Oxygen Fertilization:
A Game Changer for Soil and Crops

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Soil Hypoxia: A Major Challenge To Crop Production

Hypoxia/O_2 deficiency

1. impairs root respiration
2. Causes root damage
3. Declines beneficial microbes
4. Increases denitrification and nitrogen loss
5. Produces methane
6. Accumulates toxic compounds
7. Solubilizes iron and manganese

Photo Credit: M.J.I. Shohag

Healthiest soil Eh: +400~+450 mV

Soil Substrate	Reduction Product	Redox Potential (Eh, mV)	Conditions
Oxygen (O_2)	None (aerobic state)	**+400 to +600**	Well-aerated soil
Nitrate (NO_3^-)	Nitrogen gases (N_2, N_2O)	**+250 to +400**	Limited oxygen (denitrification)
Manganese (Mn^{4+})	Mn^{2+} (soluble form)	**+200 to +300**	Moderately reduced
Iron (Fe^{3+})	Fe^{2+} (ferrous iron)	**+100 to +200**	Poorly aerated, waterlogged
Sulfate (SO_4^{2-})	H_2S (hydrogen sulfide)	**−100 to 0**	Strongly reduced, anaerobic (rotten egg odor)
Carbon dioxide (CO_2)	CH_4 (methane)	**Below −200**	Extreme anaerobic, water-saturated

Ian L. Pepper, Terry J. Gentry, 2015

Hypoxic Soil Is Unhealthy!

What causes soil hypoxia (oxygen deficiency)?

1. Physical Factors
2. Chemical Factors
3. Biological Factors

1. Physical Factors

- Deep Well Irrigation: Low O_2 levels reduce oxygen bioavailability for plant roots and beneficial microbes
- Over-Irrigation: Excess water, flooding, and poor drainage deplete O_2, creating hypoxic conditions by displacing oxygen with water
- Soil Compaction: Heavy machinery or foot traffic compresses soil, reducing pore space and restricting air movement.
- Climate Factors:

Climate Factors

- Excessive Rainfall: Prolonged heavy rain or flooding can saturate the soil, displace O_2, and prevent roots from accessing necessary O_2, resulting in hypoxia.
- Drought : Soil cracking and surface crusting, limiting O_2 movement, reducing O_2 exchange.
- High Temperature: Increased soil respiration, consuming available oxygen, reducing O_2 solubility

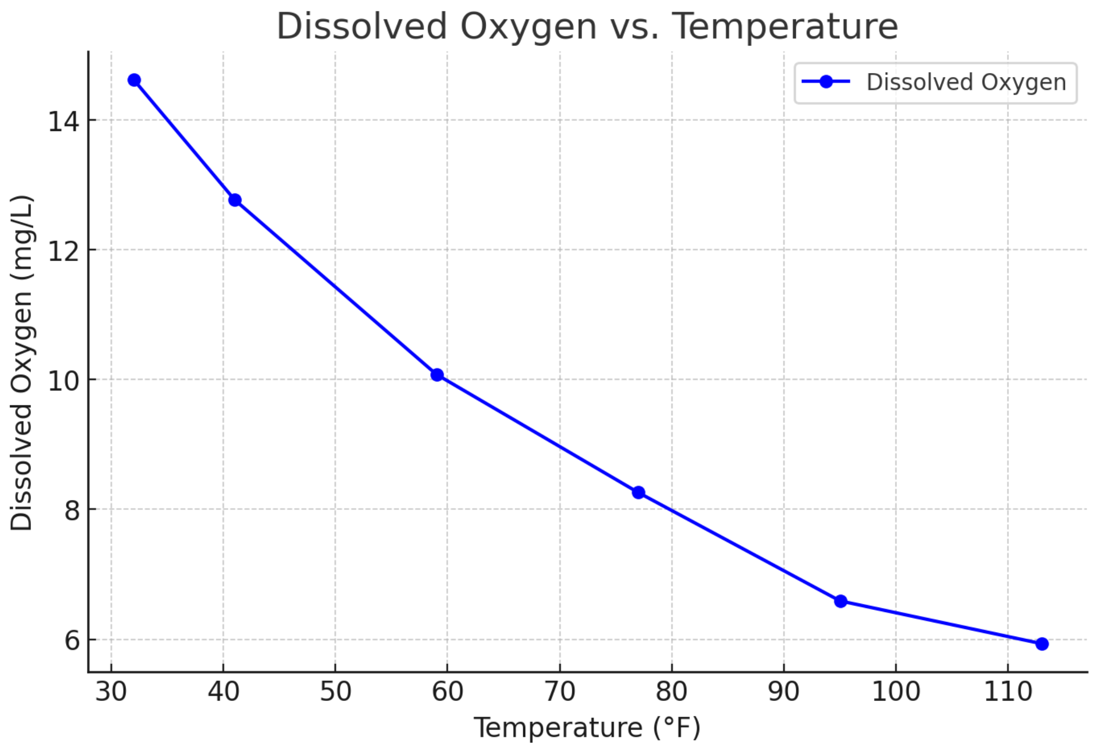
High Temperature Reduces Oxygen in Water (I)

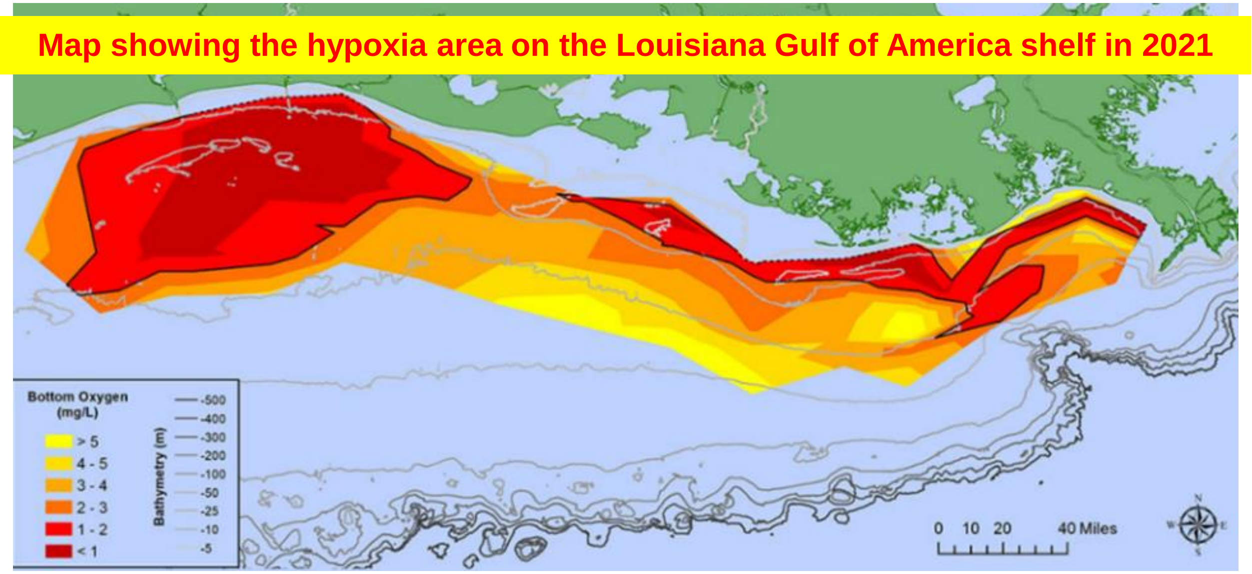
Temperature	Fresh water	9 ppt Salinity	36 ppt Salinity	45 ppt Salinity
	O_2 solubility (mg/L) in water			
32 °F (0°C)	14.62	13.73	11.36	10.66
41°F (5°C)	12.77	12.02	10.03	9.44
59°F (15°C)	10.08	9.54	8.08	7.64
77°F (25°C)	8.26	7.85	6.72	6.39
95°F (35°C)	6.95	6.62	5.73	5.64
113°F (45°C)	5.93	5.67	4.94	4.72

Source: YSI.com/DO

High Temperature Reduces Oxygen in Water (II)

1. Lower O_2 Solubility: at **59°F (15°C), 10.08 mg/L** but at **95°F (35°C), 6.95 mg/L**
2. Increased O_2 Consumption**: plant and microbe respirations speed up.**
3. More Frequent "Dead Zones“**:** Warmer temperatures also fuel **algal blooms**, which can later decay and remove oxygen from the water.





Credit: N. Rabalais, LSU/LUMCON (NOAA 2021)

2. Chemical Factors

- Salinity issues: High salinity in soil can reduce permeability, restricting oxygen flow to plant roots and microbes
- Excessive Fertilizer Use: Ammoniacal Nitrogen (NH_4^+-N) Fertilizer, $NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$

Stoichiometrically or in term of chemical math, 200 lbs/acre N as NH_4^+-N fertilizer needs to consume 365,728 gallons (13.5 acre-inches) of air for nitrification alone.

What are Ammoniacal Fertilizers (I)?

These fertilizers contain or form ammonium ions ((NH_4^+)):

1. Ammonium Nitrate (NH_4NO_3): NH_4^+ and NO_3^- ions

2. Ammonium Sulfate ($(NH_4)_2SO_4$): NH_4^+

3. Monoammonium Phosphate (MAP) ($NH_4H_2PO_4$): NH_4^+ and $H_2PO_4^-$ ions

4. Diammonium Phosphate (DAP) ($(NH_4)_2HPO_4$): NH_4^+) and HPO_4^{2-} ions

5. Ammonium Chloride (NH_4Cl): NH_4^+ and chloride (Cl^-)

6. Calcium Ammonium Nitrate (CAN): NH_4NO_3 and $CaCO_3$

7. Ammonium Carbonate ($(NH_4)_2CO_3$): NH_4^+ and carbonates, $\mathbf{CO_3^{2-}}$.

8. Urea: NH_4^+

9. UAN (Urea-Ammonium Nitrate Solution): both urea (NH_2CONH_2) and ammonium nitrate (NH_4NO_3).

What are Ammoniacal Fertilizers (II)?

These fertilizers contain or form ammonium ions ((NH_4^+):

10. Ammonium Phosphate Sulfate ($(NH_4)_3PO_4 \cdot (NH_4)_2SO_4$): N, P, S.

11. Liquid Ammonium (Ammonium Hydroxide, NH_4OH):

12. Ammonium Acetate ($NH_4C_2H_3O_2$):

13. Ammonium Perchlorate (NH_4ClO_4): N in specialized applications.

14. Ammonium Molybdate $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$: While primarily a source of molybdenum for plants,

15. Ammonium Thiosulfate $(NH_4)_2S_2O_3$: N, S.

3. Biological Factors

- Dense Planting and Root Activity: When plants are densely packed, roots can compete for oxygen (O_2), particularly in compacted or poorly-drained soils.
- Microbial Activity: microbes thrive in low-O_2 conditions, consuming available oxygen and producing harmful gases like methane (CH_4) and hydrogen sulfide (H_2S).
- High Organic Matter Decomposition: Decomposition of excessive organic material can rapidly consume O_2, particularly in waterlogged soils where air cannot circulate freely.

Why Do We Need O_2 Fertilization?

1. Hurricanes

Photo taken on 10/23/2023
After Hurricane Ian
Photo Credit: MJI Shohag

1. Hastings, $45M loss in 2009
2. Miami-Dade, $13M loss in 2000
3. Miami-Dade, $77M loss in 1999

https://edis.ifas.ufl.edu/publication/SS425

Photo Credit: News4Jax.com.

Why Do We Need O_2 Fertilization?
2. Warerlogging or Overirrigation

Photo Credit: Guodong Liu

Why Do We Need O_2 Fertilization?

3. Well Water with Low O_2 Level

Photo Credit: Guodong Liu

The range of O_2 bioavailability (ppm):

- Normoxia (normal level): 6.0-8.0
- Hypoxia (O_2 deficiency): 0-6.0
- Anoxia (total O_2 deficiency): 0

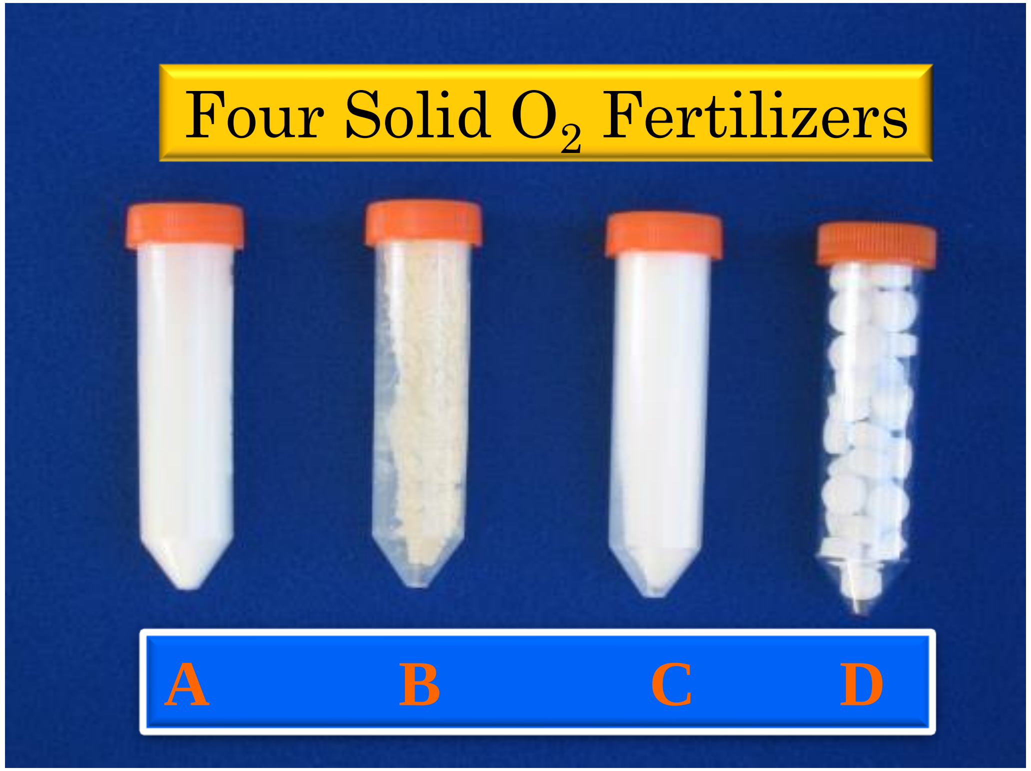
O_2 level (ppm) in well water:

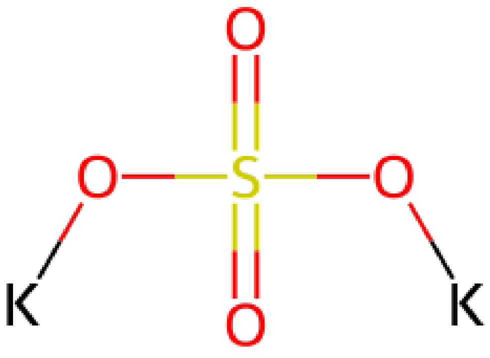
- Rainbow Star Farm (70-foot deep): 3.4
- PSREU (150-foot deep): 1.2

What Is Our Hypothesis?

The application of solid or liquid O_2 fertilizer will alleviate hypoxic or anoxic stress in crop plants caused by waterlogging, overirrigation, or low-O_2 well water, leading to increased growth and production.

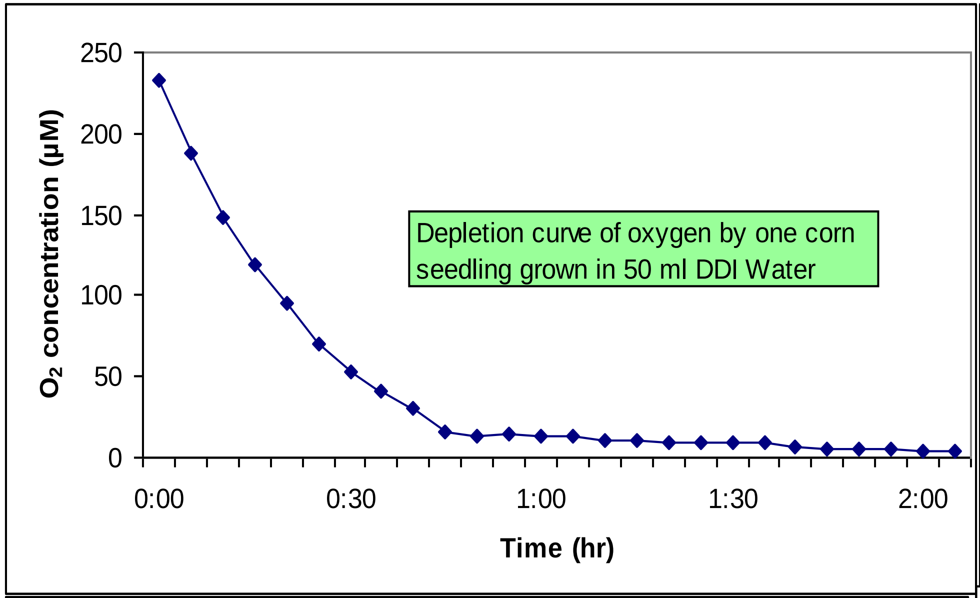
Liquid O_2 Fertilizer

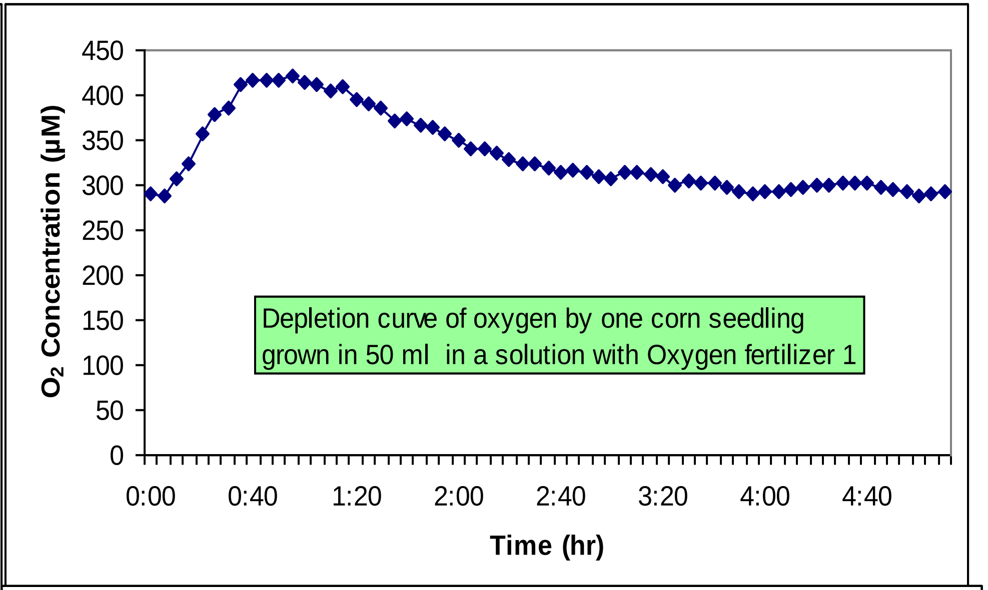


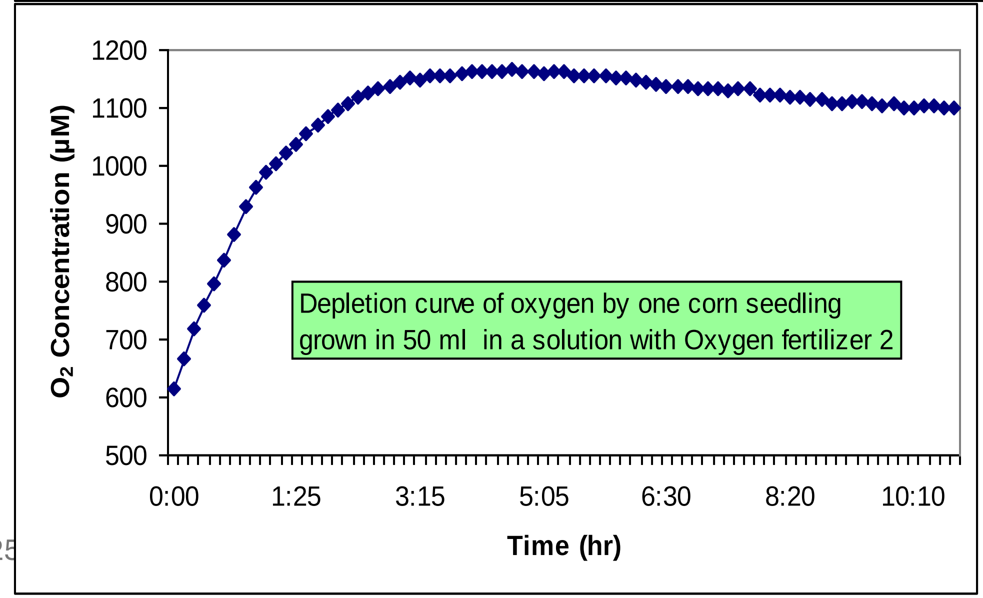


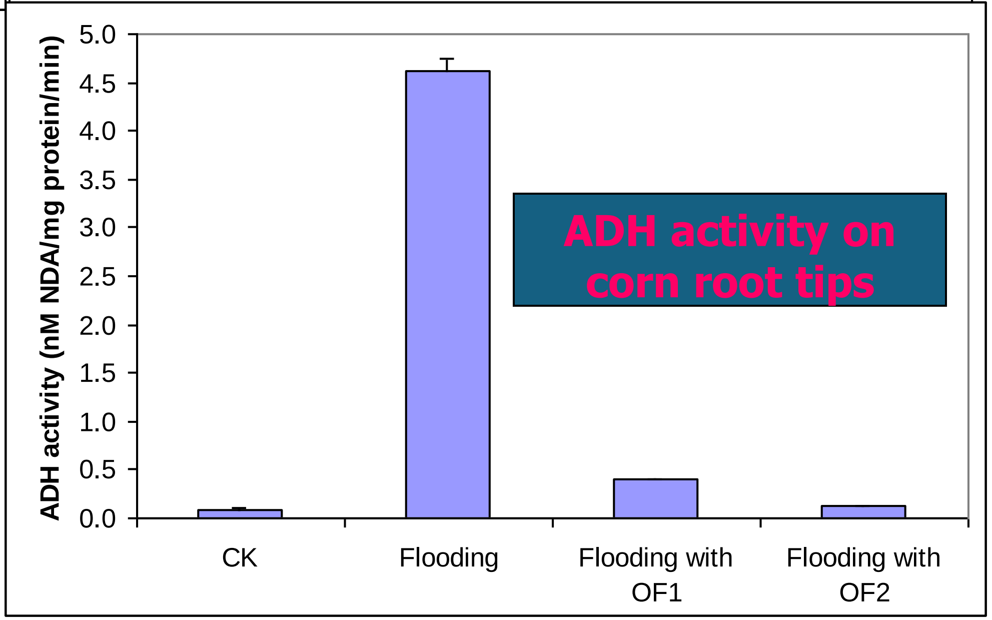
Potassium sulfate

O_2 Depletion Curve and Biomarker in Stressed Corn









Benefits of O_2 Fertilization

1. Enhance soil redox potential and soil heath
2. Mitigate salinity stress
3. Improve seed germination
4. Increase nutrient uptake
5. Enhance yield potentials
6. Reduce N_2O gas emission
7. Control soil borne diseases
8. Minimize toilet backups from septic tanks

Inoculum: ***Phytophthora capsici***

SOF **CK**

How Should We Apply O_2 Fertilizer?

- Solid: one-time pre-plant application
- Liquid: fertigation through drip irrigation

Photo Credit: Guodong Liu

O_2 Fertilization Significantly :

1. Improved O_2 Bioavailability & Soil Health

$FeCl_3$ coated PVC pipes

	I	II	III	IV
Coated	+	+	+	-
Flooded	-	+	+	-
OF	-	+	-	-

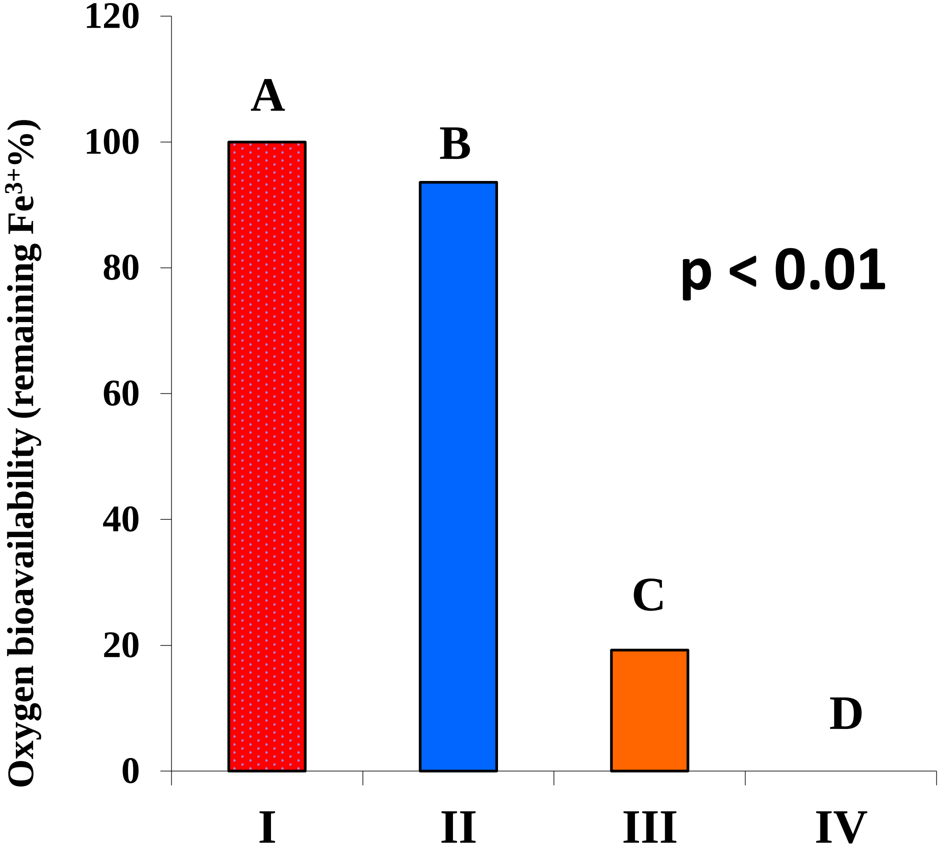
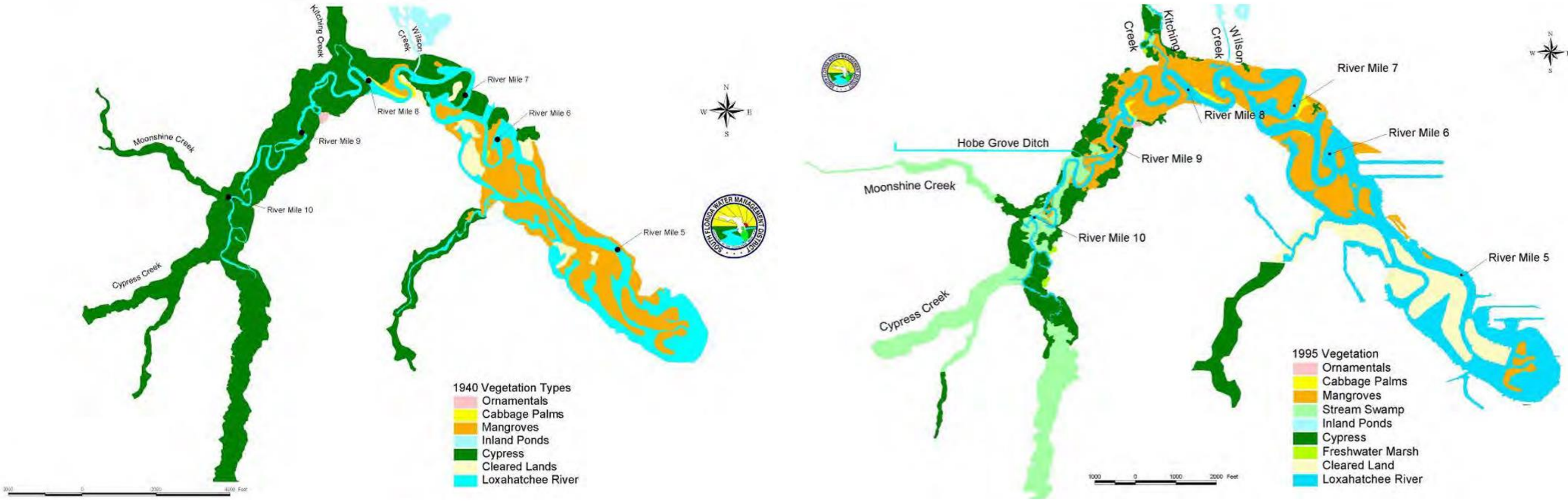


Photo Credit: Guodong Liu

Salinity Stress Transformed Floodplain Vegetation in the Loxahatchee River



Source: https://www.sfwmd.gov/sites/default/files/documents/northwestforkloxahatcheeriverrestorationplan.pdf

Plants Succumbed to Exposure to Seawater Intrusion in South Florida

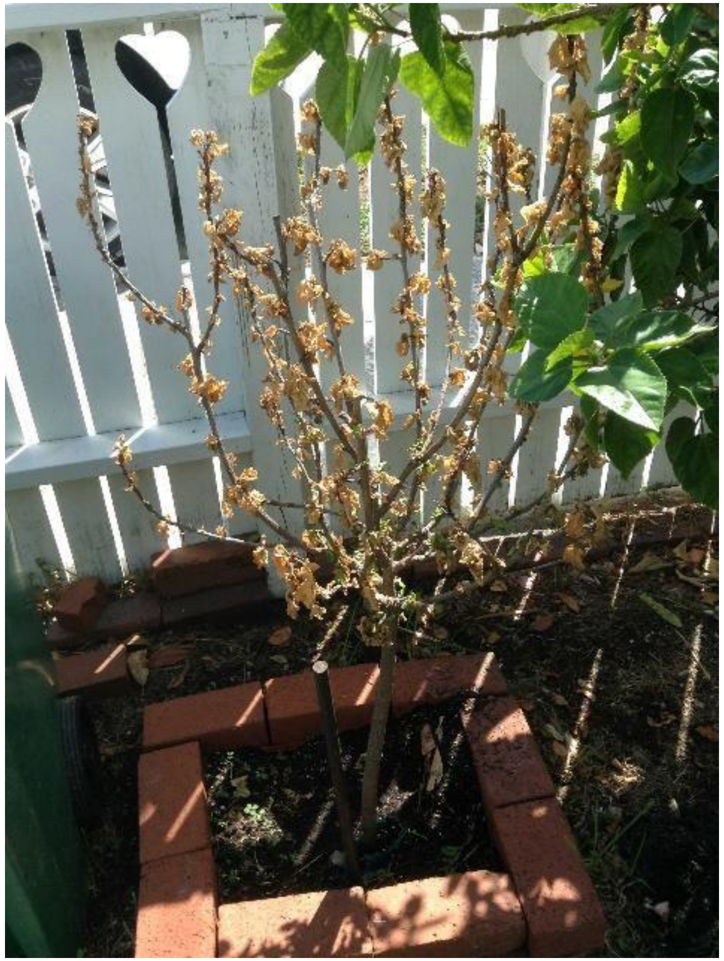


Photo Credit: Kim Gabel

Photo Credit: Guodong

2. Oxygen Fertilization (OF) to the Rescue!

Photo Credit: Guodong Liu

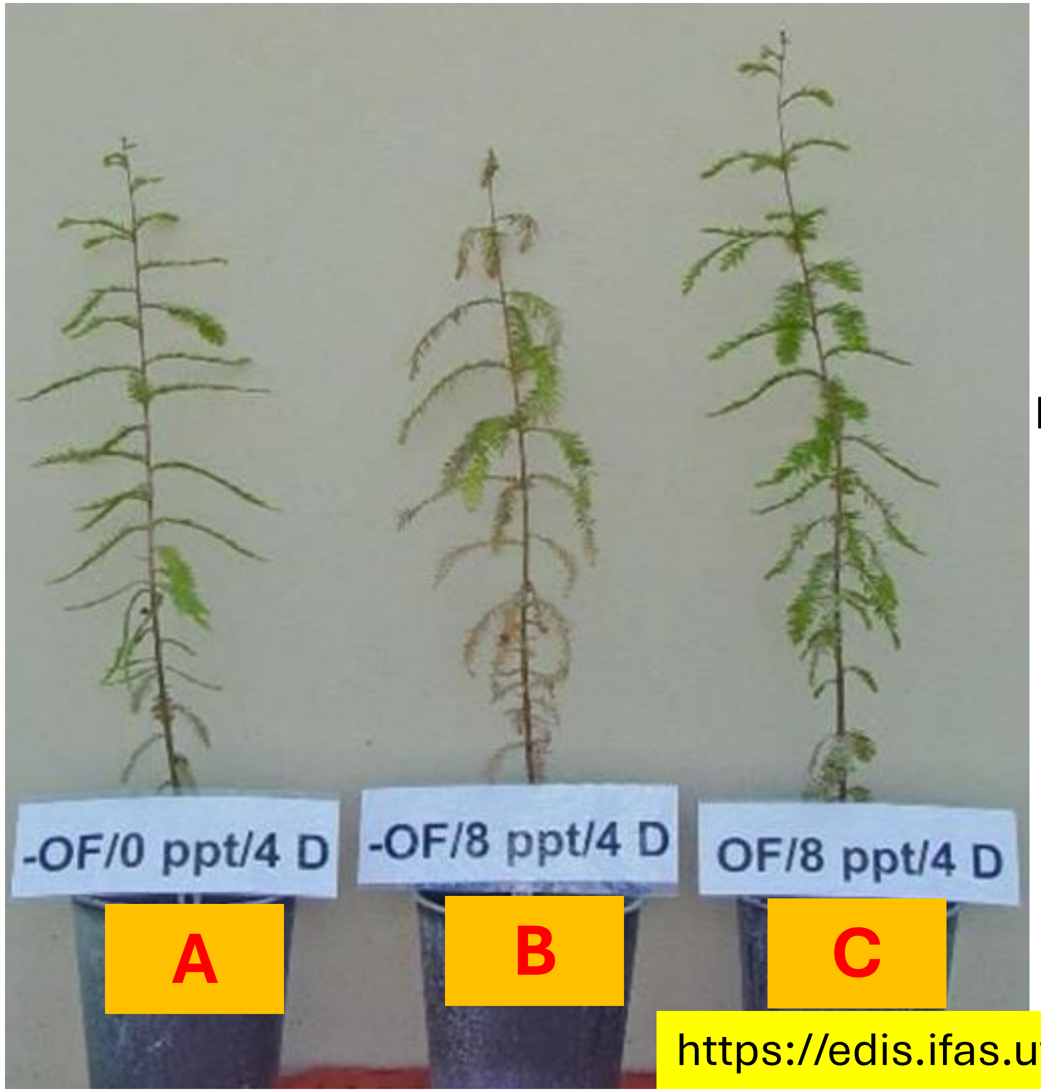


Photo Credit: Guodong Liu

https://edis.ifas.ufl.edu/publication/HS1280

Oxygen Fertilization Supercharged Bald Cypress Growth!

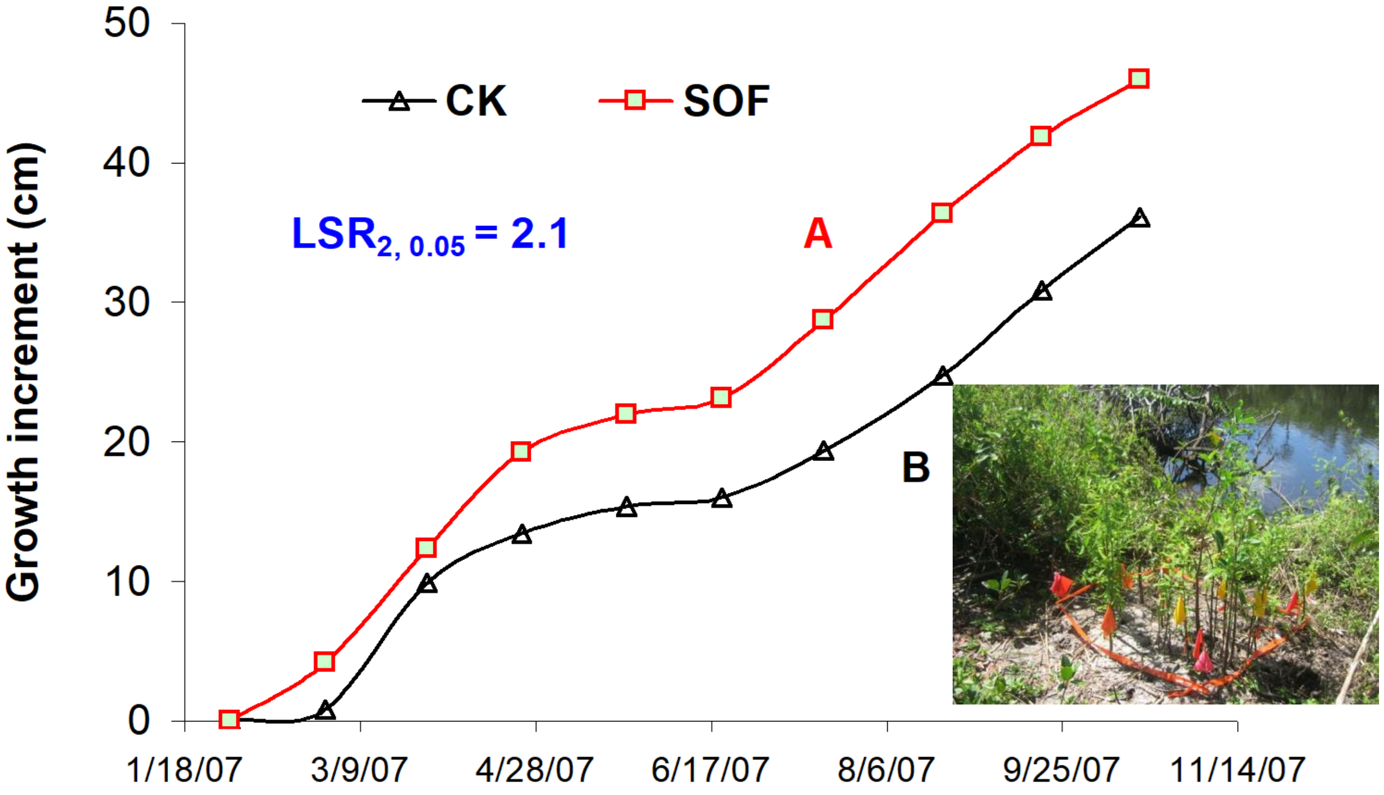


Photo Credit: Guodong Liu

3. Doubled Germination Rates of Aged Seeds (I)

Photo Credit: Guodong Liu

3. Doubled Germination Rate of Aged Seeds (II)

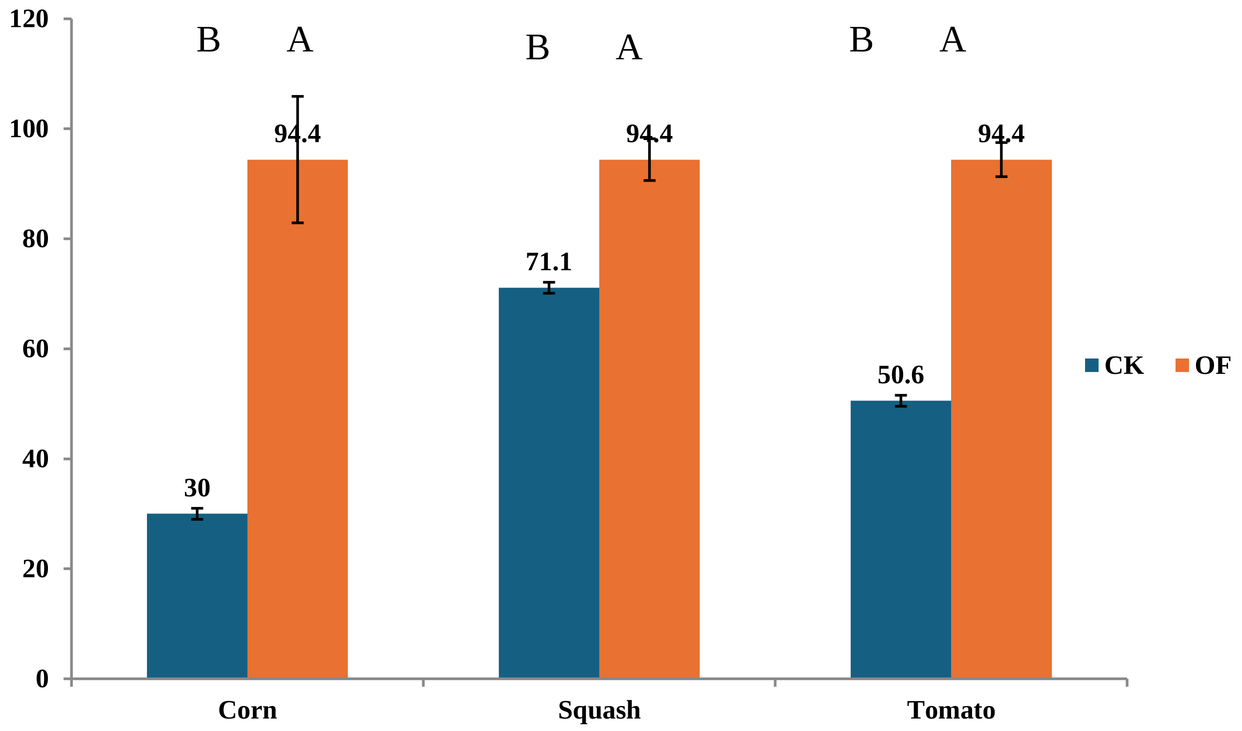
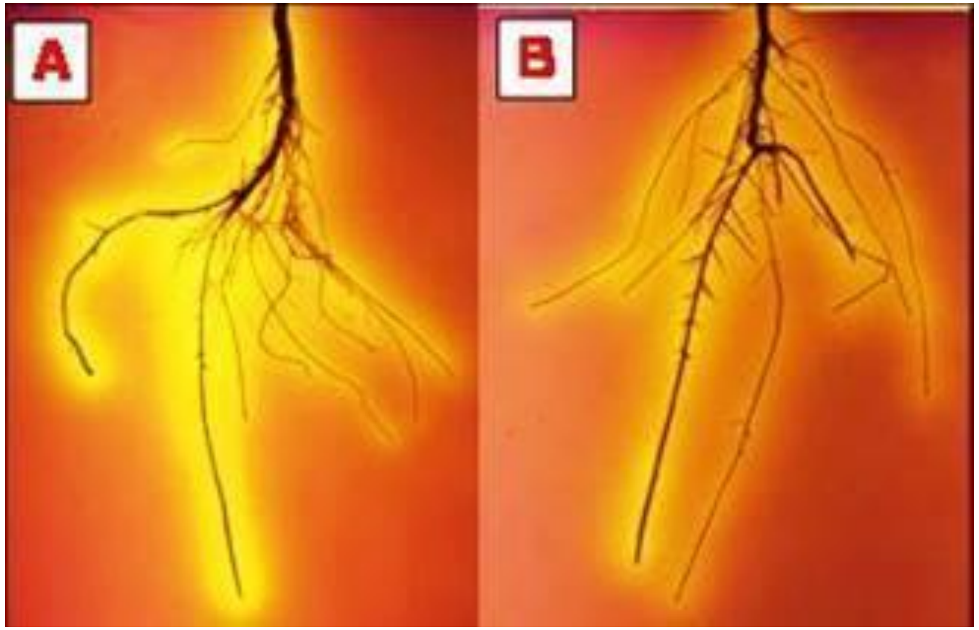


Photo Credit: Guodong Liu

4. Increased NH_4^+ Uptake Exponentially (I)

--pH mapping for qualitative analysis



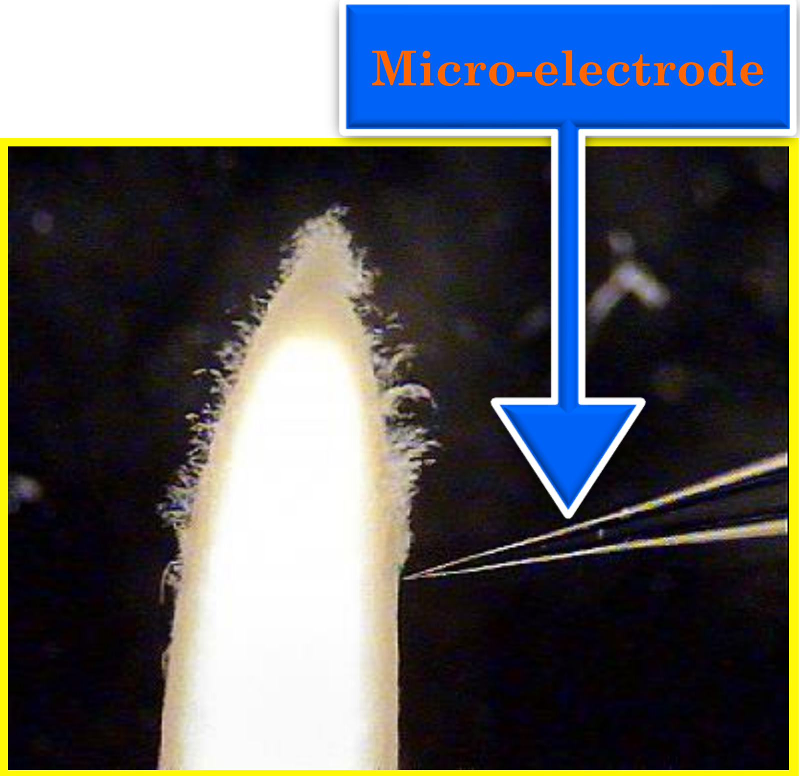
Yellow: pH5.2
Red: pH6.8

A: O_2 fertilized
B: Not O_2 fertilized

4. Increased NH_4^+ Uptake Significantly (IIa)

--Self-Referencing Ion Selective (SRIS) Technique

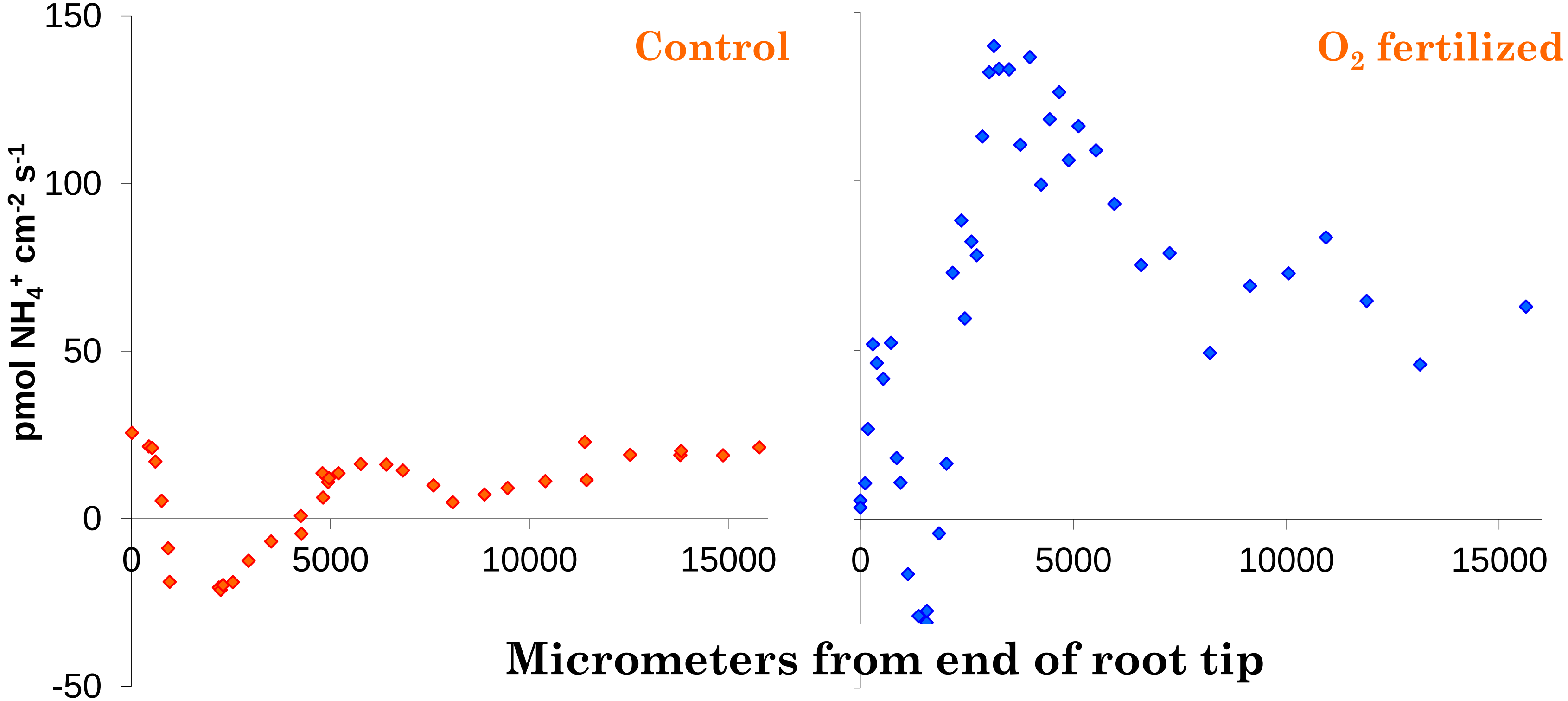
Photo Credit: Guodong Liu



1. Non-invasive
2. Real-time measurement
3. Highly-sensitive: 10^{-15} mol cm^{-2} s^{-1}
4. Scanning roots micron by micron

4. Increased NH_4^+ Uptake Significantly (IIb)

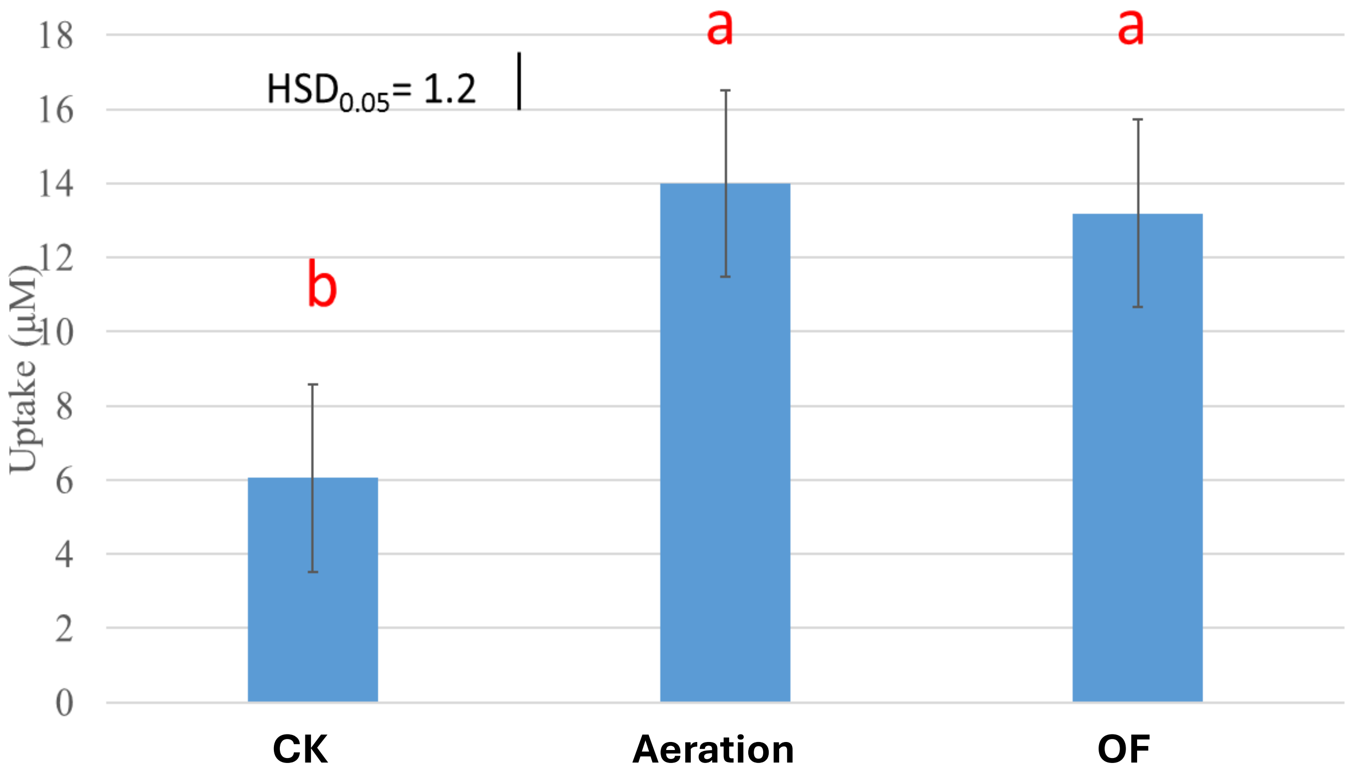
--SRIS Electrode scanning for quantitative analysis



pmol = picomole = 10^{-12} mole

5. Increased NO_3^- Uptake Significantly

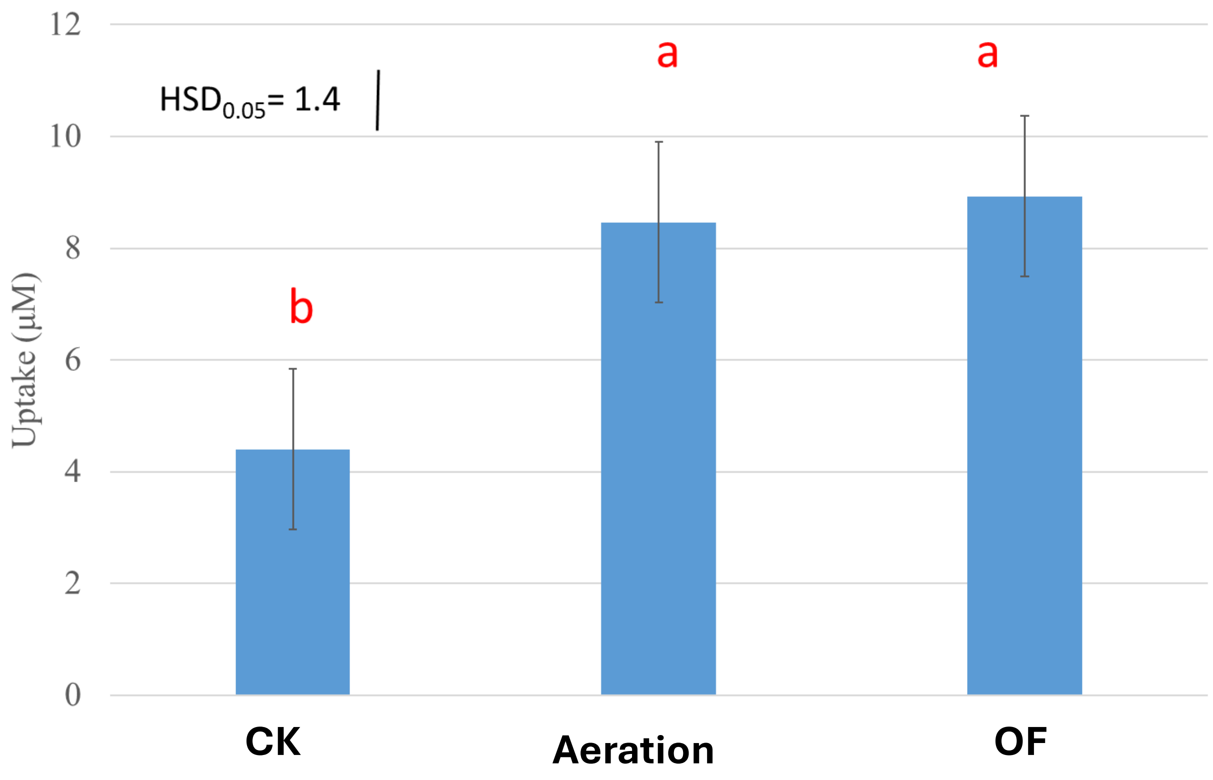
--Flooded Snapbean Seedlings



The mean uptake amount of NO_3^- for 10h experiments with three treatments and four replications each. The OF (Oxygen fertilizer) used 529 µM H_2O_2. The error bars represent ±1 std. dev. Different letters indicate significant differences according to four replicated measures ANOVA ($P \leqslant 0.05$).

6. Increased PO_4^{3-} Uptake Significantly

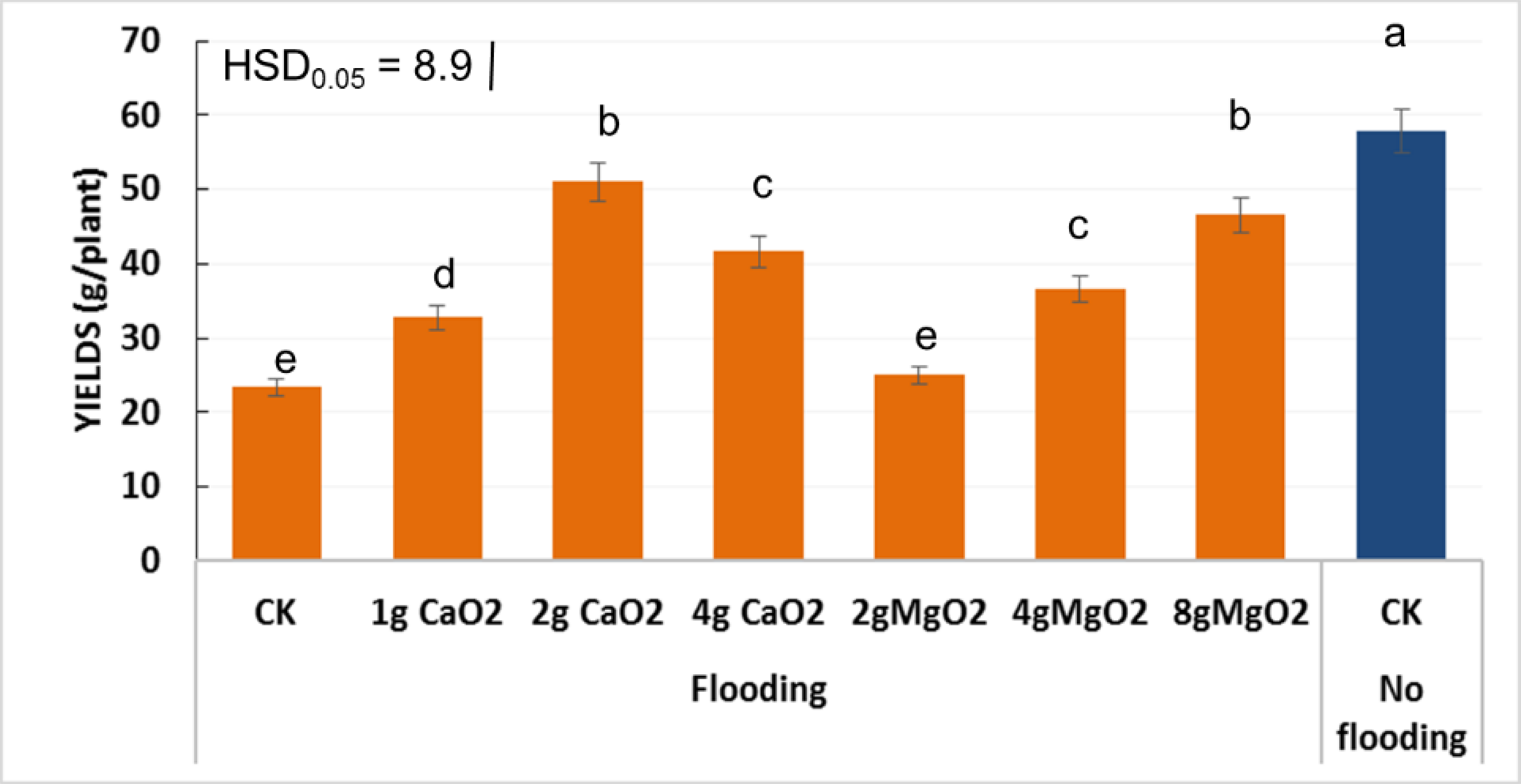
--Flooded Snapbean Seedlings

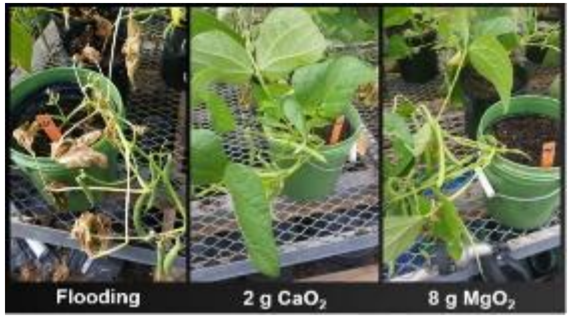


The mean uptake amount of P for 10h experiments with three treatments and four replications each. The error bars represent ±1 std. dev. Different letters indicate significant differences according to four replicated measures ANOVA ($P \leqslant 0.05$).

7. Enhanced Flooded Vegetable Yields

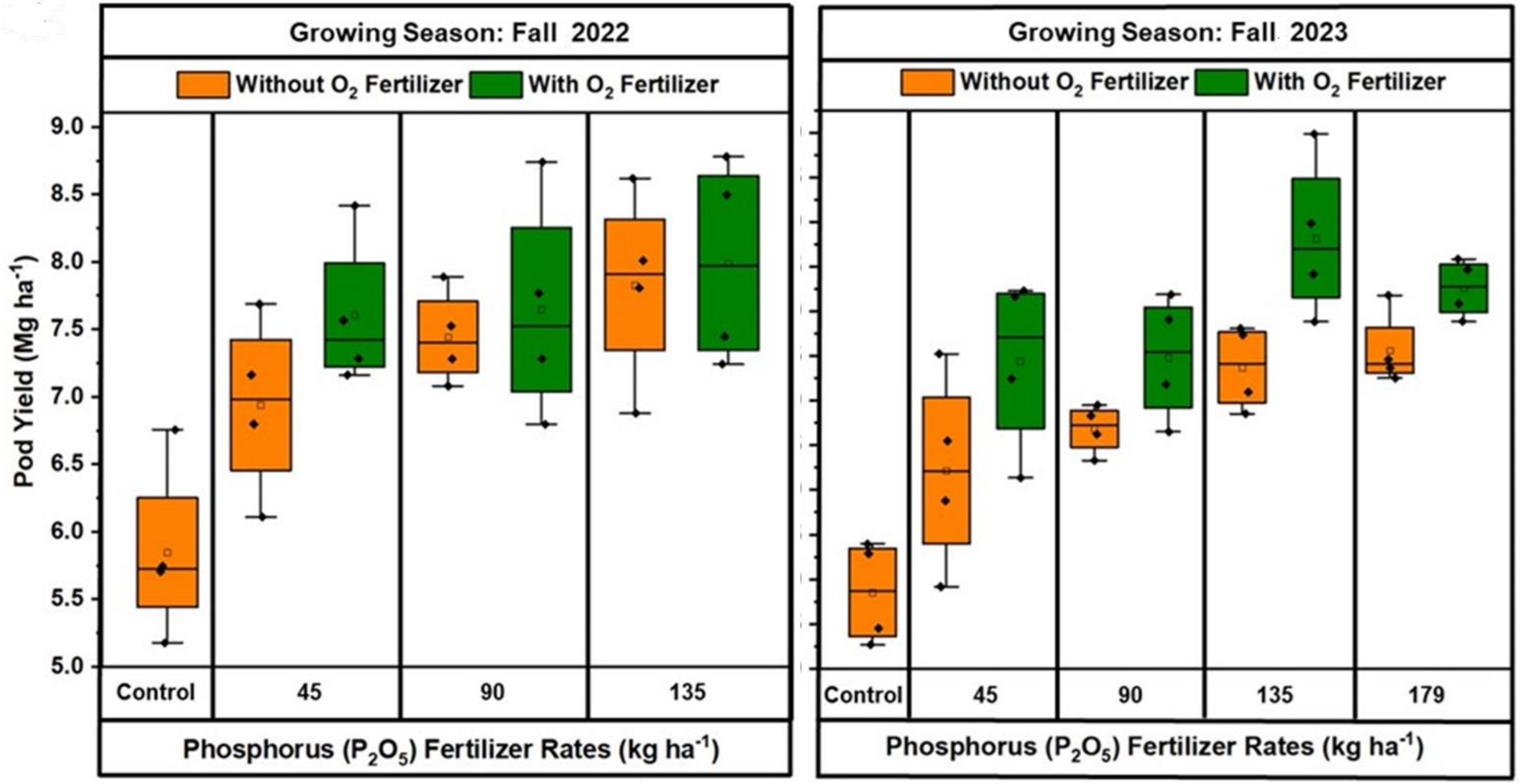
Snap Bean Plants In Pot Experiments





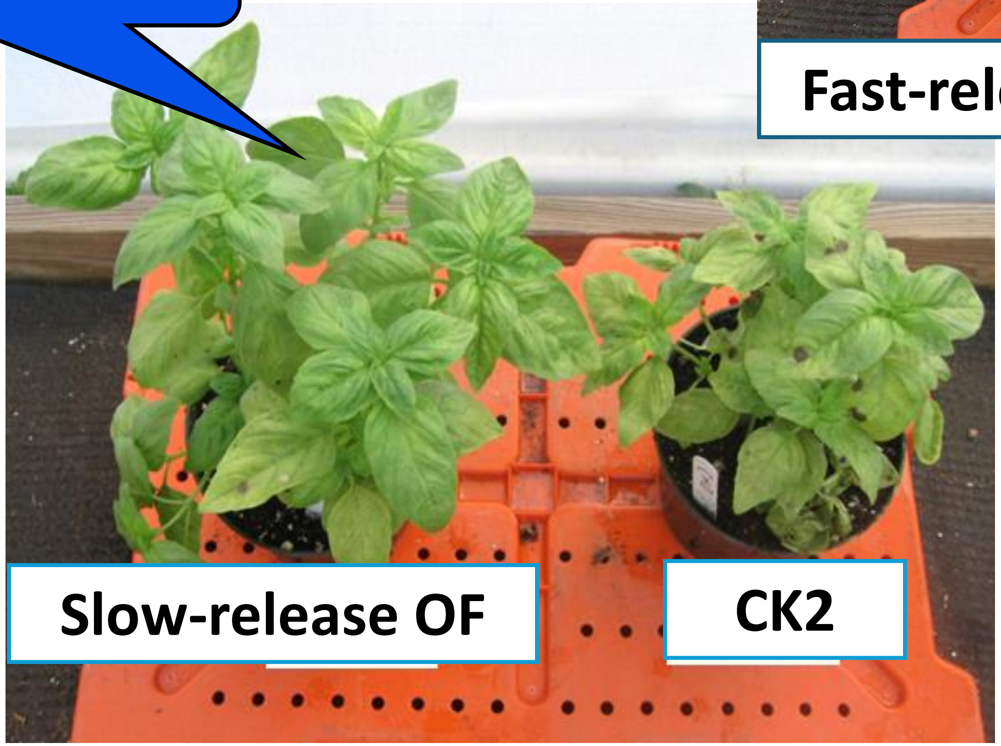
8. Enhanced Snap Bean Yields

-- *Snap Bean Plants In Field Trials*



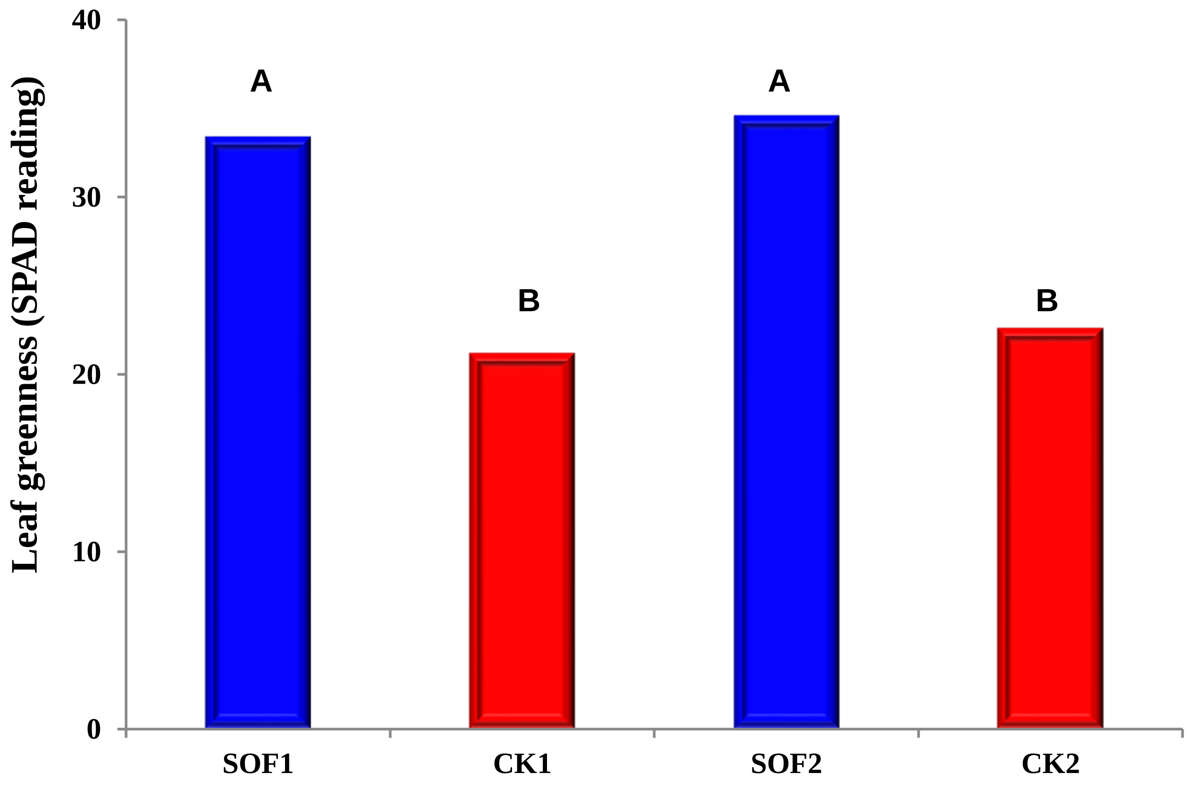
9. Enhanced Flooded Vegetable Yield (I)

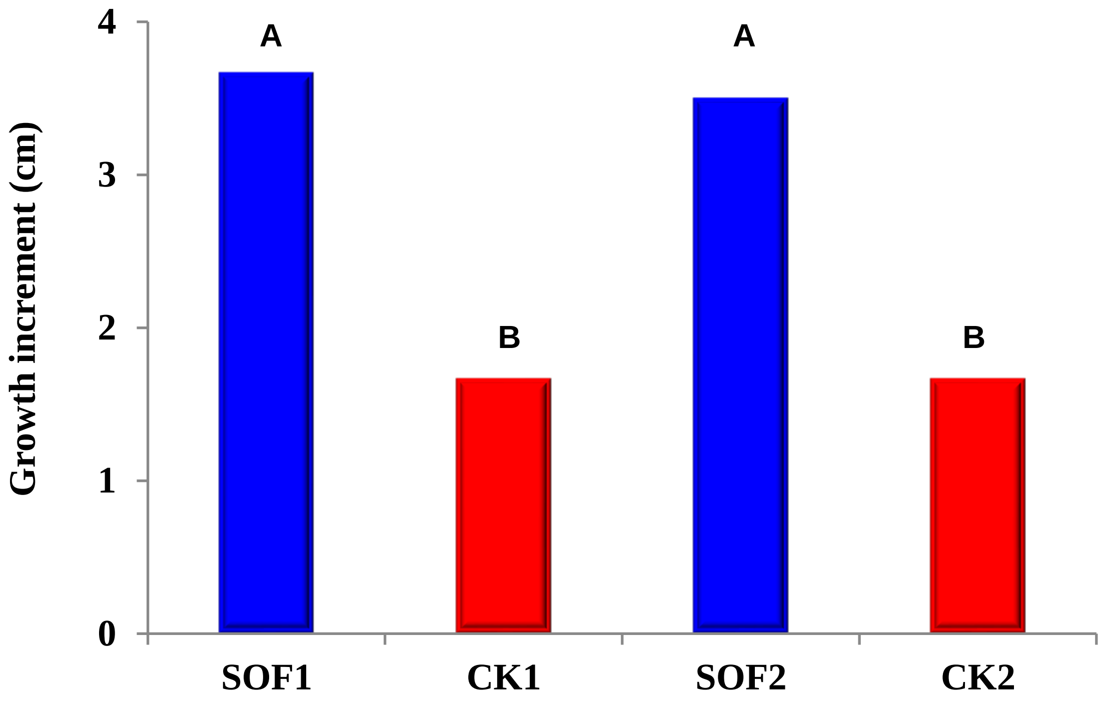
Basil Plants In Pot Experiments



- 32 days after planting
- 4 days after flooding

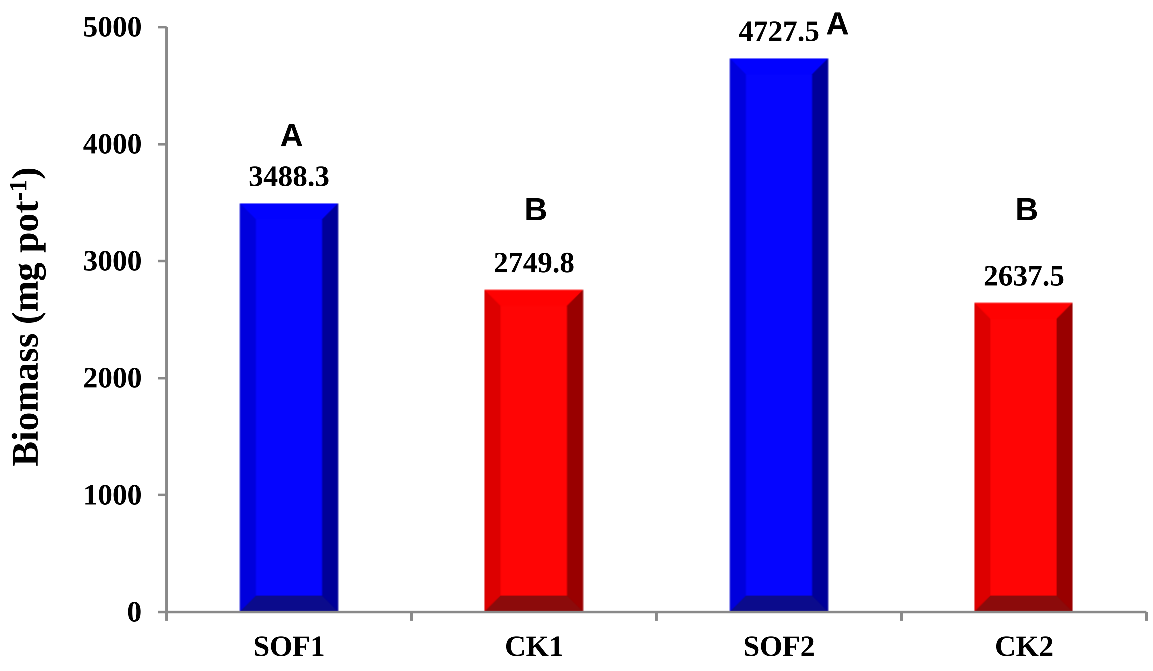
9. Enhanced Flooded Vegetable Yield (II)
--Basil Plant Growth

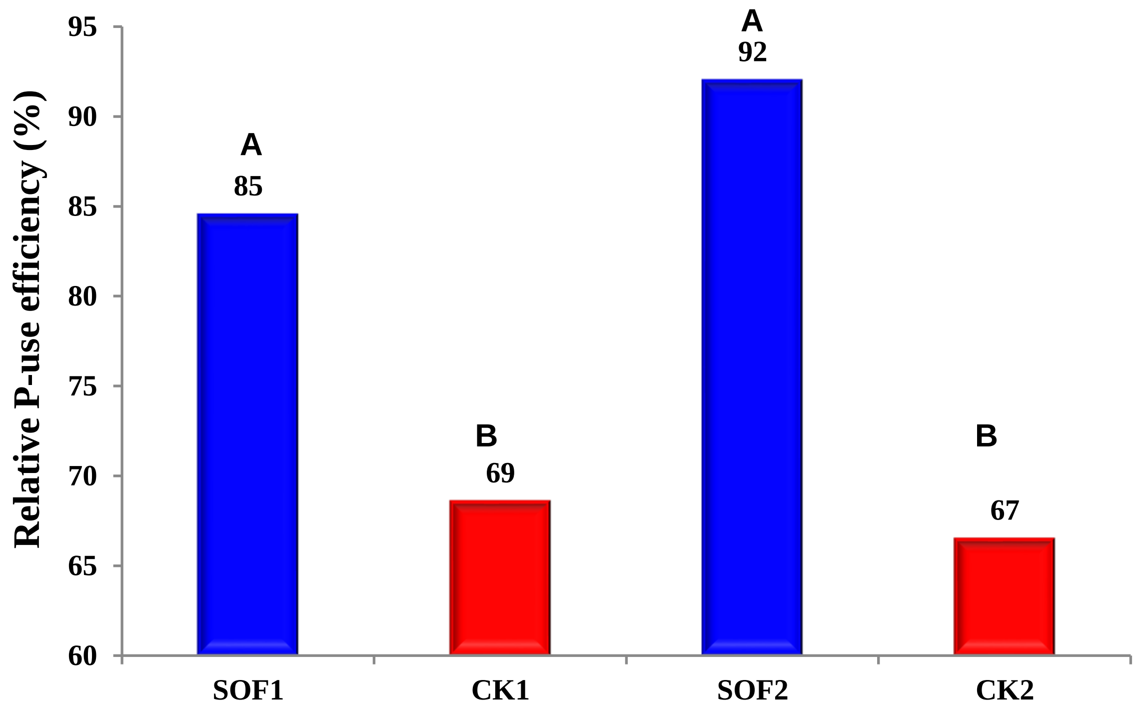




9. Enhanced Flooded Vegetable Yield (III)

--Basil Yield and P-use Efficiency



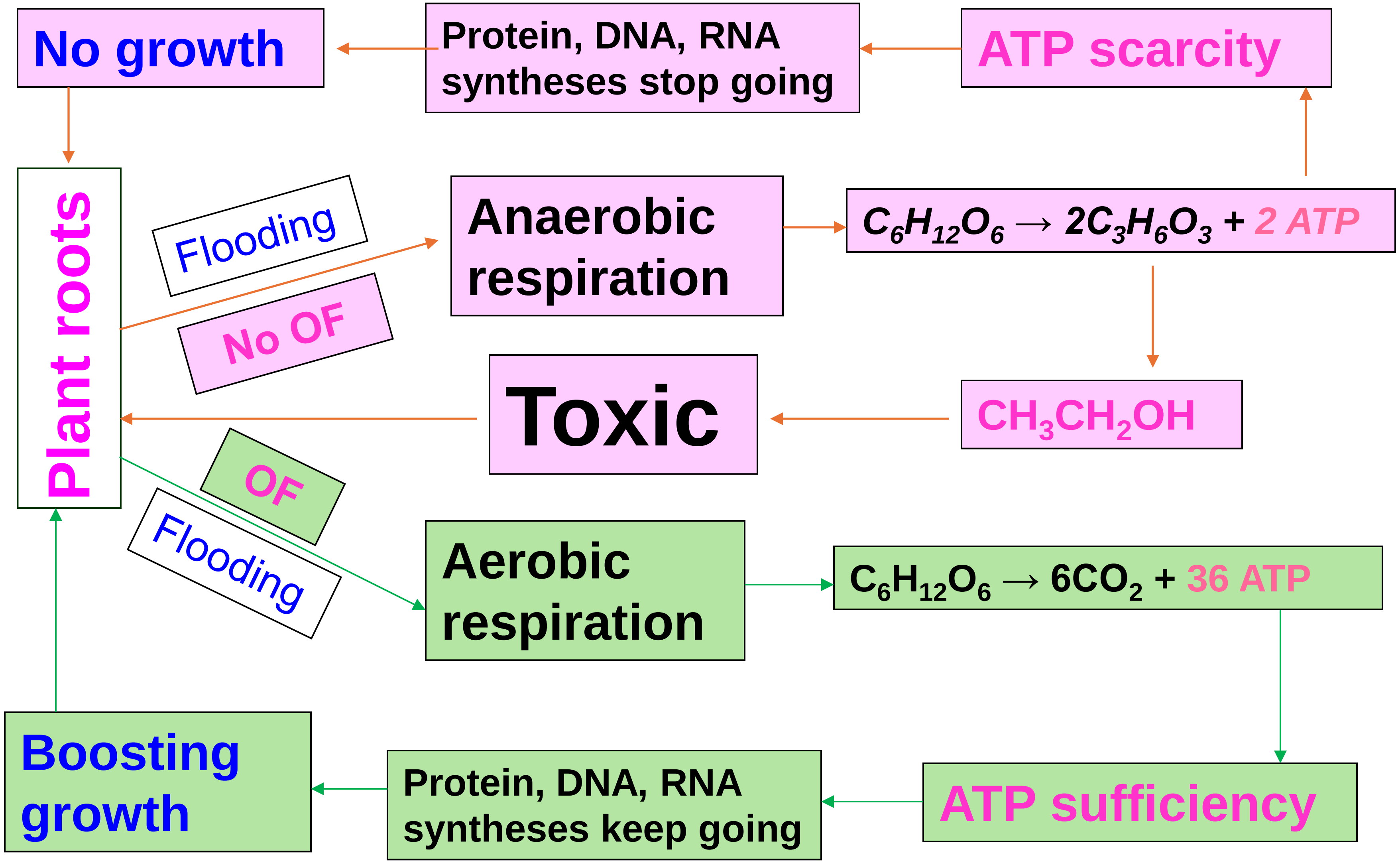


Best Practices to Reduce Flood Damage in Commercial Vegetable Production

https://edis.ifas.ufl.edu/publication/ss425

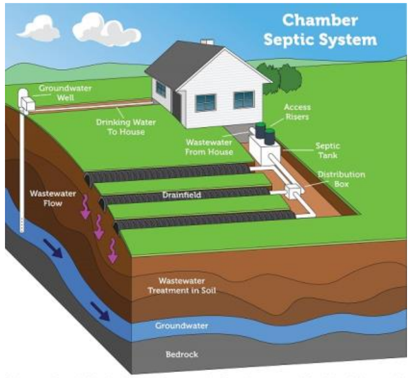
Photo Credit: Yuncong Li

Why Does OF Boost Plant Growth?



Oxygen Addition Transforms Septic Tank Efficiency

“There is concern that septic tanks leach N. recently the state has mandated that new septic tanks have electric fans to aerate the system to get better microbial breakdown of the nutrients. I think this adds energy demand not to mention an increase implementation and upkeep cost. ”



Please note: The ends of the chamber system lines are open for illustrative purposes only. In reality, and when properly installed, these lines are closed at the end. Septic systems vary. Diagram is not to scale.

Septic Systems

About Septic Systems

How Septic Systems Work

Types of Septic Systems

Webinars

Frequent Questions

Care and Maintenance

Funding

SepticSmart

Decentralized Wastewater Partnership

Additional Resources

Contact Us About Septic Systems

Types of Septic Systems

The design and size of a septic system can vary widely, from within your neighborhood to across the country, due to a combination of factors. These factors include household size, soil type, site slope, lot size, proximity to sensitive water bodies, weather conditions, or even local regulations. Below are ten of the most common types of septic systems used, followed by illustrations and descriptions of each system. The list is not all-inclusive; there are many other types of septic systems.

See below for illustrations and descriptions of various types of conventional and alternative septic systems. More detailed information on specific technologies can be found in Fact Sheets.

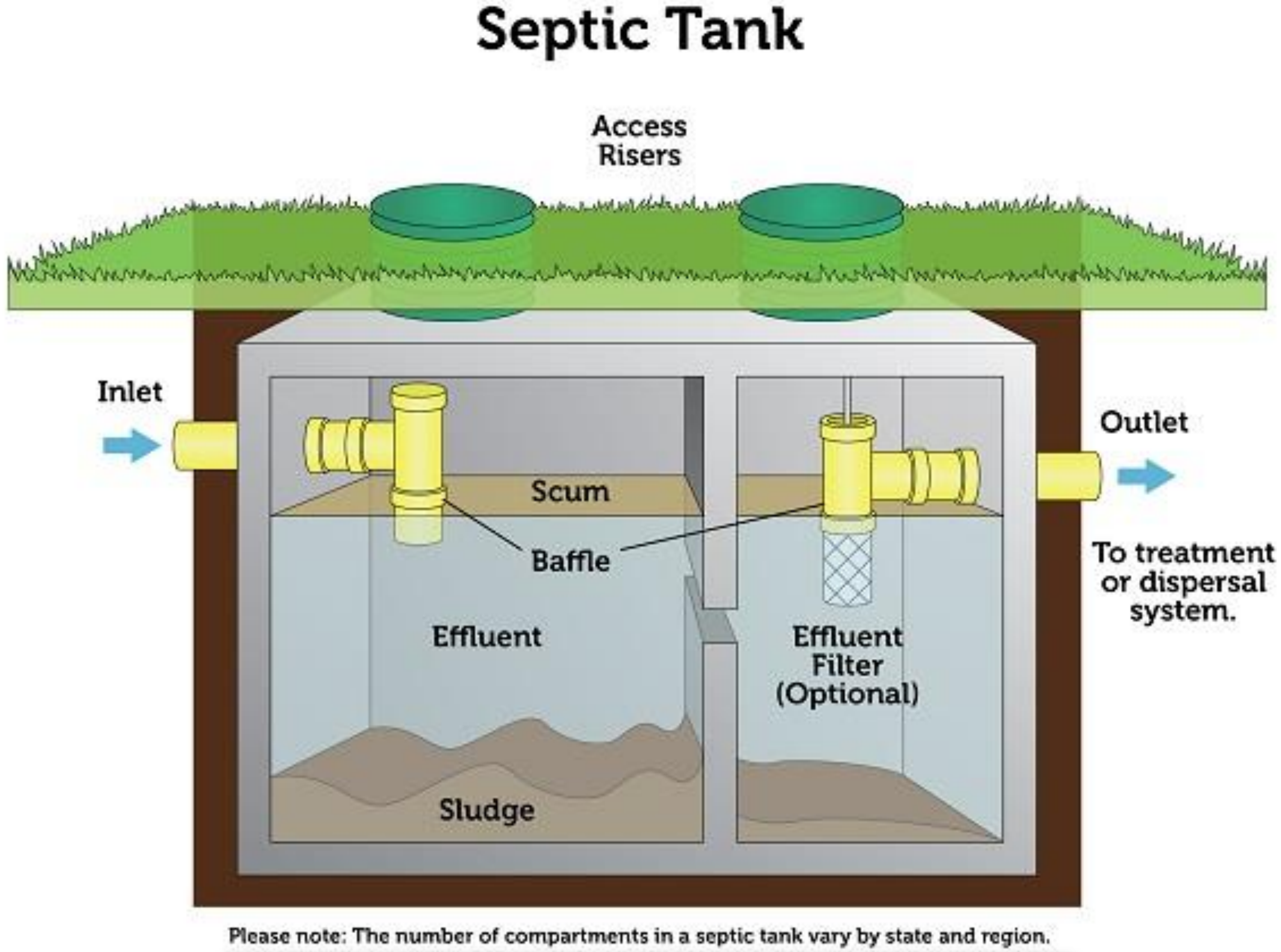
Conventional Systems:

- Septic Tank
- Conventional System
- Chamber System

Alternative Systems:

Types of Septic Systems | US EPA

Traditional Septic Tanks



Much sludge at the septic tank bottom

Image credit: Types of Septic Systems | US EPA

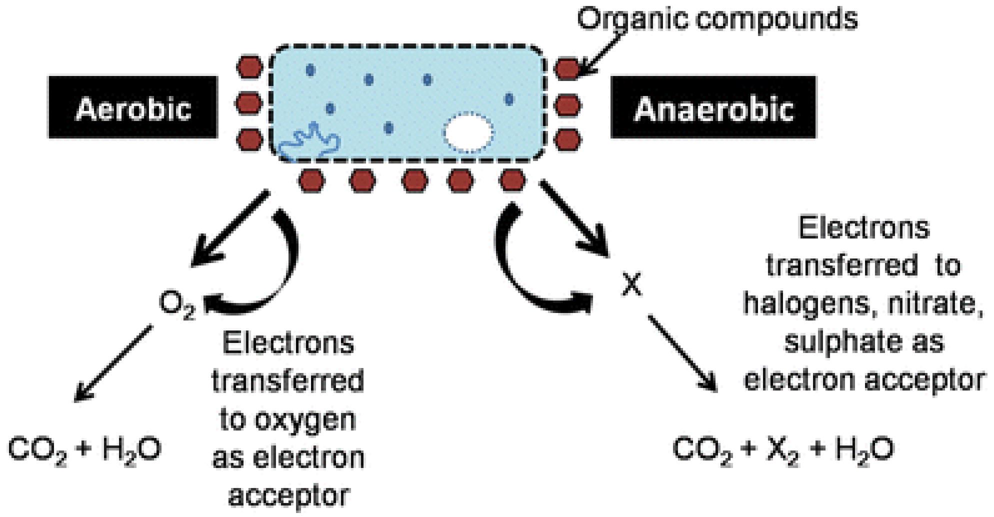


Image credit: Jaya Chakraborty

EPA's Revolutionizing Septic Tanks: Introducing the ***Air Pump***

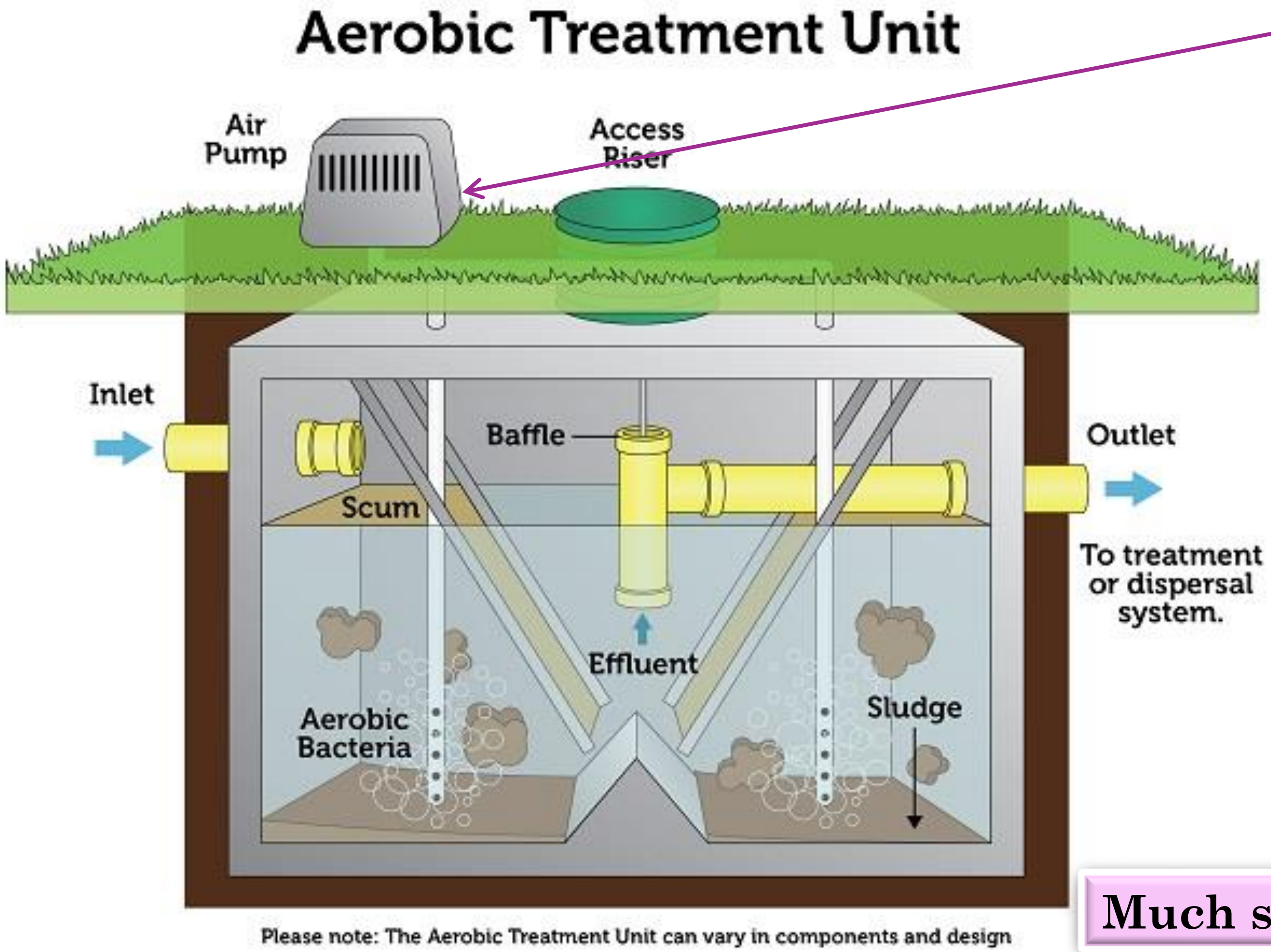


Image credit: Types of Septic Systems | US EPA

liquid O_2 displacer

Much sludge at the septic tank bottom

Conclusions

- Improved O_2 bioavailability and soil health
- Mitigated salinity stress crops often face
- Rescued aged vegetable germplasm
- Boosted growth of hypoxic crops
- Enhanced nutrient uptake and crop yield

Acknowledgements

- HAEC Crew
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