28 Years of Applied Pit Lake Research at HVC

Establishing primary productivity to promote bioreactor development with ecosystem functions

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Larratt Aquatic Consulting Ltd. (LAC)

Founded in 1980

NOTE: Speaker's notes are summarized at the bottom of slides in this version of the slide deck. Enjoy. - HL

Acknowledgements: LAC would like to thank the following:

Land: The Lower Nicola Indian Bands and Secwepemc, Nlaka'pamux, Stk’emlúpsemc te Secwépemc Nations have provided the lands HVC resides on with generations of environmental stewardship. We thankful to work on these lands and provide water sampling.

HVC: Our continued thanks for the opportunity to serve HVC for decades - especially to Jaimie Dickson and Dale Robertson for being amazing ol’ timers, to Richard Doucette for getting on site well before a summer dawn to allow sunrise photography, and to many other phenomenal staff over three decades.

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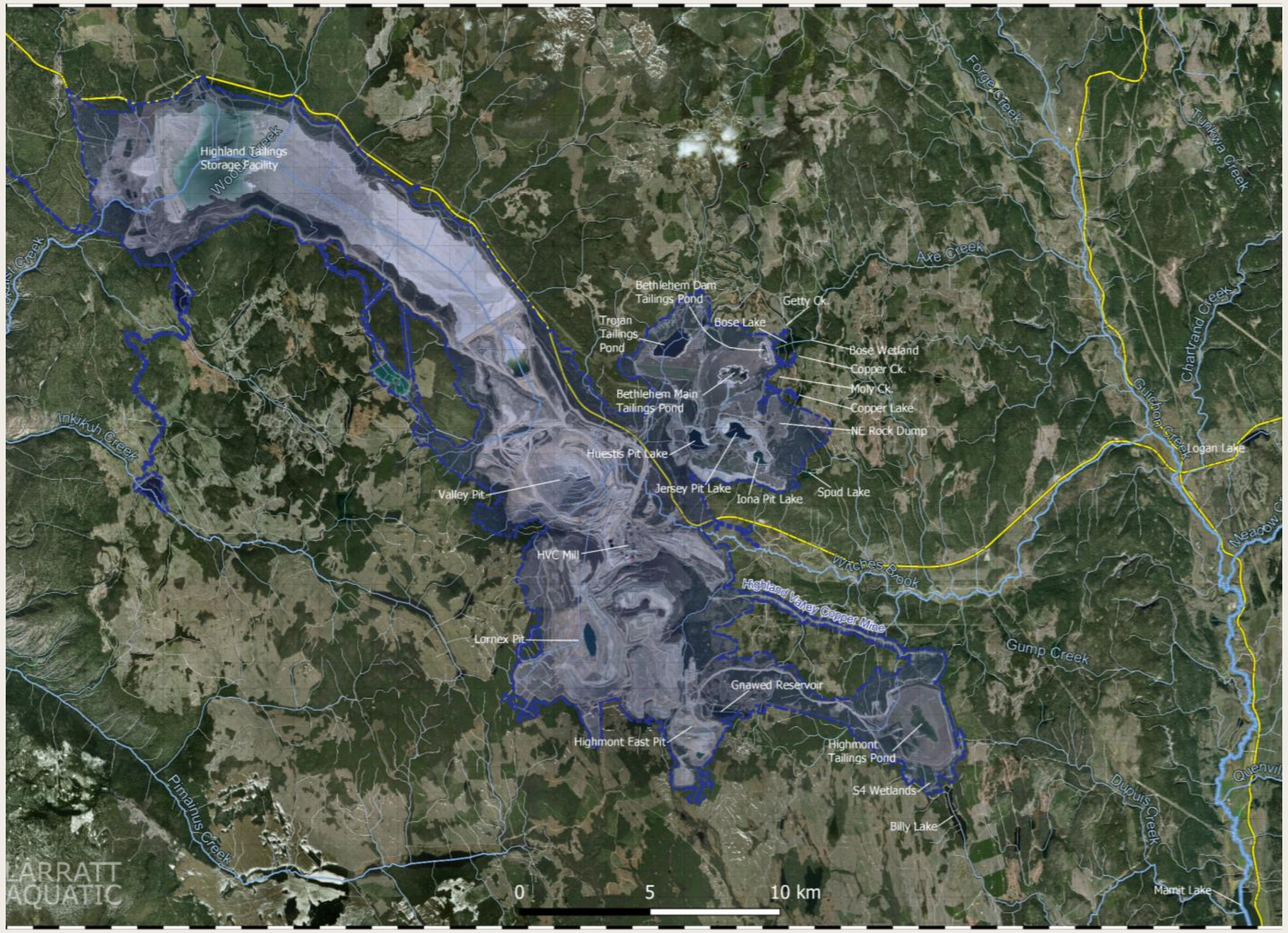
Bill Price: Thank you for your tireless and brilliant leadership of MEND.

The HVC Pit Lake Challenge:



Unproductive Waters

Pit lakes behave like crater lakes. Both tend to be incredibly clear with secchi depths exceeding 30m and minimal biological activity.

Limited lake potential

Steep shorelines, restricted wind fetch, and small catchments create environments with extremely low aquatic productivity.

Metals of concern COPCs

Mining operations led to COPCs **Cu, Mo** and some concern about SO_4 NO_3 Se concentrations requiring long-term water treatment solutions.


Highland Tailings Storage Facility
Wood Creek
Forge Creek
Tunkwa Creek
Axe Creek
Bethlehem Dam Tailings Pond
Getty Ck.
Trojan Tailings Pond
Bose Lake
Bose Wetland
Copper Ck.
Moly Ck.
Copper Lake
NE Rock Dump
Bethlehem Main Tailings Pond
Chartrand Creek
Guichon Creek
Logan Lake
Inkikuh Creek
Huestis Pit Lake
Valley Pit
Jersey Pit Lake
Iona Pit Lake
Spud Lake
HVC Mill
Witches Brook
Highland Valley Copper Mine
Meadow C
Lornex Pit
Gump Creek
Gnawed Reservoir
Highmont East Pit
Highmont Tailings Pond
S4 Wetlands
Billy Lake
Dupuis Creek
Quenvil
Pimainus Creek
LARRATT AQUATIC
0
5
10 km
Mamit Lake

Post-Closure: Mining with the End in mind

Active "Short-Term" Pit Lake Uses

CONSIDER: Technology-driven applications requiring ongoing investment and management.

The lifecycle question becomes critical: what happens when the current technology becomes obsolete or the investment period ends?

EXAMPLES

Energy production & storage

Water storage – seasonal, managed

Aquaculture (fish farming)
birds

Carbon capture + GHG management

Dive parks ???...
education/studies

Passive "Long-Term" Pit Lake Uses

EXAMPLE: Nature-based solutions with minimal ongoing intervention.

These approaches use natural processes and require limited infrastructure, making them sustainable over decades or even centuries.

EXAMPLES

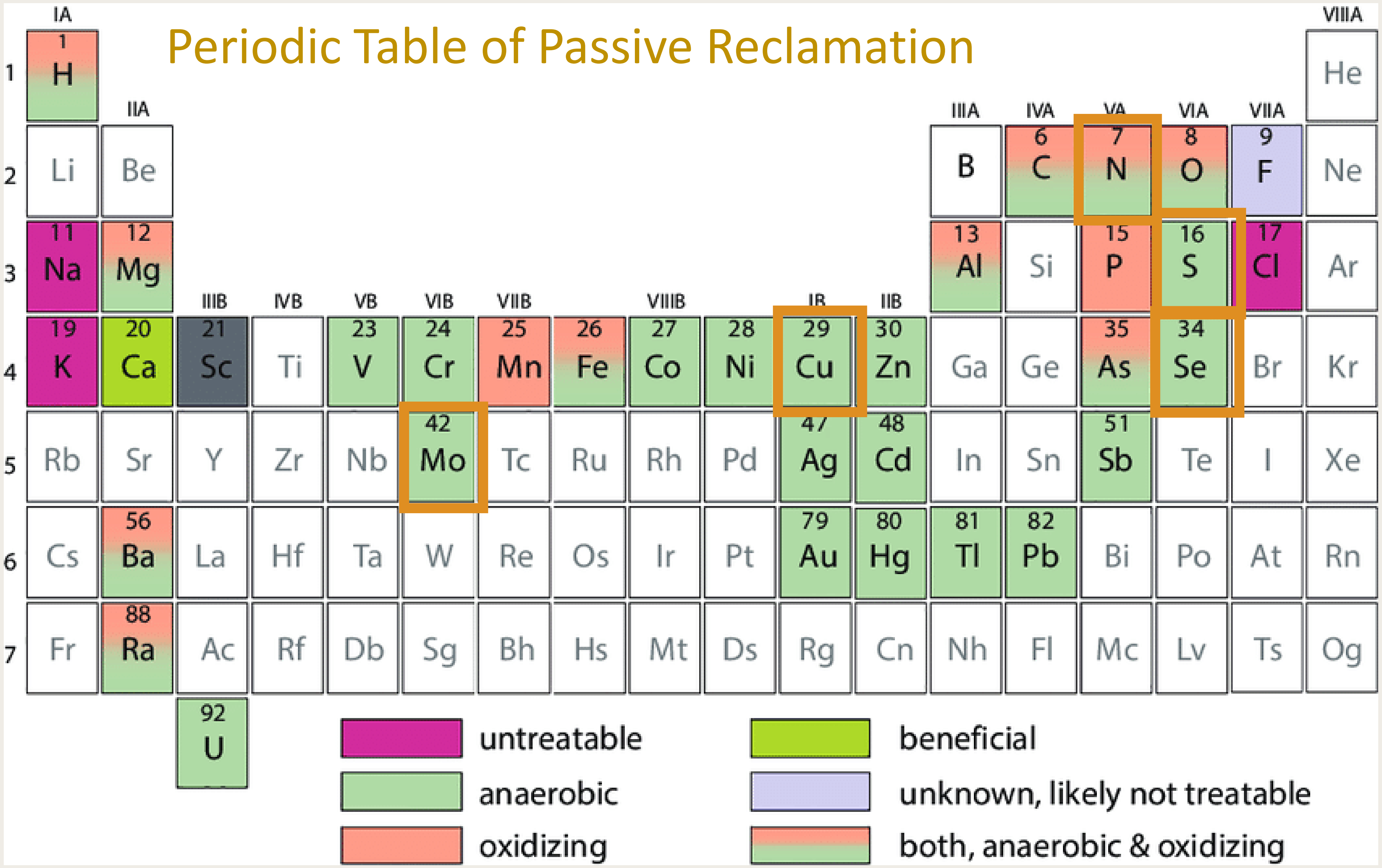
Passive bioreactor

Water storage – long-term

Habitat for aquatic animals, birds

Carbon storage long-term

Environmental education/studies



This Periodic Table illustration shows the COPCs for HVC in brown outlines – all COPCs are amenable to anoxic treatment.

Periodic table for passive treatment (modified after Gusek 2009)
image courtesy Christian Wolkersdorfer.

The HVC Bioreactor Vision

Assess physical characteristics

Vertical stratification is a key determinant of the future end use of a reclaimed water-filled pit

1

Encourage strong algae growth

Phytoplankton blooms adsorb dissolved metals from water column and transport them to deep water along with their grow-in-place carbon
Algae forms a carbon sink and supply deep water anoxic bacteria.

2

Bacterial Action

Sulfate-reducing bacteria use the algal carbon to convert adsorbed metals into stable sulfide compounds

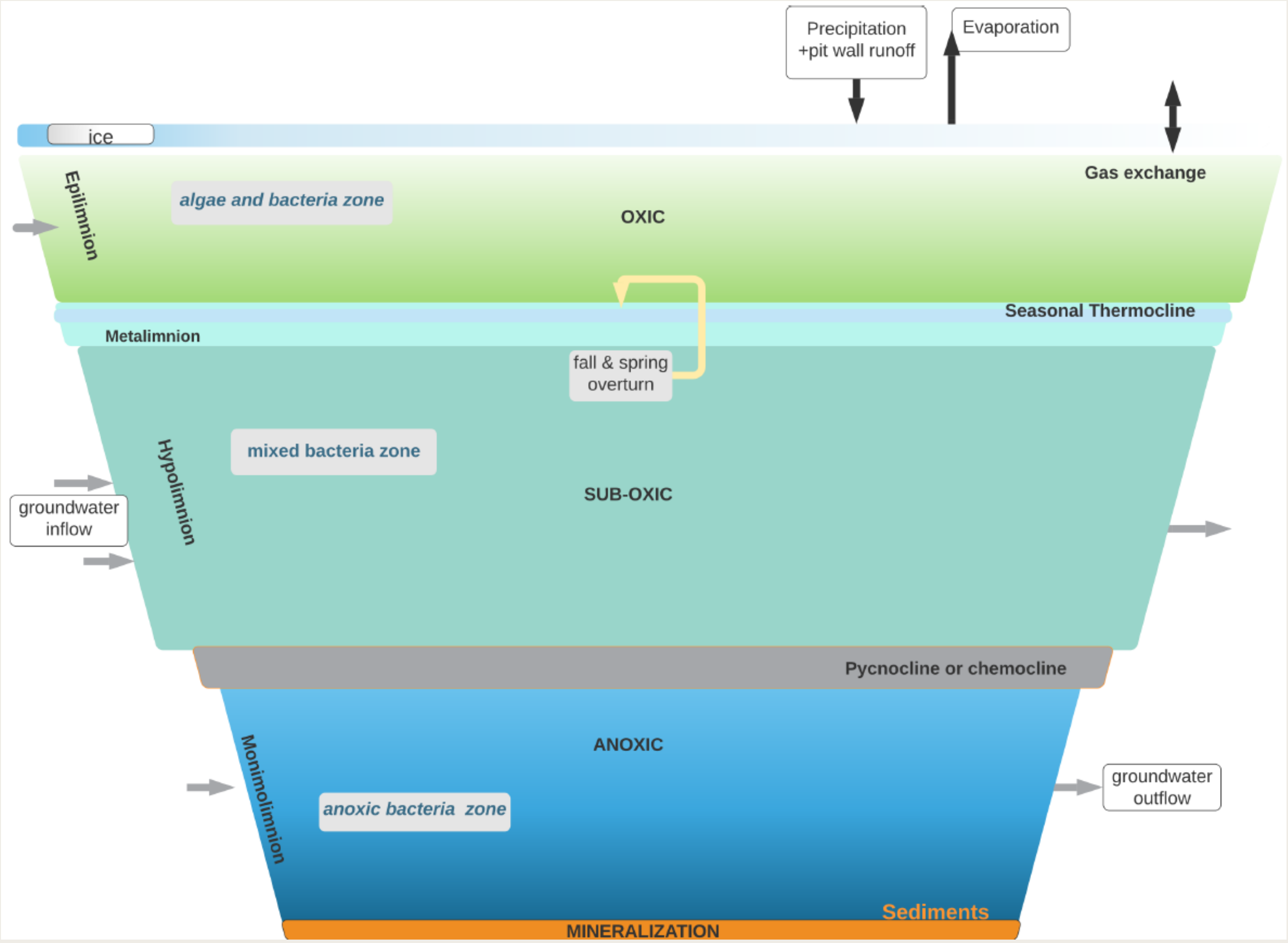
3

Metal Storage

Immobilized metals remain in anoxic sediments for permanent storage with a permanent water cover, as in all natural lakes

GOAL

Development of a pit lake reclamation **toolbox** for use on three much larger pit lakes that will form after mine closure

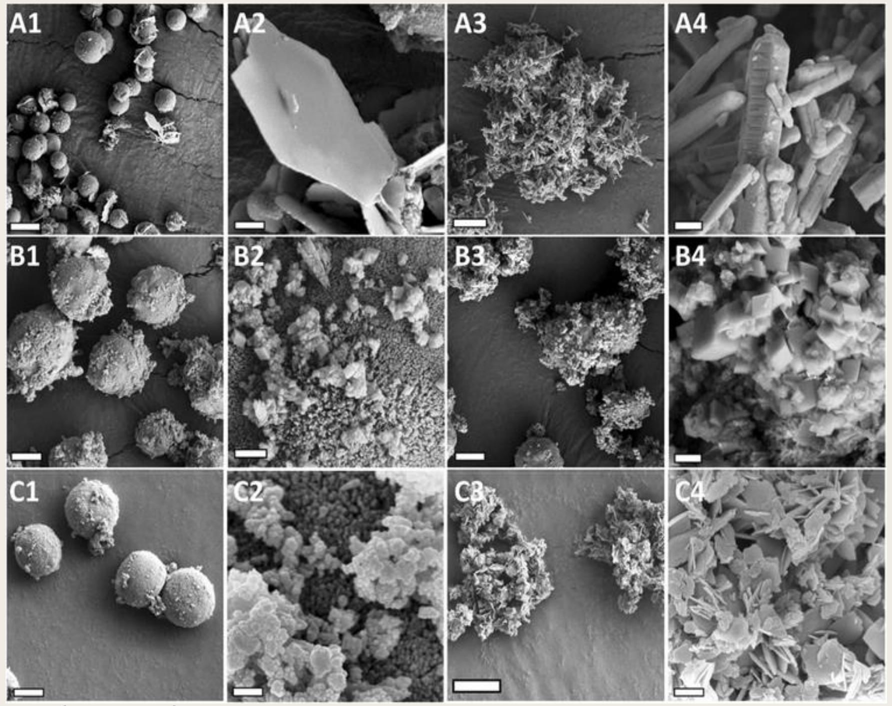


Conceptual diagram of meromictic pit lake

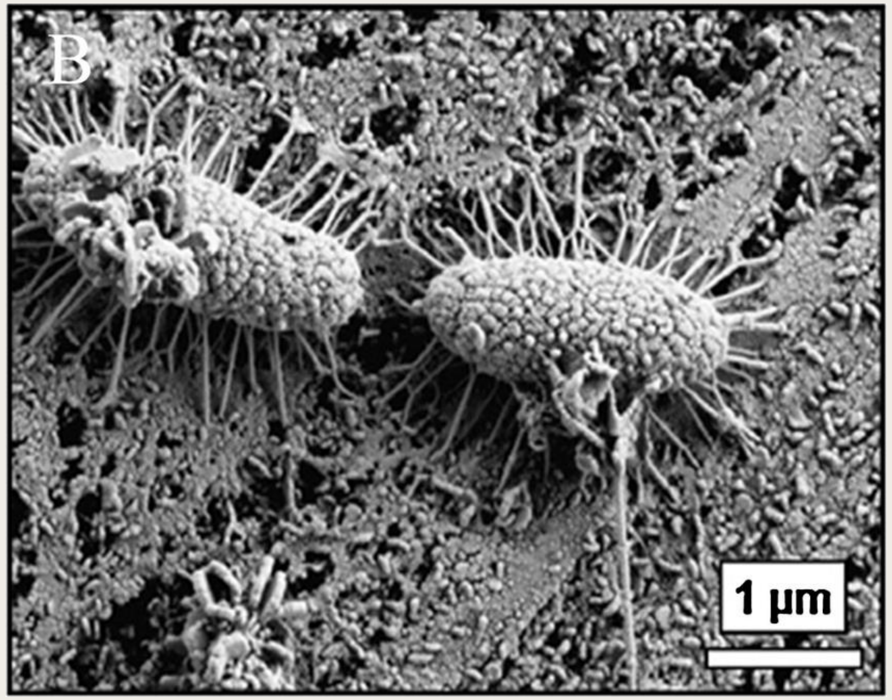
Key Bioreactor Mechanisms

Adsorption

A variety of phytoplankton surfaces (silica, polysaccharides, protein etc.) marl microcrystals, and iron compounds adsorb dissolved metals during pH increases from algae bloom photosynthesis.



Zhang et al 2018

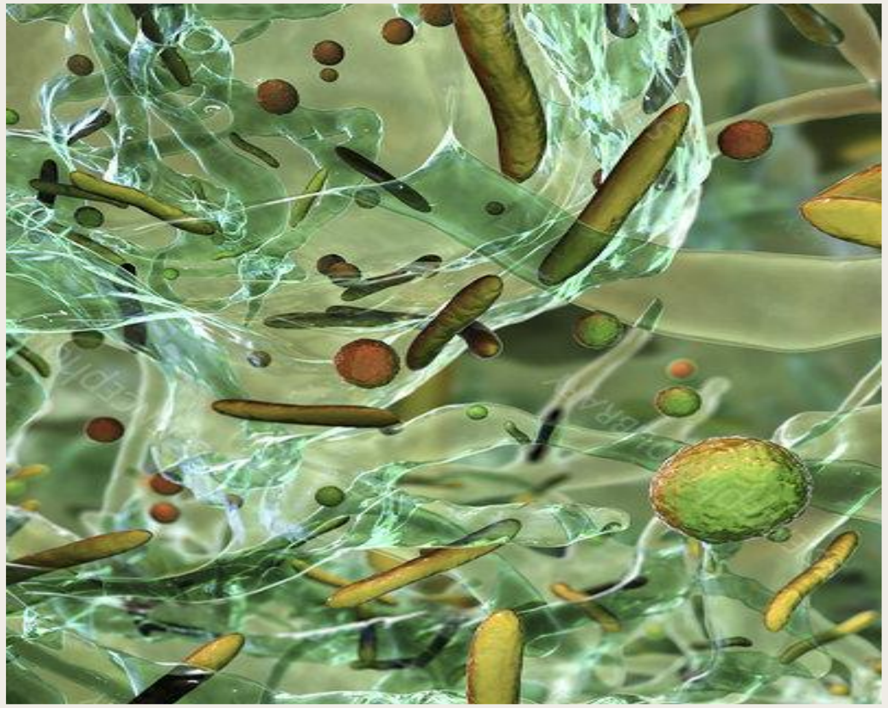


Bacterial Reduction

Sulfate-reducing bacteria in anoxic sediments convert metals into stable sulfide compounds for “permanent storage”.

Nutrient Recycling

Established periphyton populations retain and recycle nutrients while generating essential compounds for sustained productivity.



HVC Research Site: Bethlehem Pit Lakes

Three Decades of Mining History

Located at Canada's largest open pit copper mine, the Bethlehem area was mined from 1962 to 1982. Research began in 1996 on three pit lakes:

- **Huestis** - Dynamic bioreactor (23 m) with shallow areas
- **Iona** - Deep bioreactor 62 m depth; classic pit lake shape
- **Jersey** - Minimally modified control pit lake 26 m

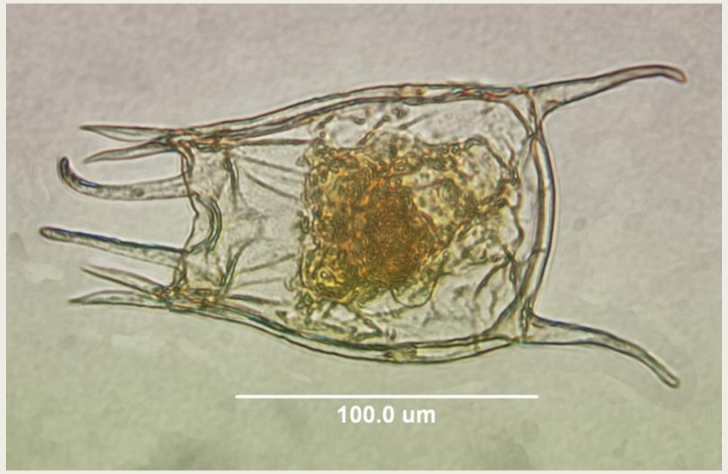
	Present Pit Lakes			Future Pit Lakes		
	Huestis	Jersey	Iona	Highmont	Lornex	Valley
Surface area	13.5 ha	15 ha	6.1 ha	80 ha	350 ha	540 ha
Volume	5×10^5 m^3	2.4×10^5 m^3	11.8×10^5 m^3	7×10^7 m^3	3.7×10^8 m^3	1.35×10^8 m^3
Maximum depth	22.7 m	25.5 m	62.5 m	180 m	450 m	750 m


HVC Location
Vancouver
Jersey pit lake
Huestis pit lake
Iona pit lake
0
500
1,000 m

Initial Conditions:
A biological desert.

Minimal Productivity

Primary production barely detectable. Periphyton layers dominated by bacteria. Only occasional Keratella rotifers present.



Missing Ecosystem Components

No zooplankton except 1 rotifer (Keratella), no benthic invertebrates, no aquatic macrophytes detected in initial surveys.

Pit lakes behave much like crater lakes because both lake types have:
steep, barren shorelines with low habitat complexity, limited shoreline for macrophytes, shorter lower insolation times and far less wind forcing compared to a natural lake.
Pit lakes also have limited substrate-water column interactions from their restricted turbulence and small catchments
Less Sunlight means lower water temperatures thus lower productivity and therefore decreased bioreactor function potential.

Just add phosphorus!

Phytoplankton Success - once

Initial fertilization with granular 11-52-0 and liquid ammonium polyphosphate, dosed to a theoretical 0.01 mg/L as P
(we actually needed 0.005 mg/L as P, in a DIN:DIP 7:1 to 15:1).

This fertilizer triggered spectacular first-year algae blooms every pit, every time - once.

Periphyton Success - ongoing

While phytoplankton stalled, periphyton thrived - growing 3-10 mm thick layers on sunlit rock walls within two years.

We used a bottom-up approach building the trophic sequence natural to aquatic ecosystems. After physical conditions were understood, bioreactor function was promoted by adding the limiting nutrient – P. We conducted whole pit lake treatment in preference to installing mesocosms because we did not have surface discharge, and each pit provided a relatively closed system. Our plan called for augmenting the limiting macronutrient by adding high phosphate fertilizer, followed by introductions in the trophic sequence: bacteria, algae, zooplankton, macrophytes, benthic invertebrates.

Just add phosphorus!

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Periphyton Success - ongoing

While phytoplankton stalled, periphyton thrived - growing 3-10 mm thick layers on sunlit rock walls within two years.

The Mystery: Subsequent fertilizer applications failed to produce any blooms, regardless of amount, type, or timing. Adding standard micronutrients also failed.

The Plot Thickens… The limited interaction between the substrates and the water column is a problem for a pit lake but not a problem in shallow water bodies like tailings pond with similar water chemistry.

The Missing Ingredient: What would the sediment interaction in a shallow water body be providing? Something bacteria make…..

The Missing Ingredient: B-Vitamins

01

Experimental Discovery

Container trials with emulsified eggs triggered algae blooms - over 5,000 cells/mL within two weeks.

02

Vitamin Confirmation

Testing egg yolk, B vitamin tablets confirmed B-vitamins as the limiting factor.

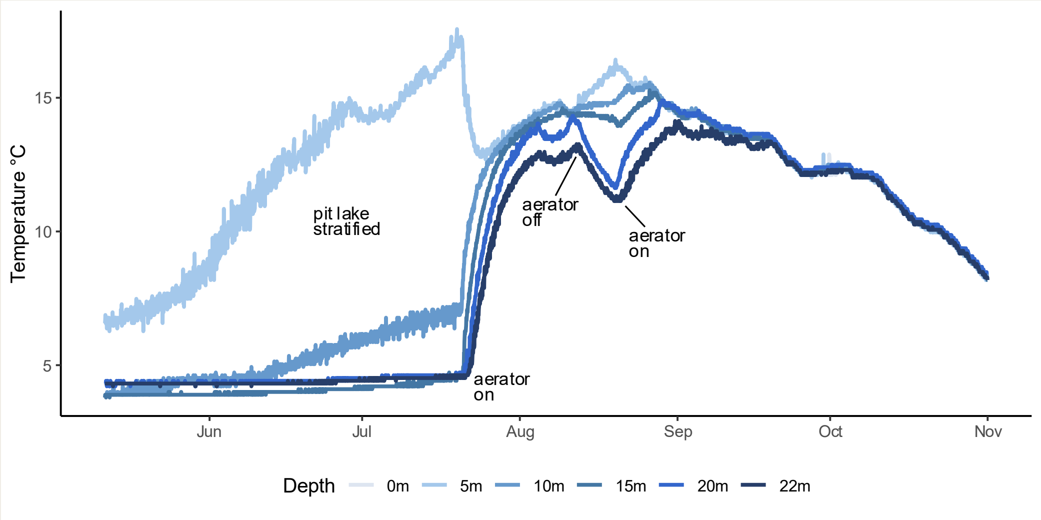
03

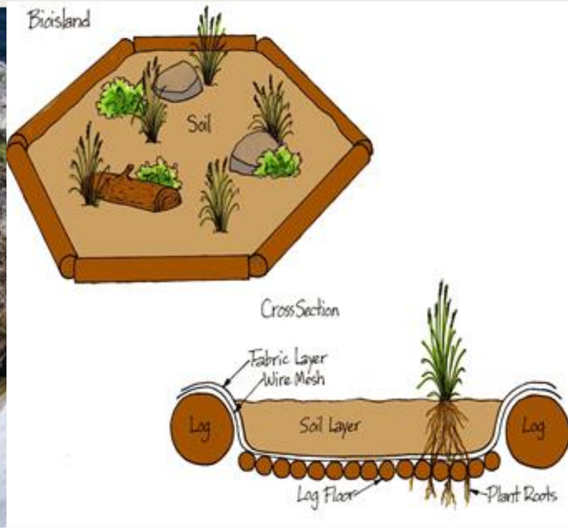
Bacterial Partnership

Periphyton bacteria produce essential B-vitamins (B12, B1, B7) that phytoplankton require for growth.

The B vitamin hypothesis also explains why every substrate we added rapidly grew diverse periphyton. Bacteria and algae coexisted on the substrates, supplying each other with vitamins and carbon.

Solutions to B vitamin + nutrient deficiency





Artificial Upwelling

Aerators mixed vitamin-rich bottom water to surface, increasing chlorophyll from <1 to 1.4 µg/L and accelerating bacterial growth. And the zooplankton loved the food conveyor belt.

Biosolids Rafts

Permeable rafts containing 20 metric tons of sterilized biosolids provided phosphate and B-vitamins.

No longer in use – but it works! because biosolids provides B vitamins and nutrients

Biorafts

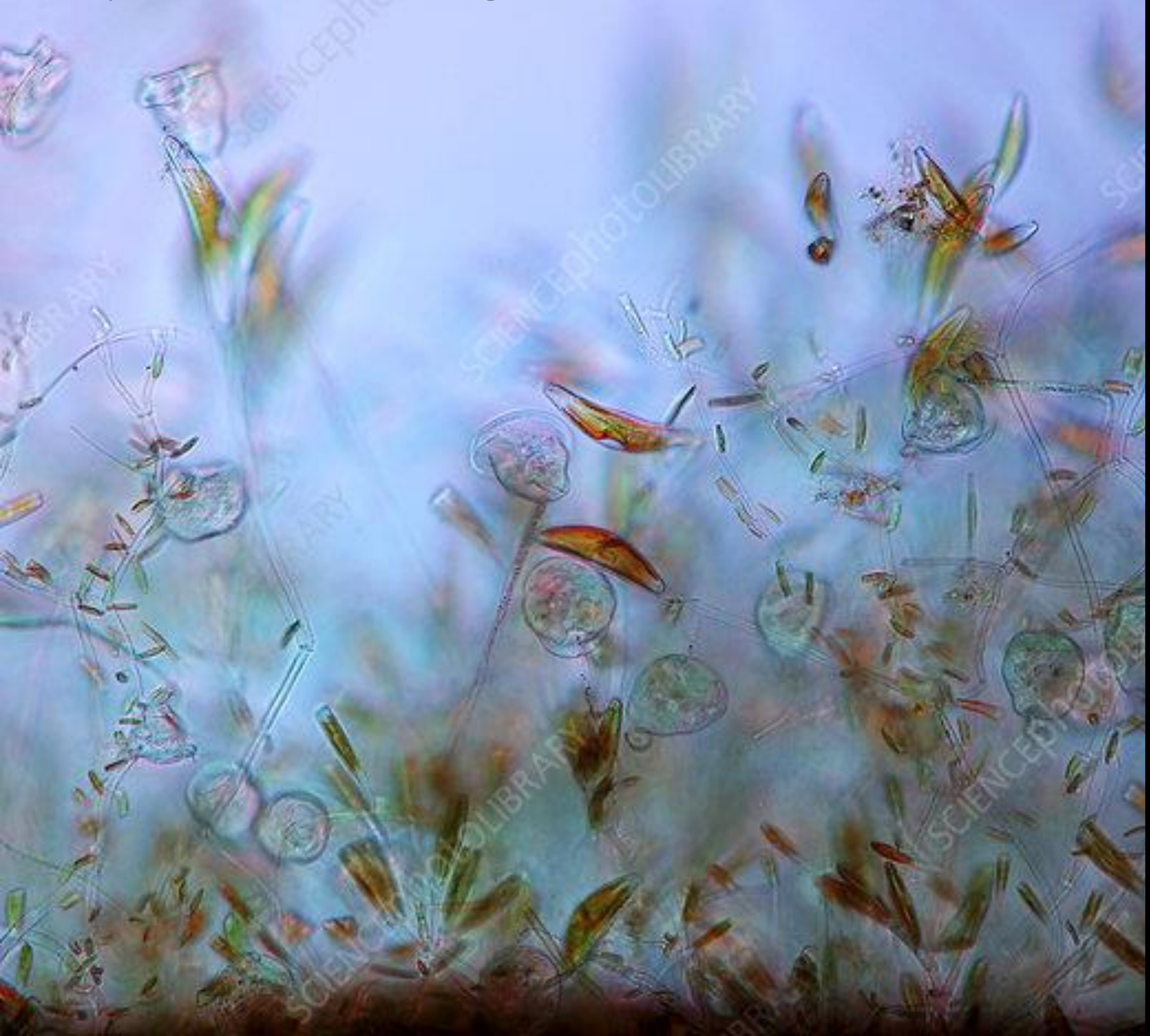
Biorafts made of wood – need replacing every ~5 years but that's okay?

Plant roots, wood, straw, soil and algae substrates increased periphyton surface area and species diversity from 7 to over 25 taxa. (root hairs represent a fixed film bioreactor)

Know what your grown-in-place carbon is – its not just green goo

PERIPHYTON

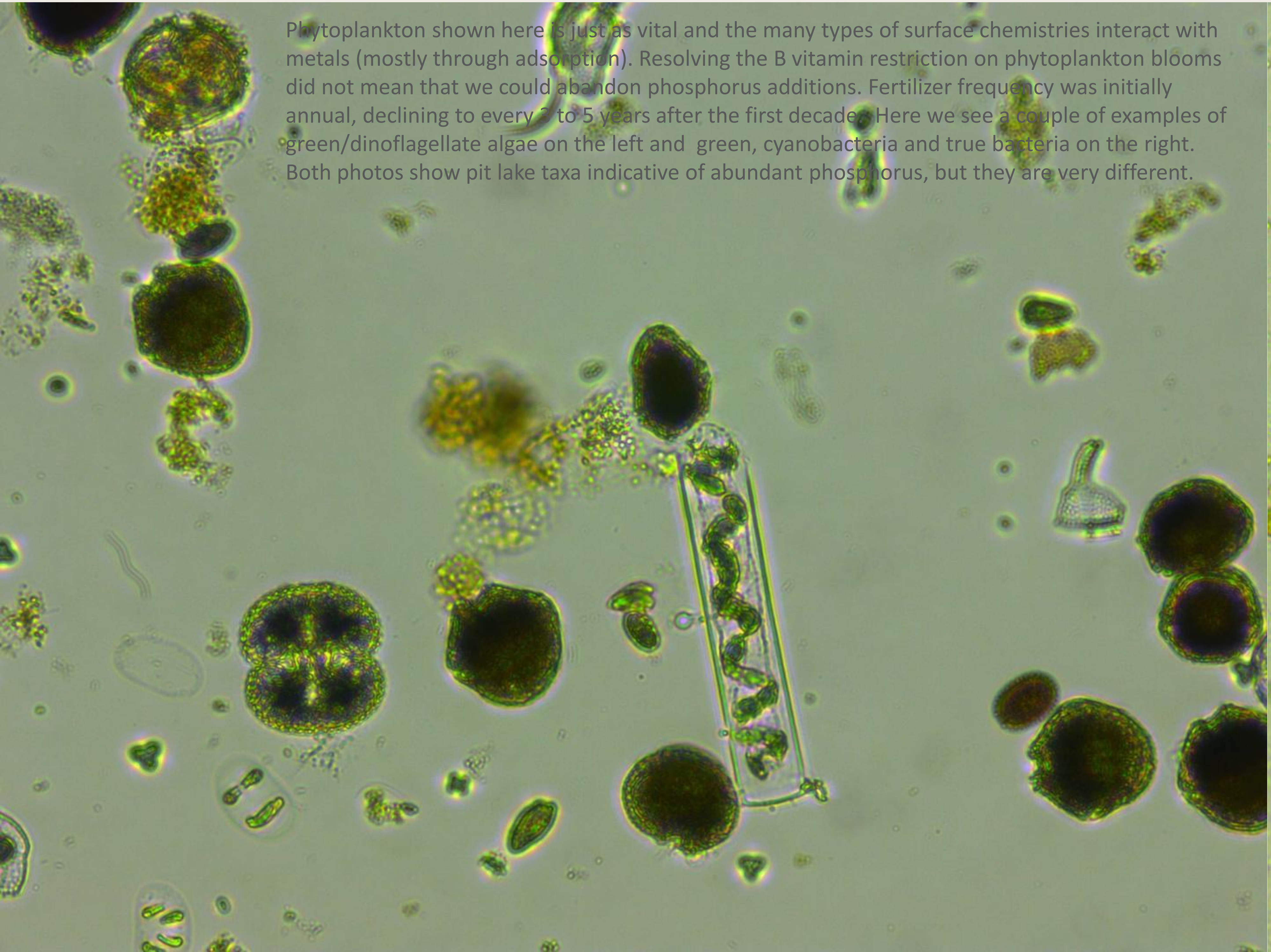
Periphyton biofilms that form a crucial foundation for pit lake food chains are complex. Diatom chains and diatoms on polysaccharide stalks are most visible here. The upper periphyton layers are photosynthetic while the deeper layers are dominated by decomposers such as bacteria and fungi.

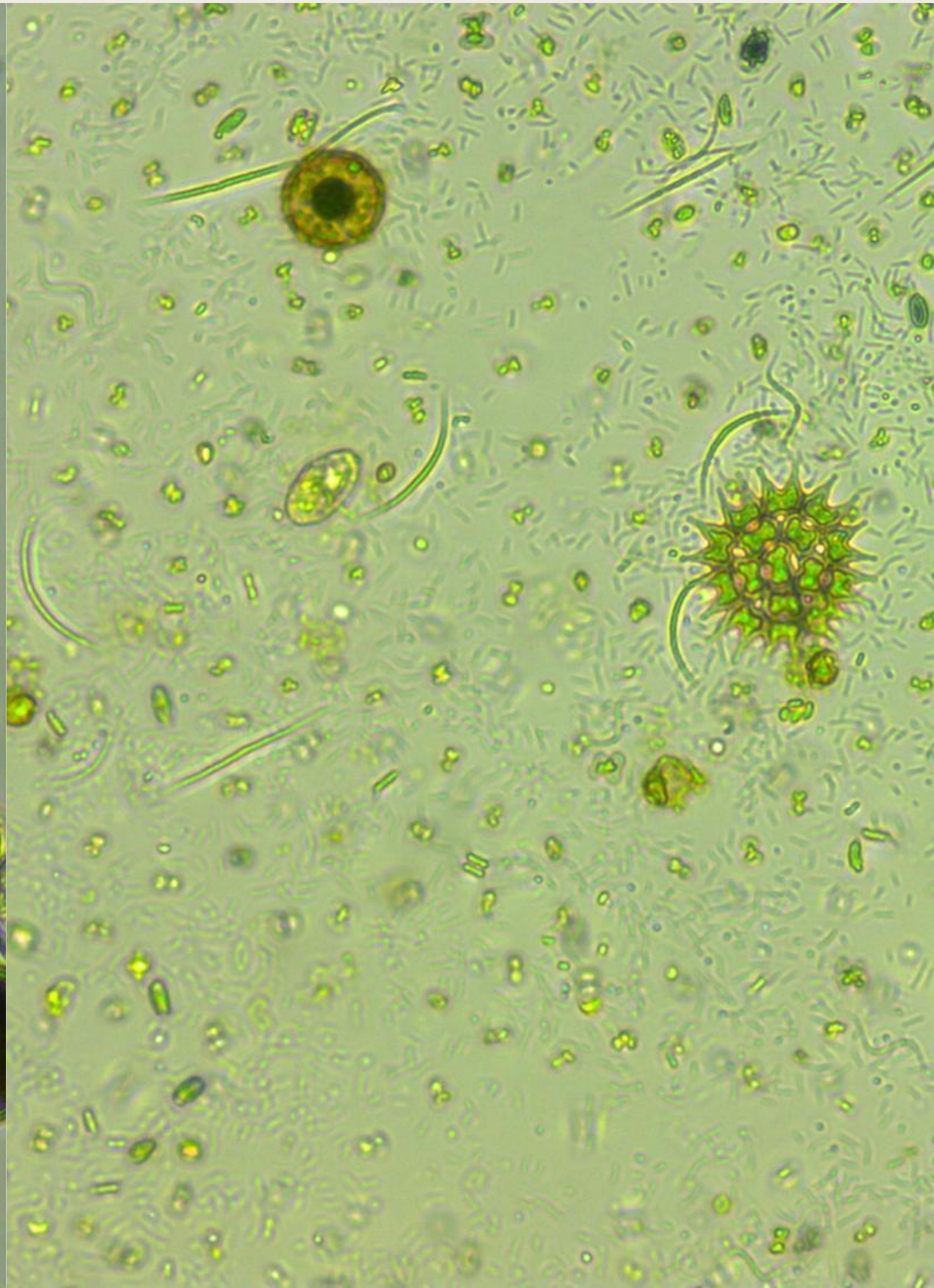


Know what your grown-in-place carbon is – its not just green haze

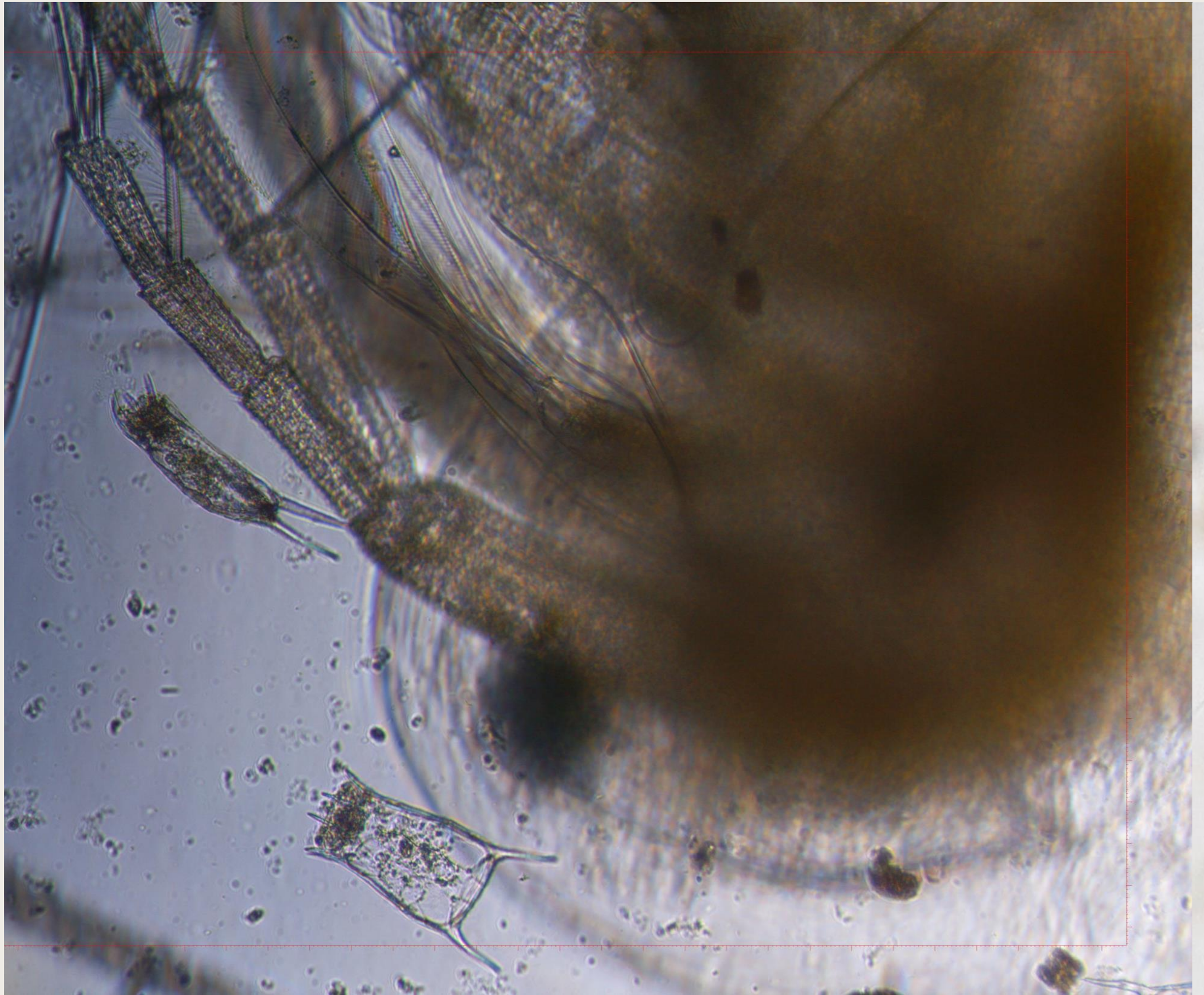
PHYTOPLANKTON

Phytoplankton shown here is just as vital and the many types of surface chemistries interact with metals (mostly through adsorption). Resolving the B vitamin restriction on phytoplankton blooms did not mean that we could abandon phosphorus additions. Fertilizer frequency was initially annual, declining to every 3 to 5 years after the first decade. Here we see a couple of examples of green/dinoflagellate algae on the left and green, cyanobacteria and true bacteria on the right. Both photos show pit lake taxa indicative of abundant phosphorus, but they are very different.





Know what your grown-in-place carbon grazers are – many types, different roles



The humble Keratella rotifer is one of the first colonizers of basic pit lakes. It grazes on small algae and bacteria. Daphnia (if you have cladocerans, chances are you will pass toxicology testing) and copepods (calanoid) come next. These larger grazers represent food for planktivorous fish such as kokanee – in case you're interested in considering fish farming

You could almost think you were at a natural lake…

Rock substrates did not host as many invertebrate species as macrophytes, but these plants die down seasonally and therefore provide intermittent substrates.

Woody debris can provide year-round stable surfaces for decades. In both pit lakes, adding woody substrates increased the number of benthic invertebrate species.

Table 1: Benthic invertebrates found in Huestis pit lake substrates, 2011 (individuals per m^2)

	Substrate and Depth				
Invertebrate taxa Water depth (cm)	Rock 10 to 20 cm	Pondweed 40 cm	Log 10 to 20 cm	Sedge 25 cm	Cattail 25 cm
Gammarus (shrimp)*		3			
Hyalella (shrimp)*				6	14
Diptera (true flies)	1				1
Chironomus (midges)				1	4
Gyrinidae (water beetles)*		5			1
Corixidae (water boatmen)		1			
Ephemeroptera (mayflies)		1			
Anisoptera (dragonflies)	5	10	1	16	15
Zygoptera (damselflies)	2	17		12	14
Hemiptera (true bugs)		1			1
Gastropoda (snails)*			12		
TOTAL	8	37	13	35	50

* Introduced

Supply a diversity of surfaces, and you will grow more diverse plant, microbe and benthic invertebrate communities

Biological Inoculation Strategy

We will not bring materials to inoculate a mine site from further away than 2 km and when possible, only from donor sites on the mine property.

1

Bacteria & Algae

Nutrient-rich mud from tailings ponds, periphyton from established ponds, and plankton transfers established *local* microbial communities.

2

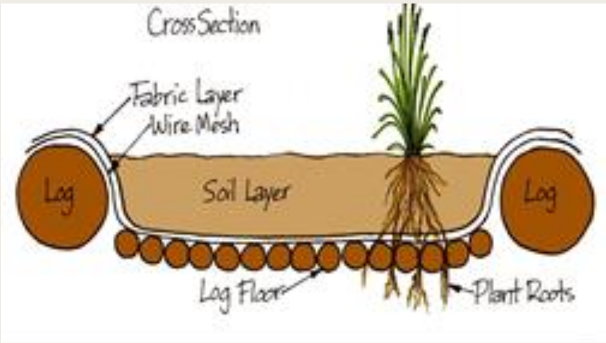
Macrophytes Introduction

Slender pondweed and aquatic buttercup successfully introduced to pit lakes using "plant sandwiches" – weighted wire cages enclosing rooted plant fragments.

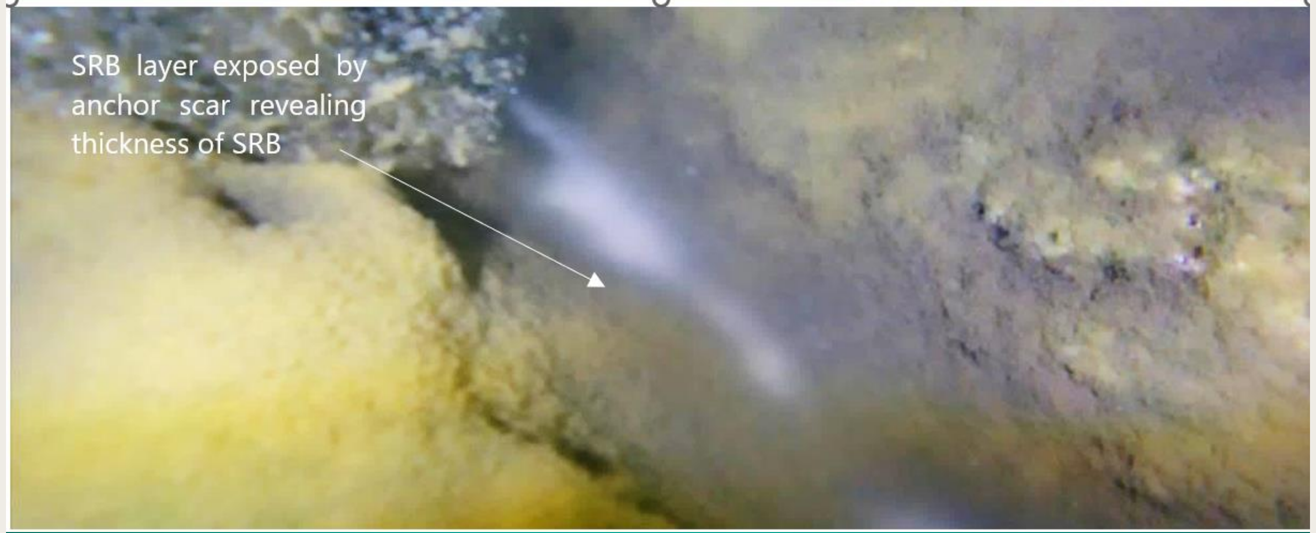
3

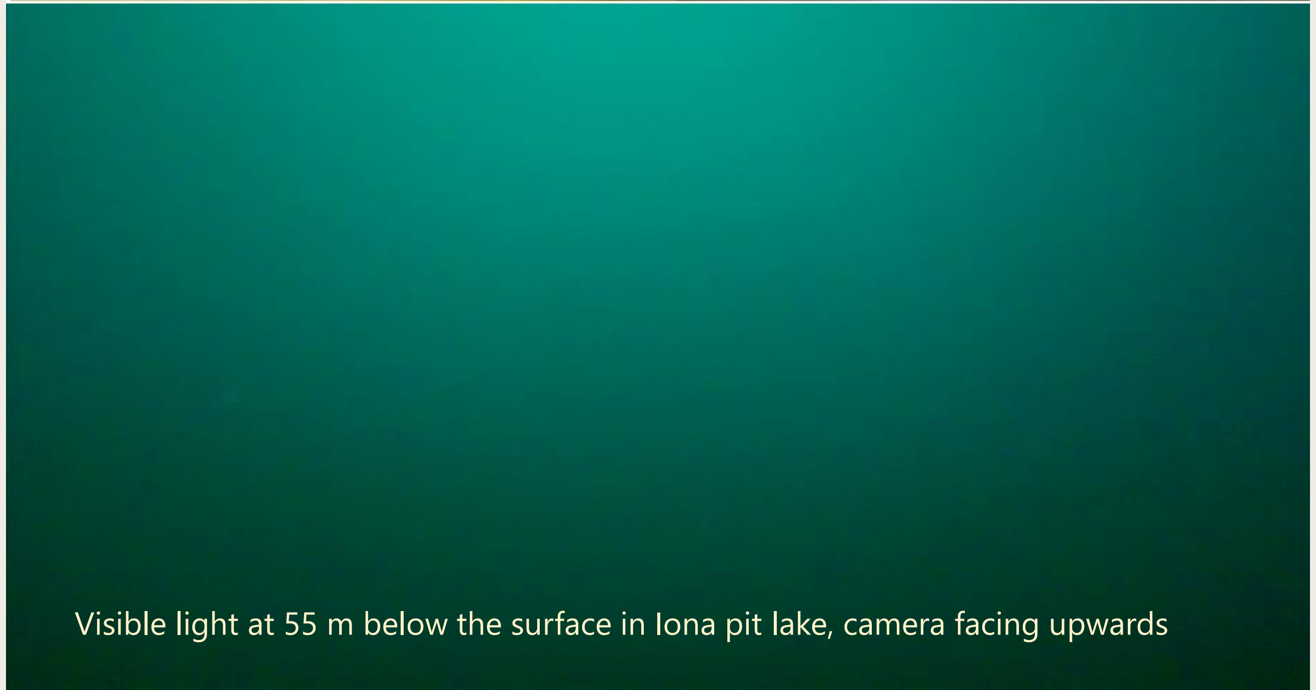
Bioislands Creation

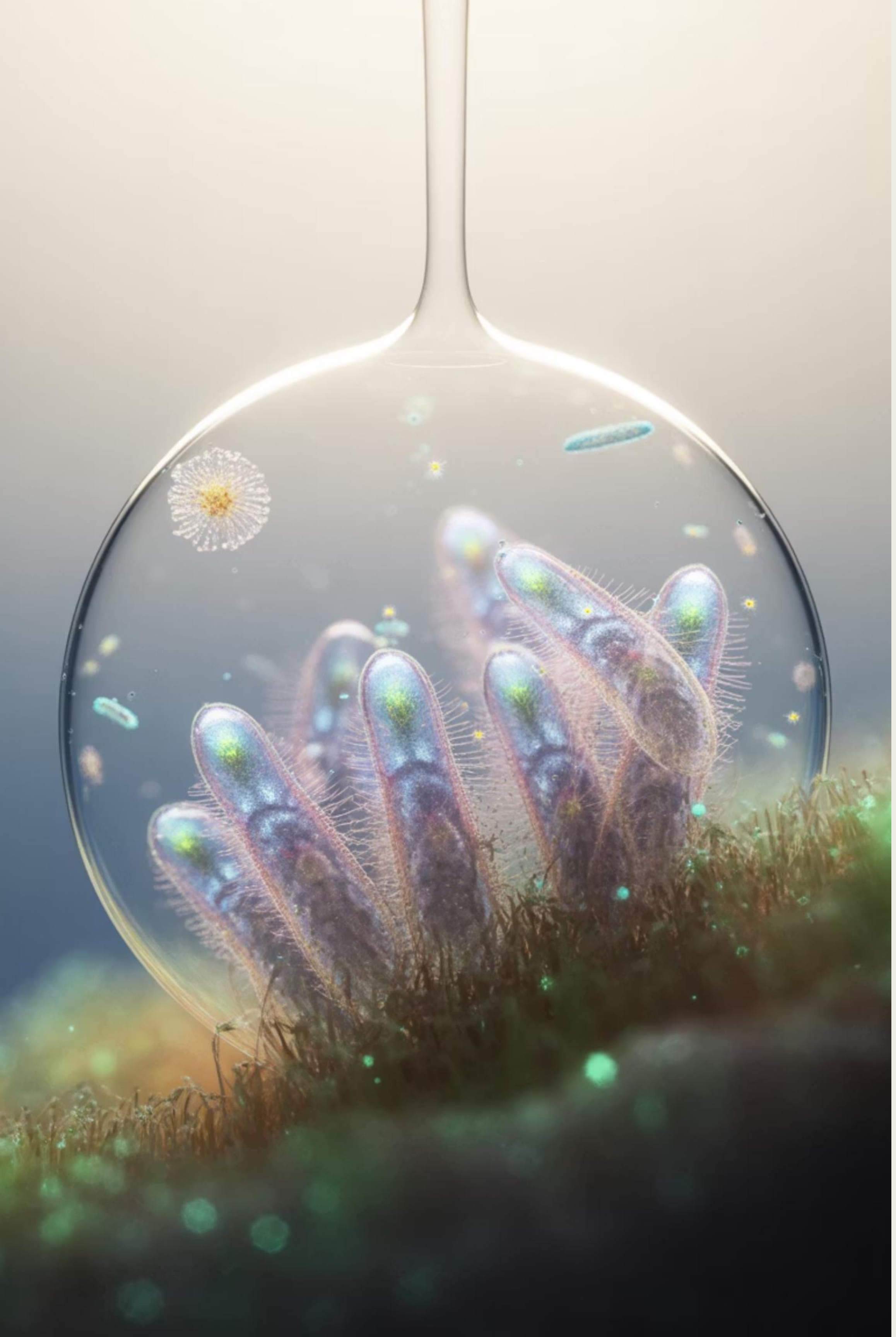
Floating islands with willow, rushes, and smartweed developed meter-long roots, creating massive surface areas for periphyton growth. The roots are sites of intense bio-remediation.



ROV images from the chemocline and the bottom of Bethlehem pit lakes







Introducing Secondary Consumers

Zooplankton and benthic invertebrates provide vital food sources for fish populations. You need permits if moving live invertebrates from off-property. Beware of aquatic invasives and Clean-Drain-Dry ALWAYS!!!!!

1

Soaked Hay Flakes

Brought from functional tailings pond ecosystem to introduce organisms including invertebrates.

2

Pond Sediment

Transferred from tailings seepage pond supporting existing fish populations to introduce bacteria, fungi, yeasts etc..

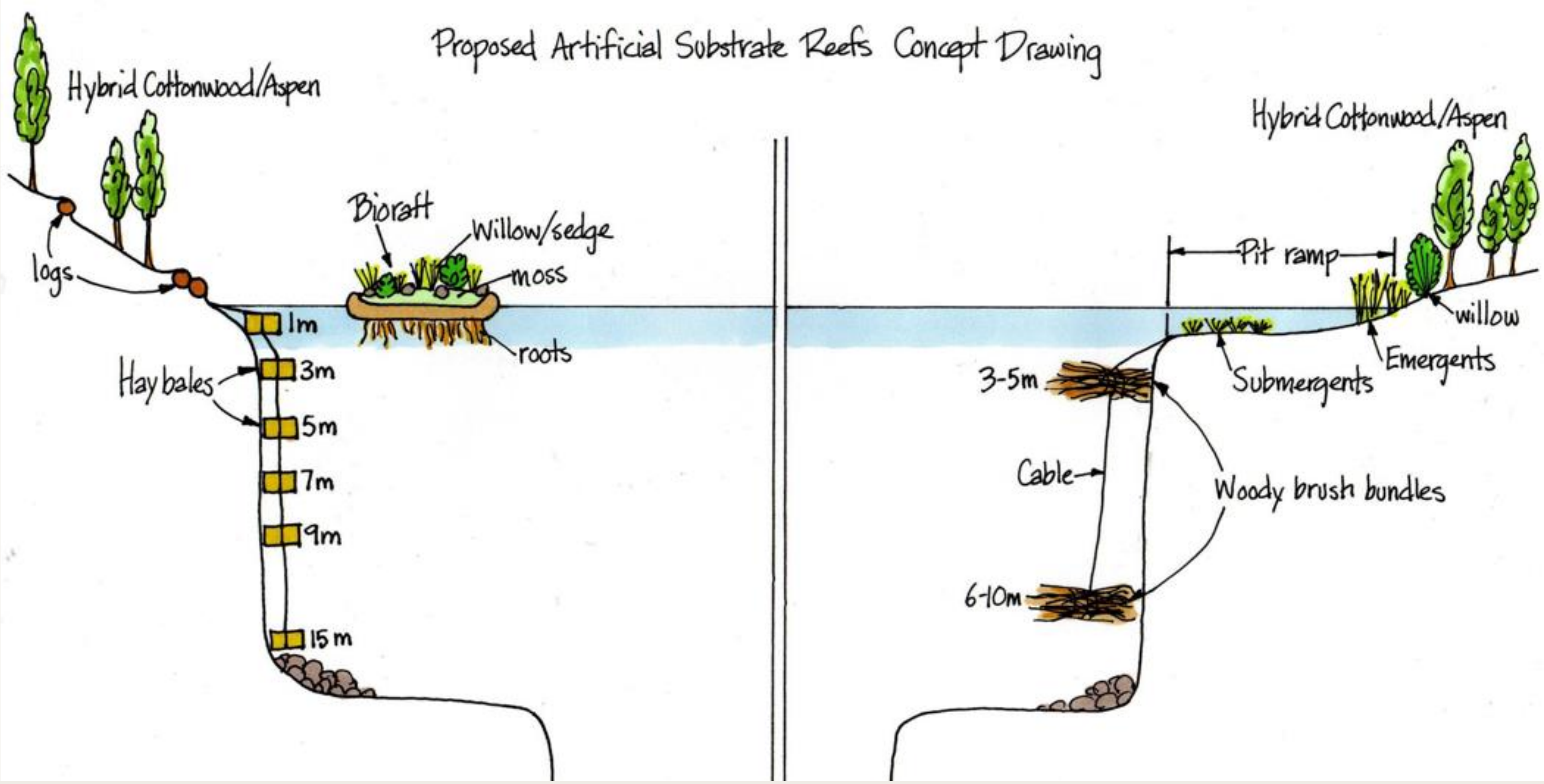
3

Filamentous Algae

Netted from nearby reservoir with established trophy fishery to introduce the algae (hopefully) and introduce invertebrates.

Biological function during pit filling important for **Closure Planning**.

- fertilizer + B vitamin supplements, regularly at first
- rely on phytoplankton and periphyton for carbon and adsorption surfaces for metals
- cannot rely on macrophytes and extensive shallows that will only happen intermittently when the rising water levels flood another bench, so use vertically-mobile biorafts and constructed reefs of wood bundles and hay bales



Pits can take decades, even centuries to fill so two options that allow the bioreactor to accommodate the steadily rising water level: (1) To construct a model reef, we installed a depth sequence of hay bales and woody brush bundles at 1, 5 and 10 m. Like all the other substrate trials, the sunlit surfaces grew most of the biomass. (2) For pit lakes with long filling times, constructed reef/bio-islands could help maintain productivity during pit filling when littoral zones are otherwise formed and lost to increasing water depth.

Huestis Pit Lake
Metal Removal Performance

6-30%

Molybdenum Removal

Annual dissolved molybdenum removal during ice-off algae blooms

4-43%

Copper Removal

Annual dissolved copper removal through bioreactor processes

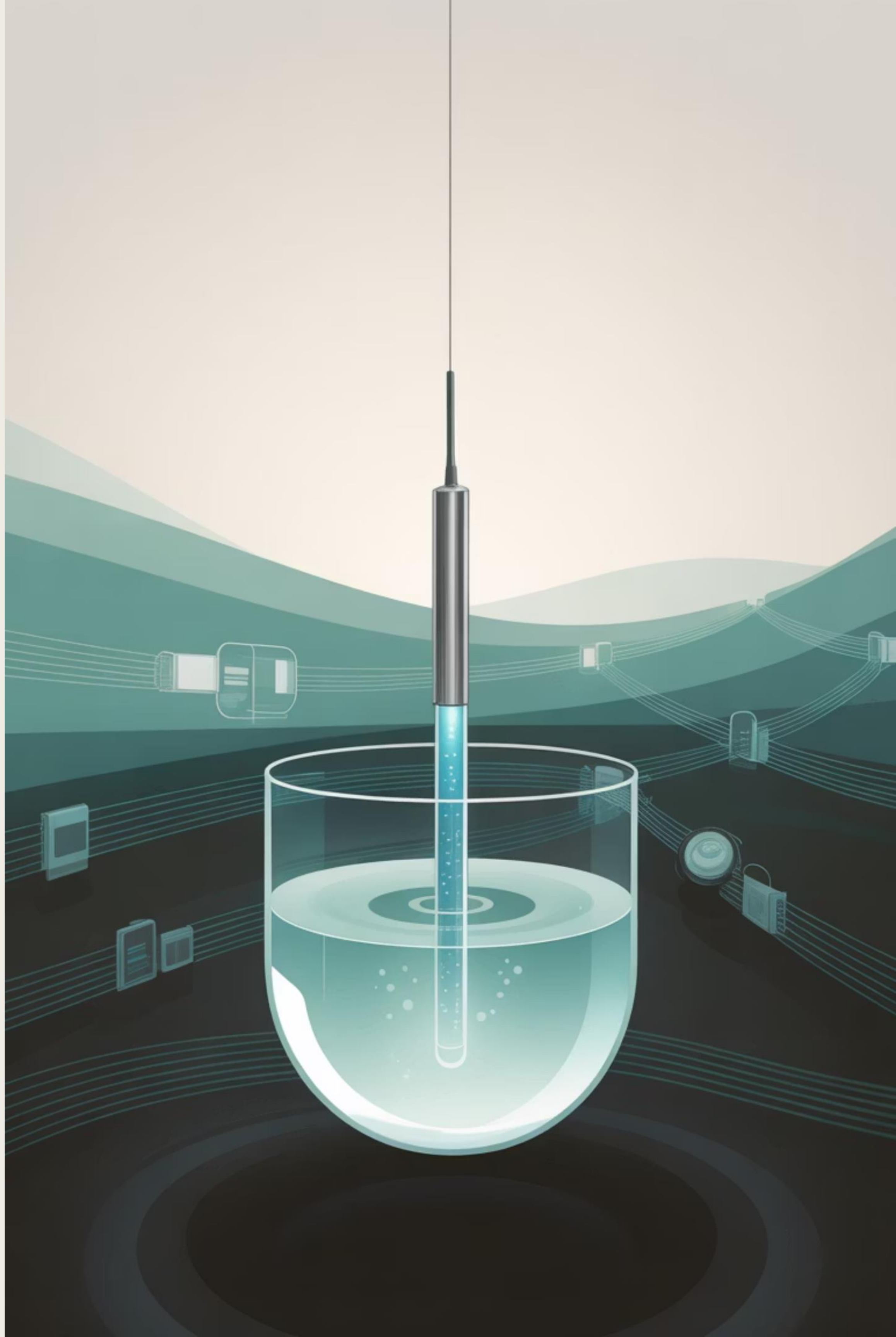
3

Years to Function

Time required for cost-effective bioreactor development

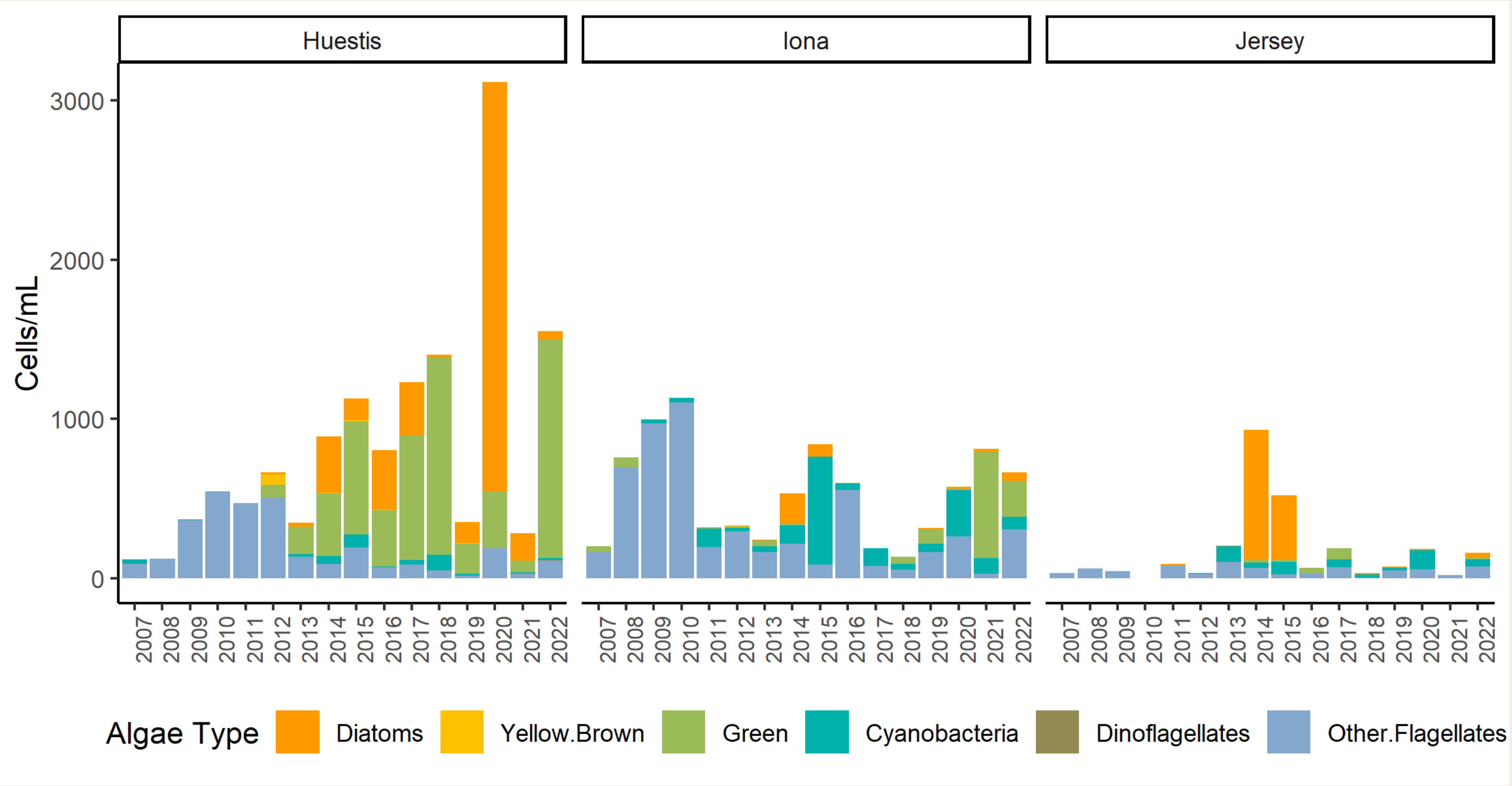
Total copper concentrations in Huestis surface and 10 m samples fell below the hardness-based aquatic life guideline after 2013 (<15 years).

Seasonal removal of dissolved copper in HVC pit lakes averaged 11 ± 14% at Huestis and 6.4 ± 22% at Iona compared to no net removal at the control pit lake.
Seasonal removal of dissolved molybdenum in HVC pit lakes averaged 26 ± 41% at Huestis and 3.7 ± 8.6% at Iona with no net removal at Jersey pit lake.



Long-term Success Indicators

Ecosystem Resilience



SHALLOW (20 M) DEEP (60 M) CONTROL

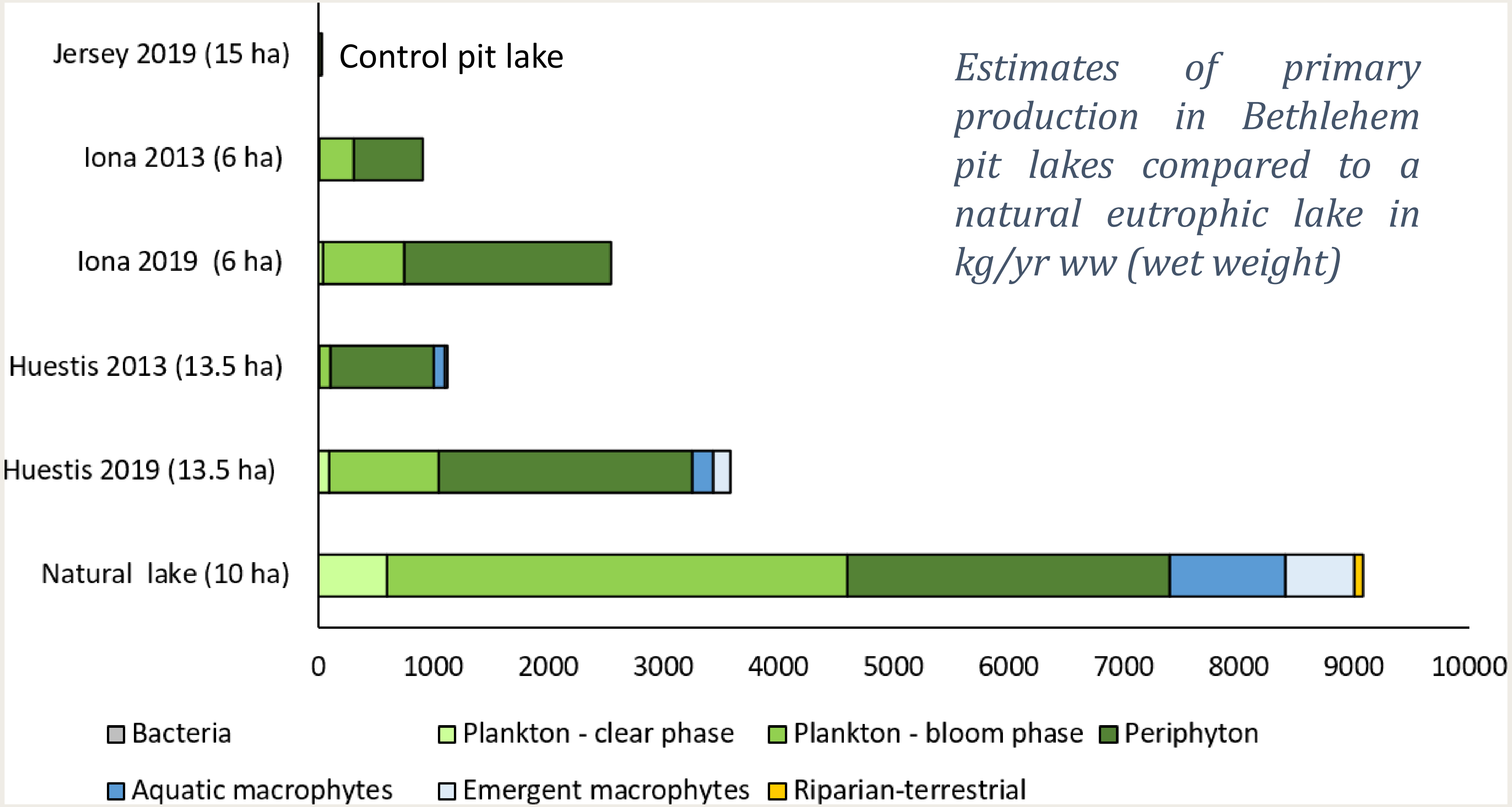
- The longer pit lakes were fertilized, the more resilient their bioreactor functions became through established periphyton communities:
- Over time (1 decade), the relapse when fertilizing was suspended diminished and slowed.
- Over time (1 decade), primary productivity and diversity increased.
- Over time (2+ decades), productivity approached that of a local, natural lake.

You can see the shifts towards complexity in the treated Huestis and Iona pit lakes and the differences between the algae groups shown here:

Long-term Success Indicators

Periphyton layers were able to generate sufficient B vitamins to supply annual ice-off blooms in Huestis (20 m) and Iona pit (60 m) lakes after 3 and 10 years, respectively.

Approximate primary productivity in the pit lakes is compared to productivity in a nearby natural eutrophic lake in the Figure below.



Estimates of primary production in Bethlehem pit lakes compared to a natural eutrophic lake in kg/yr ww (wet weight)

Biomass estimates indicated that periphyton coating the rock walls was the mainstay of Bethlehem primary productivity. Periphyton produced 65 to 90% of biomass, while phytoplankton produced 9 to 20% of total primary production, However, they performed different and complementary roles

Pit lakes can seldom catch up with their natural counterparts when it comes to the shoreline (blue) and riparian (orange) productivity provided to natural lakes.

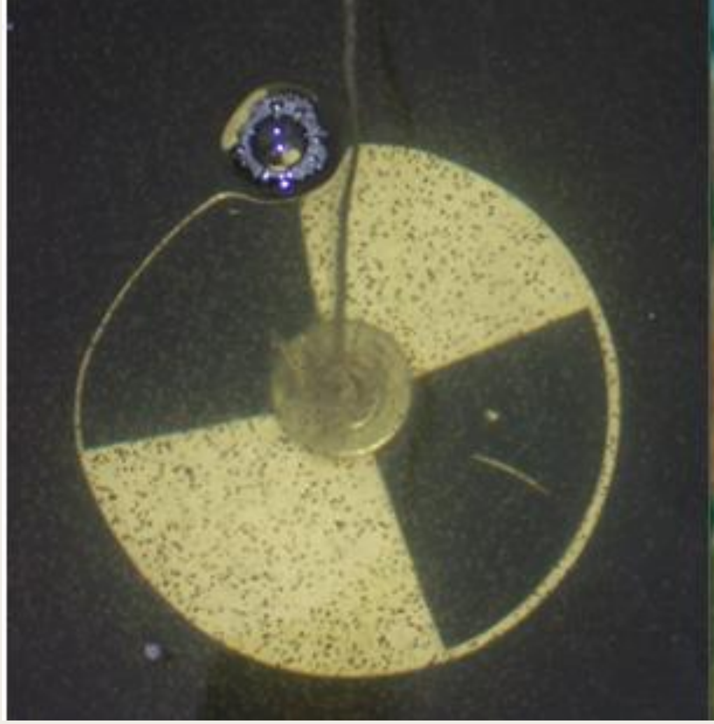
Zooplankton Success Indicators

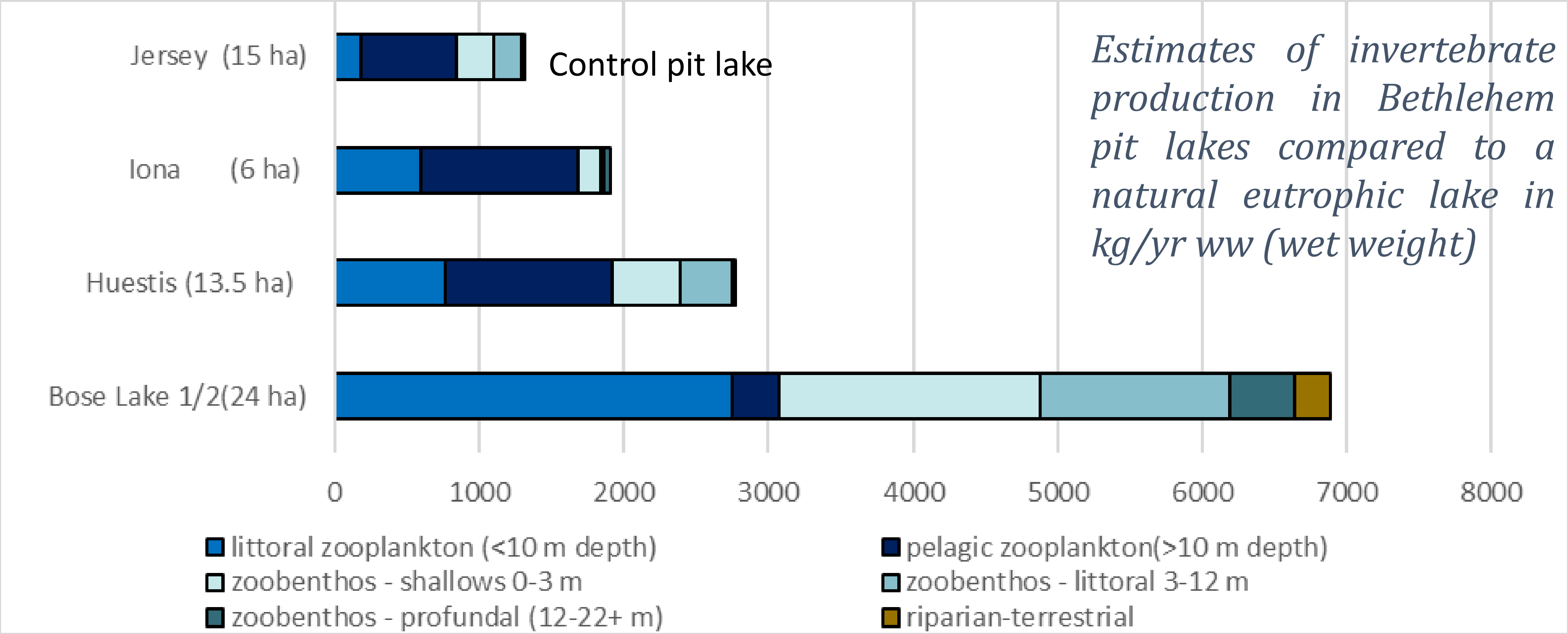
Population Growth

- Chironomids common within three years
- Daphnia dominated plankton samples
- Strong copepod growth in aerator plumes and along surfaces with periphyton

Distribution Patterns

Zooplankton congregated above sediments shallower than 20 m, forming visible hazes over rock benches and plant beds.

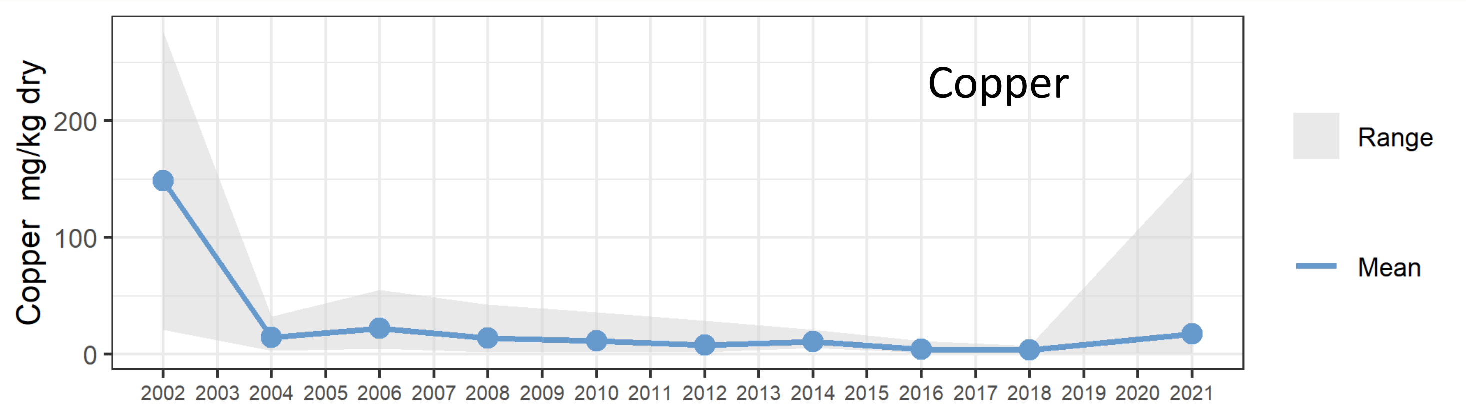


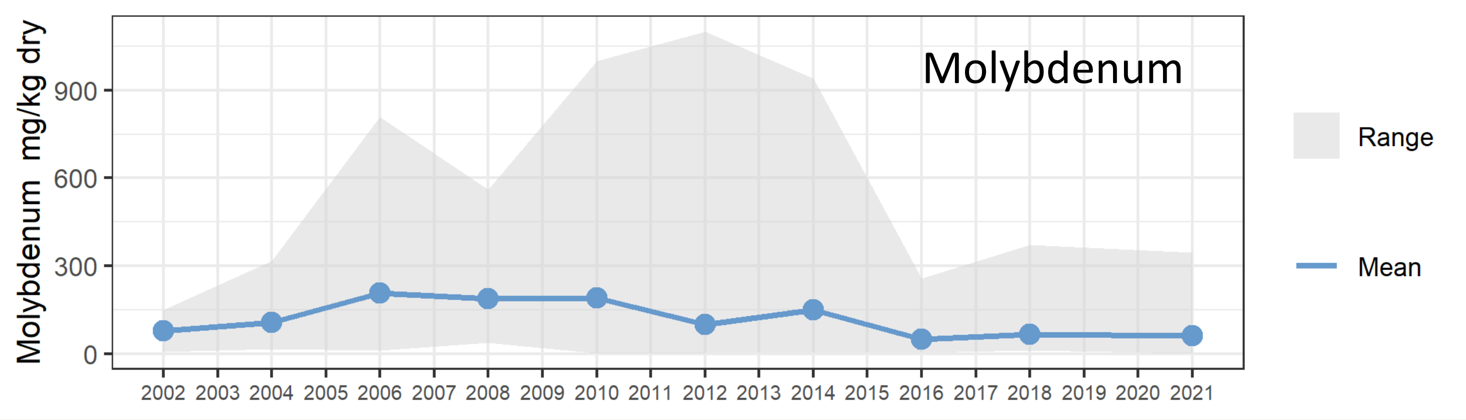


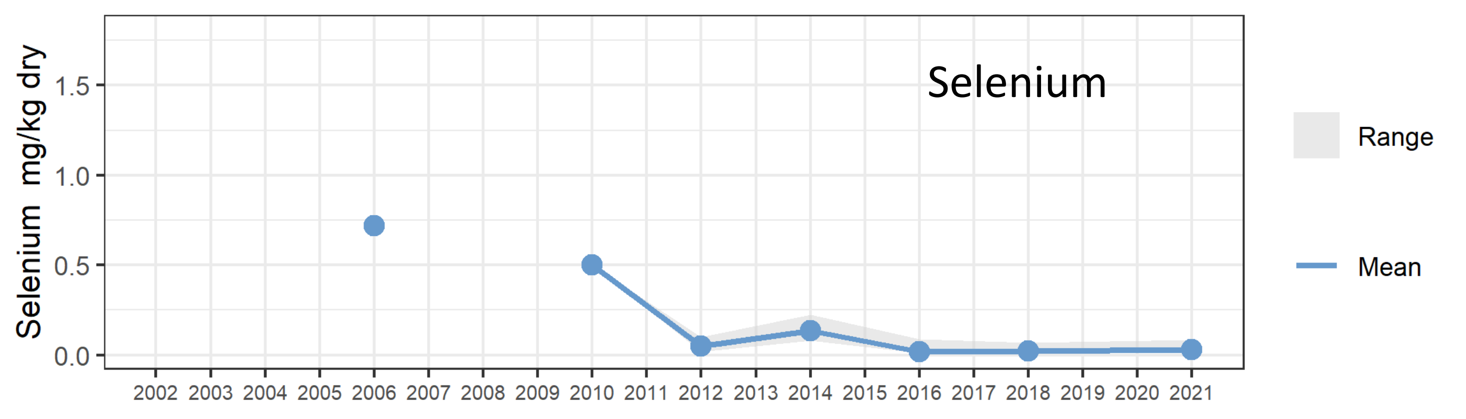
The secondary productivity shown here is similar to the primary productivity illustrated in the last slide.

Huestis got close to the natural lake production in 2024! As you saw in the videos, we made zooplankton heaven in the pit lakes.

Riparian plant tissues over time:







In terms of aquatic food chains, when we checked all the trophic levels there was no evidence of biomagnification through the trophic levels for Cu or Mo. Similarly, riparian plant tissues showed stable or declining metal concentrations Cu Mo Se mg/kg dry means over two decades.

Risk of limnic eruption (spontaneous degassing)?
Very Low Risk.

Table 1: Chemistry results for dissolved gas samples from Huestis Pit Lake during 2023

Analyte	Units	2023-05-18	2023-05-18 (duplicate)	2023-08-30
Hydrogen Sulfide, total	mg/L	<0.01	0.03	<0.01
Methane	µg/L	<0.01	<0.01	<4.00
Temperature, field	°C	3.9	3.9	4.9

1 m above bottom water samples

Figure 3: Photograph comparing colour of water samples from Hu

Samples were collected from Huestis pit lake bottom water shortly after ice-off and mid-summer. Sampling dates were chosen to coincide with the end of the winter stratified period and the peak of the summer stratified period when gas accumulation within the hypolimnion was expected to be greatest. The results were encouraging with relatively low concentrations of hydrogen sulfide, ranging from below detection to 0.03 mg/L. Methane was not detected during the sampling. Carbon dioxide is another gas of concern but can only be sampled in-situ using a specialized meter that could not be sourced for this study.

Like all lakes, pit lakes are active, changing and important regulators of the greenhouse gasses: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

CARBON

Pit lakes, like other bodies of water, consume atmospheric carbon dioxide

And store it in:

(1) biomass,

(2) carbon accumulatios on anoxic sediments

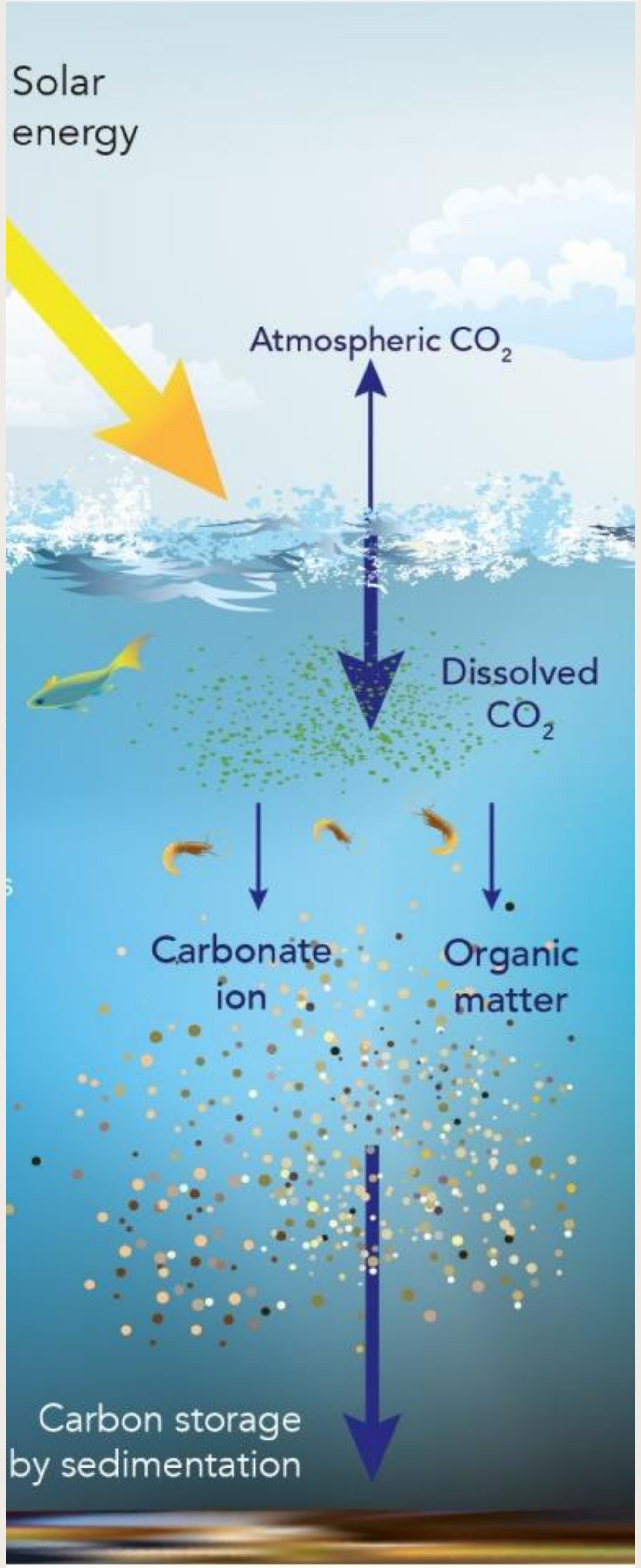
(3) Sulphate suppression of methanogen bacteria

(4) marl – mainly calcite precipitation $CaCO_3$ that locks away carbon in non-mixing layers. Marling is triggered by warm water, high pH and phytoplankton algae.

The best carbon sinks would be deep productive non-mixing lakes with short ice cover in winter PIT LAKES SHOULD BE GOOD

Carbon trading?? Another income stream?

In the global carbon cycle, lakes, reservoirs and wetlands are hot spots of carbon cycling and important players in the global carbon cycle. They absorb large amounts of carbon from their watersheds.
Methane has 27x the GHG warming potential of CO_2 and N_2O has 273x the warming potential of CO_2
Marl or CaCO3 can also lock away carbon – unusual compound though, it dissolves more readily in cold water than warm.



Biological carbon pump

NITROGEN

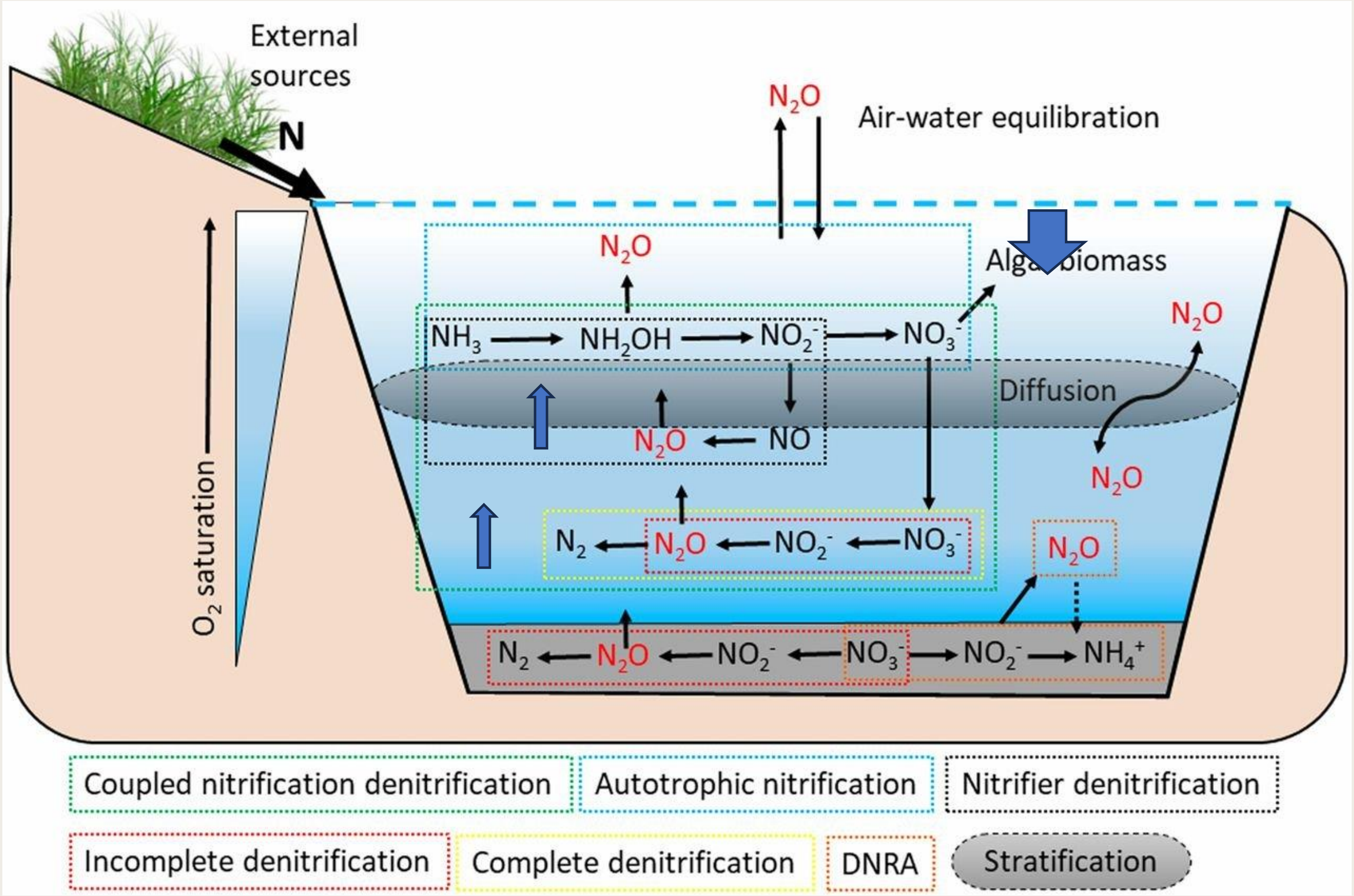
Lakes and other freshwater resources are also sources of nitrous oxide (N_2O) cycling, a potent greenhouse gas that is produced in warm lakes by bacteria and other microbes.

Shallow lake sediments contribute most to N_2O emissions, compared with round, deep lakes = pit lakes (Wang et al 2023).

The lowest N_2O emissions from N- enriched reservoirs occurred under strong water column stability and high algal biomass production (Webb et al. 2019).

Pit lakes should be fine*

*DISCLAIMER: The fate of nitrogen in pit lakes is influenced by elevated nitrogen (nitrate nitrite ammonia) concentrations, organic matter, redox conditions, and the presence of nitrifier/denitrifier/DNRA microbial communities.



Conceptual diagram of potential N_2O processes and pathways in N-enriched reservoirs

The known physical and microbial processes that influence N_2O concentrations are depicted by solid arrow lines. The dashed arrow line indicates the potential for N_2O uptake via DNRA bacteria, although evidence is limited (after Webb et al. 2019).
DNRA= dissimilatory nitrate reduction to ammonium

SUMMARY most pit lakes will trap C and lower GHG emissions:
Warm (Shallow) lakes are important sources of nitrous oxide (N_2O) produced by bacteria and other microbes. Shallow lake sediments contribute most to N_2O emissions.
Lake shape can be an important predictor of N_2O release, as shallow lakes with expansive shorelines can release more N_2O compared with round deep lakes (AKA pit lakes).
As you may have noticed, biologists have this irritating habit of qualifying every statement with “well…. That depends….” – because it does!

Lessons Learned: Challenges

Equipment Failures

Failed to plan backup equipment/budget for inevitable pump and transformer failures.

Wildlife Damage

Underestimated browse and trampling damage from deer and feral horses on riparian plantings.

It All Takes Time (or lots of money)

Development of the key anoxic conditions is slow using the inexpensive grown-in-place algae approach.

Water Level Changes

Permanent water level changes, or oscillating water levels affect ecosystem function.

Secret Sauce for HVC Pit Lake Development:

Determine baseline

Assess existing limnology constraints, water quality, and phytoplankton, periphyton, zooplankton, benthic invertebrates, aquatic macrophyte populations.

Establish goals with stakeholders. Start planning for donations from local sites.

1

Make water chemistry desirable for microbes

Locate the limiting factor(s) and provide them.

Start with P and $B_{vitamin}$ to maintain algae blooms.

2

Build the pit lake ecosystem from the bottom up

Introduce microbes in trophic order: sediment consortia, photosynthetic bacteria, periphyton, and phytoplankton, *then* benthic invertebrates (local!).

3 Plan for economically sustainable long term data sets

Watch for meromixis

Help build meromixis or disrupt it according to end-use goals:

maintain it to build anoxia in deep water for a bioreactor;

disrupt it to keep nutrient, vitamin, oxygen circulation going for a fishery.

4

Periodically supplement limiting nutrients & diversify substrates

Add nutrients and B-vitamins to maintain phytoplankton in-situ biomass production.

Install biorafts especially during filling of large pits.

5

Assess and adapt

Build datasets, assess them and review progress towards goals, *then* pivot based on results.

Continually assess opportunities for economic returns from pit lake after mine closure.

6

From Liability to Asset

More than just a pretty water feature

Cost-Effective Solution

Bioreactor functions achieved within three years without large capital investments or ongoing maintenance costs.

Global Applications

Techniques developed at Bethlehem pits can be applied to many basic pit lakes, transferring them from liabilities into ecological assets.

Contribute to End Land-use Plans

Remediated pit lakes provide passive water treatment, habitat and water storage to help meet end-use objectives.

WE GOT OUR RECIPE; Pit lake research at HVC developed techniques for generating bioreactor functions and enhancing primary productivity that can be applied to the larger pit lakes that will form after HVC closure, and to other pit lakes globally. Bethlehem pit lakes began providing the bioreactor services of natural lakes within three years of reclamation without large capital investments or maintenance costs. Remediated pit lakes can become assets.

HVC - A model for (basic) pit lake reclamation

The HVC Bethlehem pit lake research projects prove that thoughtful ecosystem development can be inexpensive, "fast" and effective.

Sustainable Potential

Viable long-term aquatic ecosystems and bioreactor ✓

Community Benefits

Water storage without a dam for flood/drought assistance ?

Potential Economic Value

Offset mine closure costs ?

Too much potential value to ignore! ✓


Final Video. I’ll let the water have the final word.