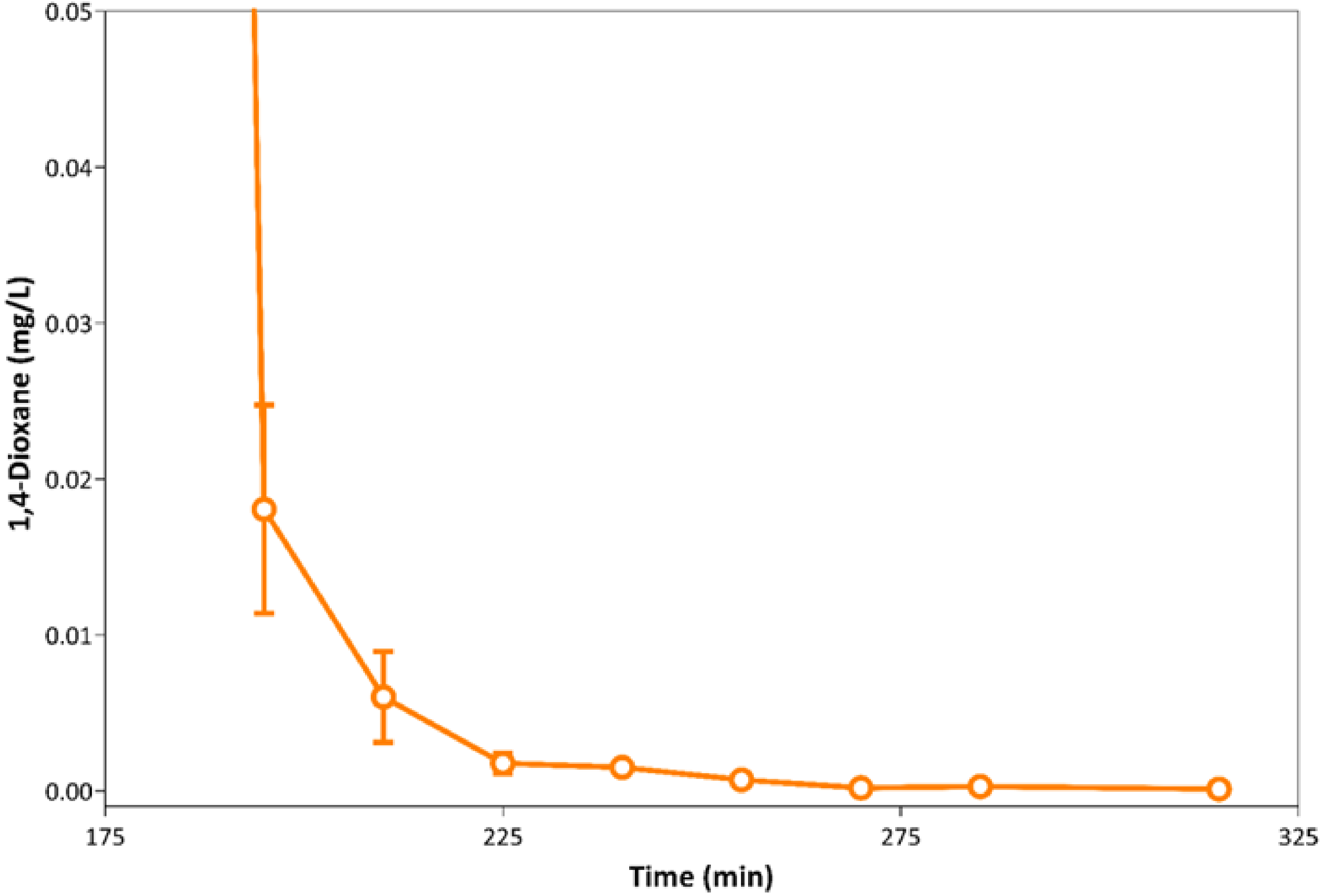

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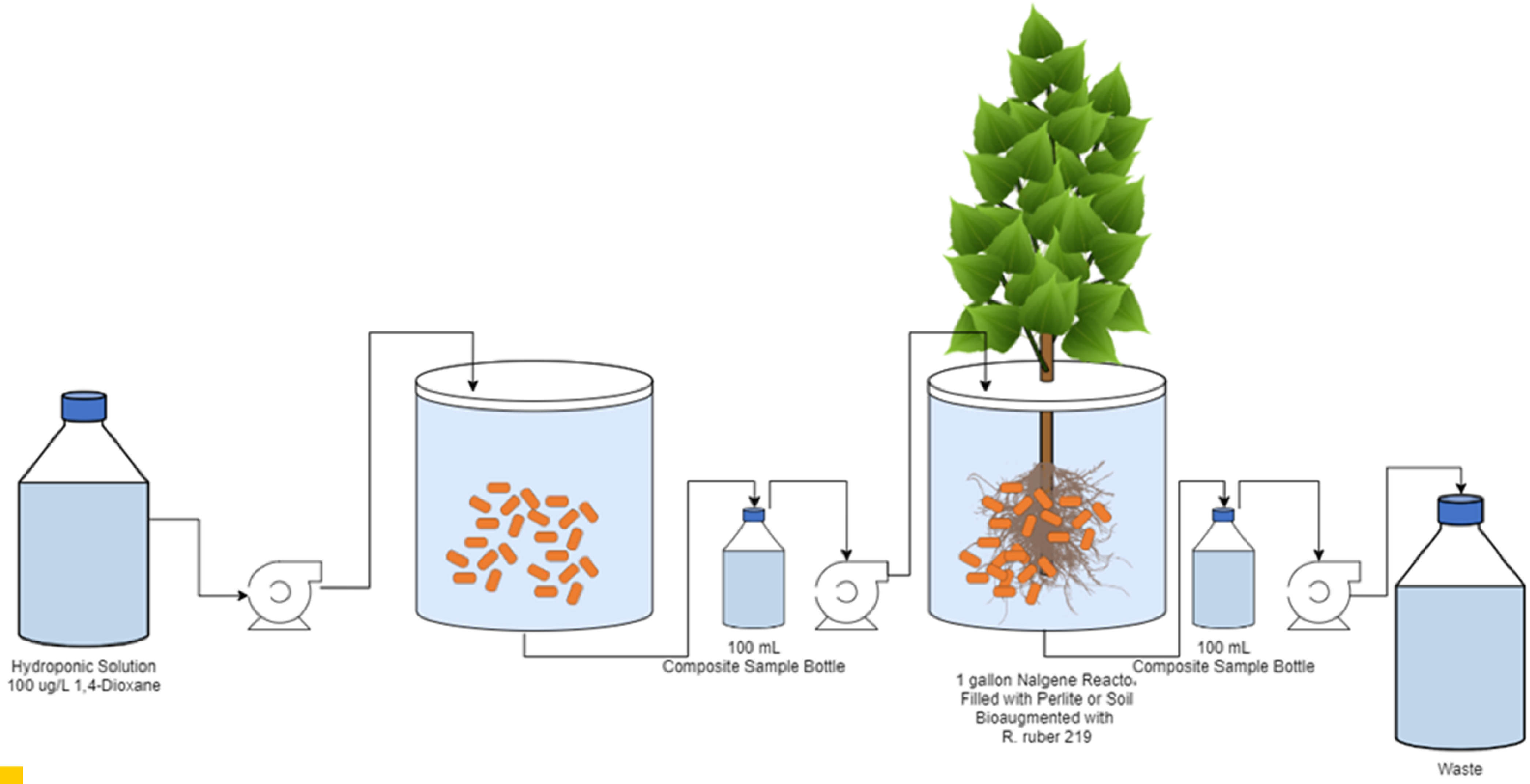
In-series arrangement tested to improve long-term treatment



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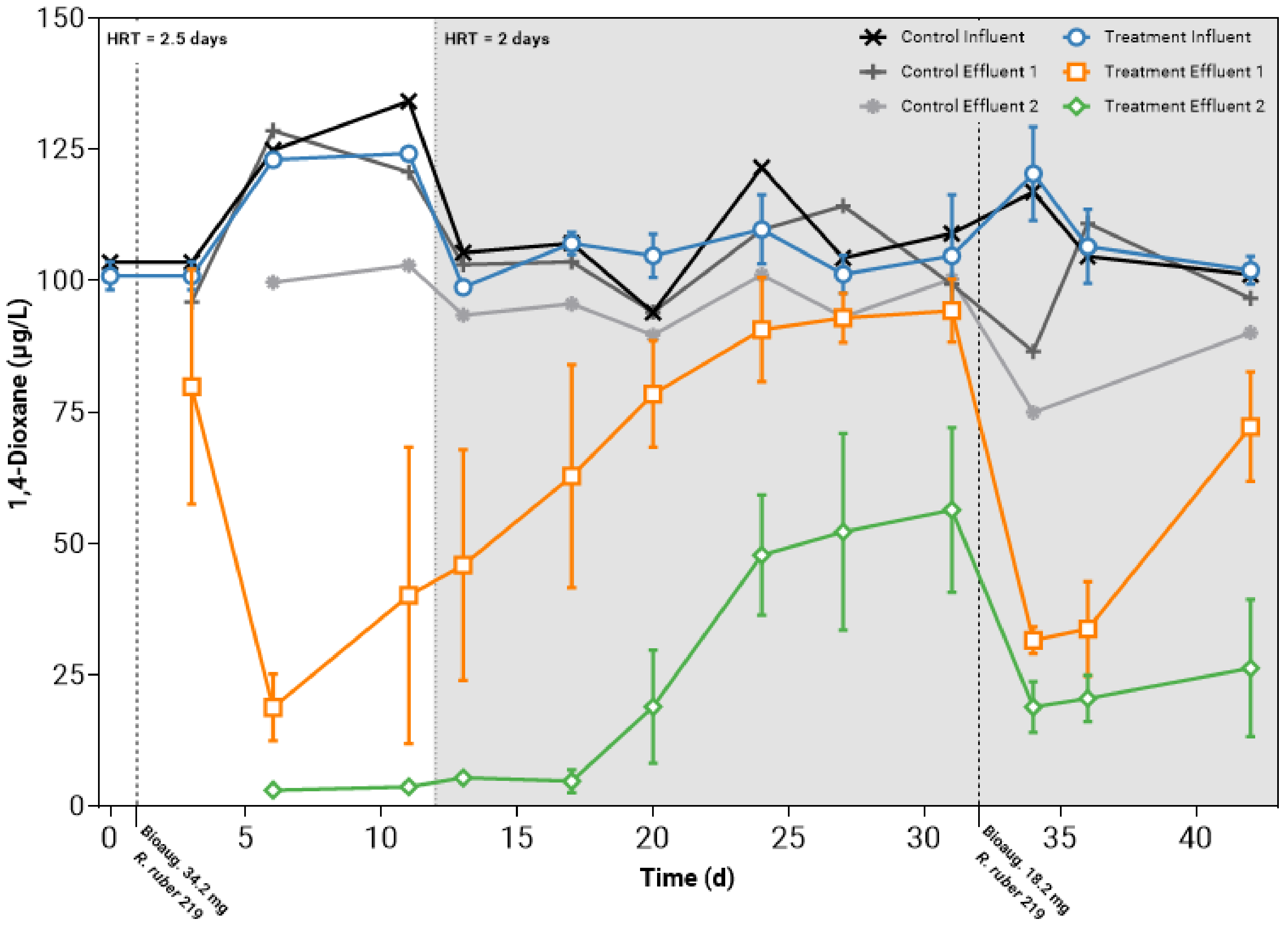
In-series arrangement significantly improves effluent concentration from second reactor



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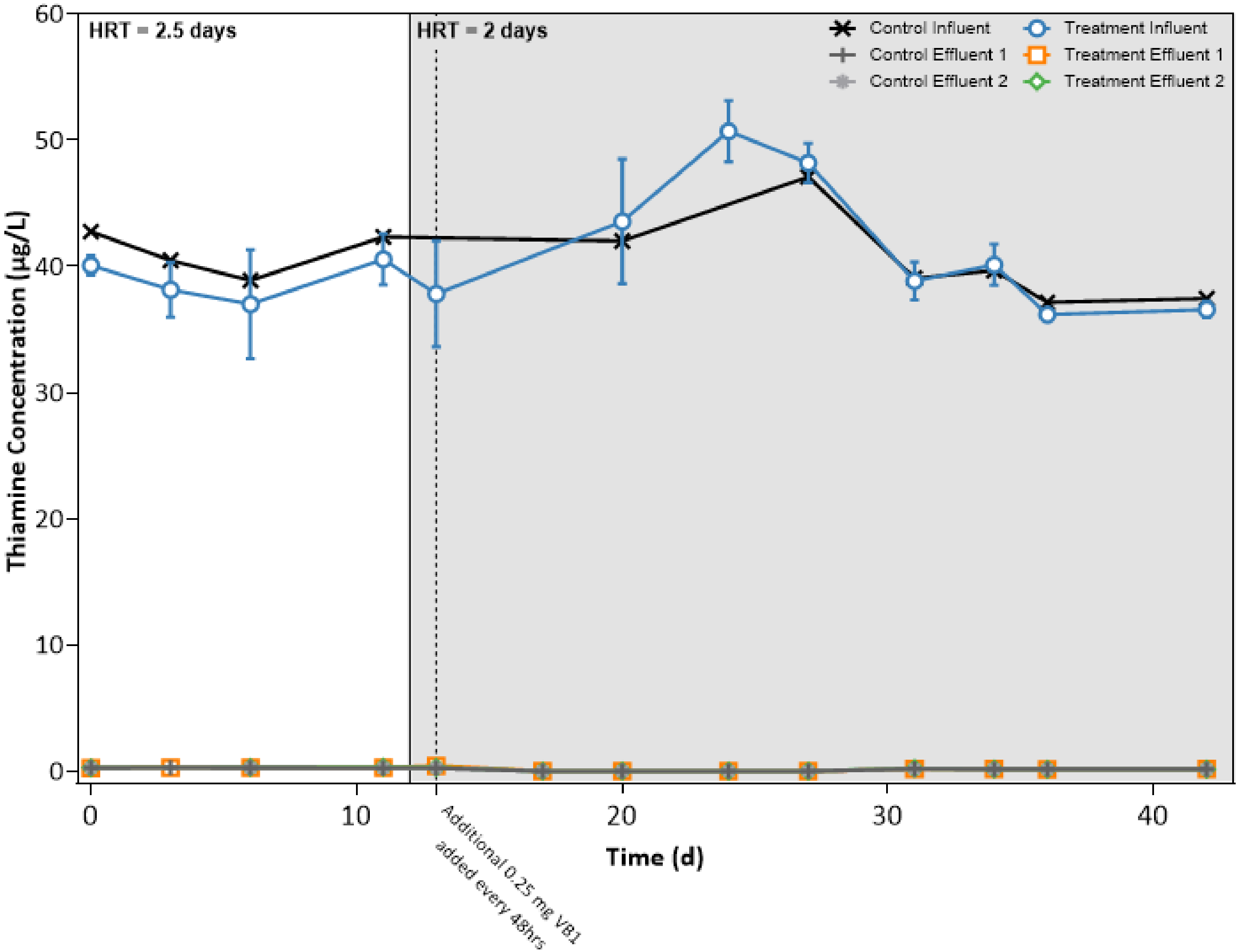
Essential nutrient thiamine (50 ppb) was absent from effluent likely due to sorption



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