Overcoming Low Productivity of Pit Lakes used as Bioreactors and Fisheries at Highland Valley Copper, BC.

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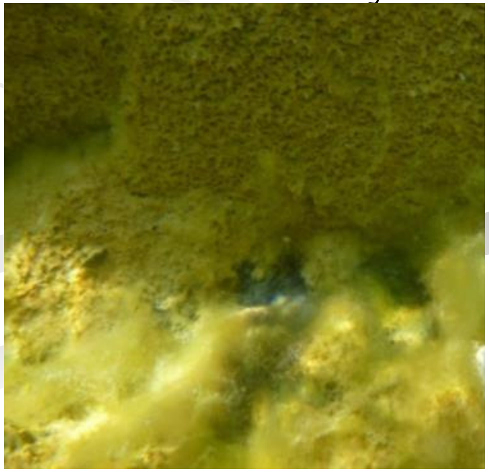
Presentation Outline

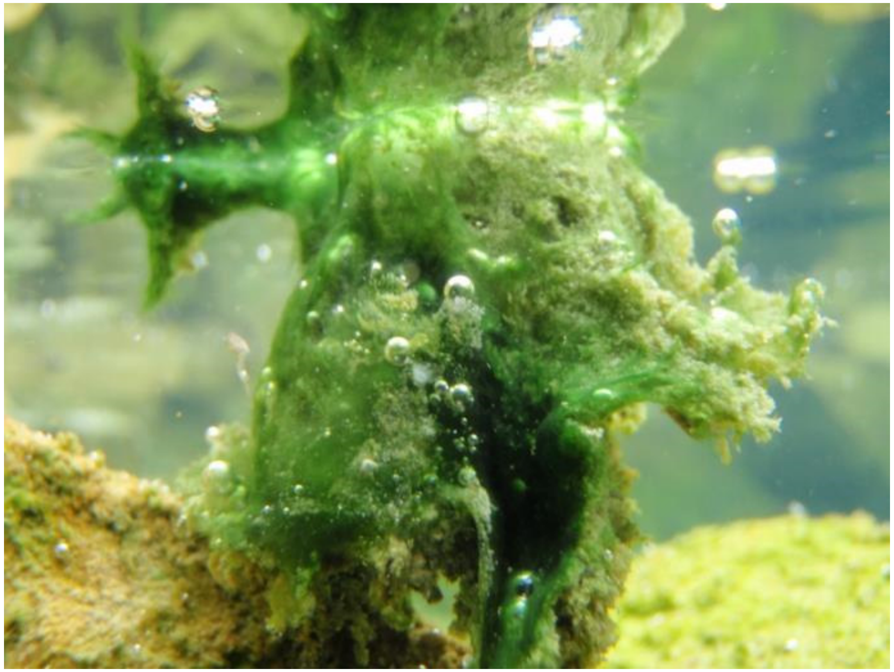
- Two goals for pit lake reclamation at HVC
- What's wrong with pit lakes?
- Inner workings of a pit lake
- Missing factor
- Research for conversion to bioreactor + fishery
- Solutions and techniques
- Can you ever walk away?



2 complementary goals of HVC pit lake reclamation

- Bioreactor

- Fishery
- Replace a lake

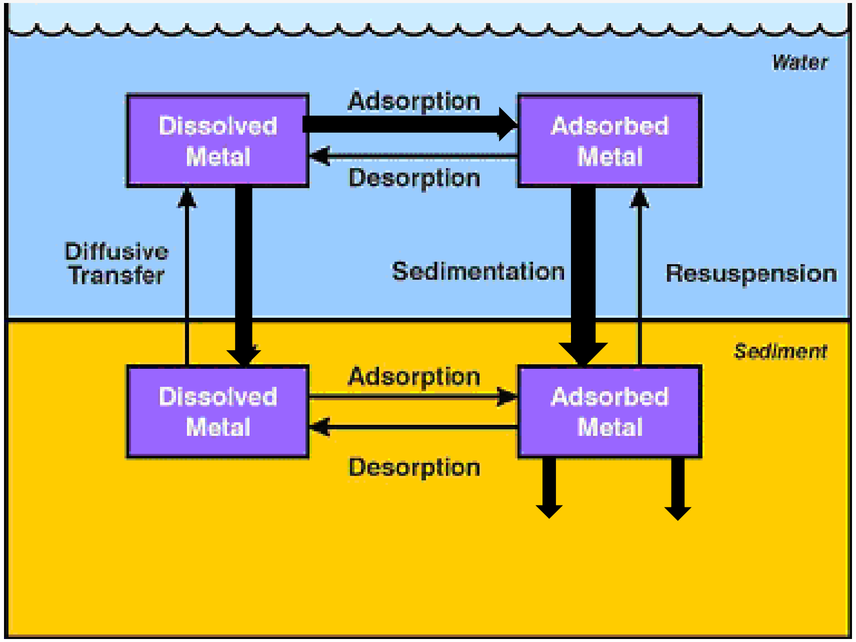


(I hope to convince you that green goo is a thing of rare beauty)

The fishermen's law of pit lake reclamation as fishery habitat:

3 x 3 lb fish ≠ 1 x 9lb fish

Metal removal in natural and pit lake waters:



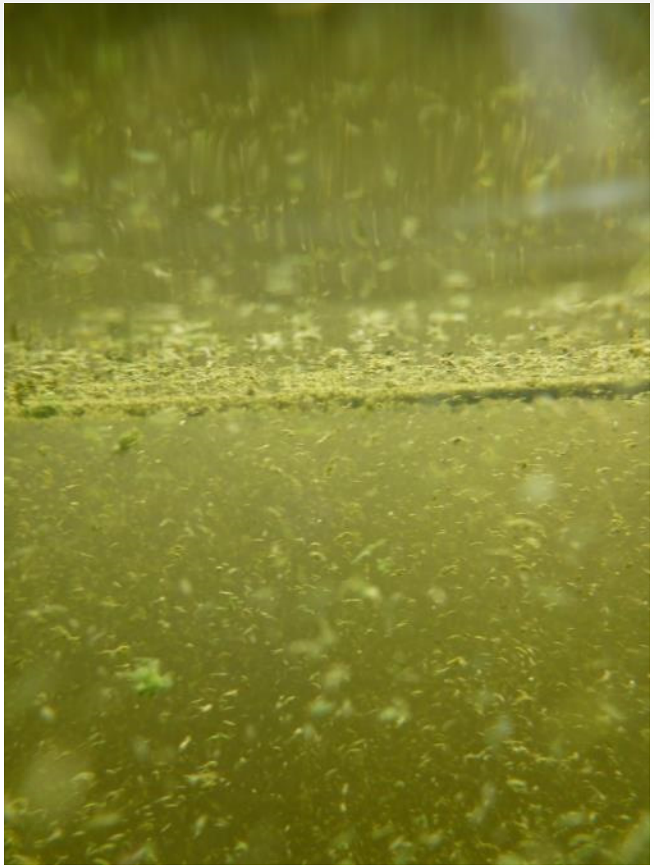
Type of Particle	Role in Metal Removal
Phytoplankton	-Many algal surfaces have affinity for heavy metals such as Cu(II) Pb(II) Zn(II) Cd(II) Ni(II) via surface complex formation. -Microflora absorb nutrient metals such as Cu(I) Zn(II) Co(II) and metal ions mistaken as nutrients such as Cd(II) and As(V). - aging microflora mineralizes and sediments
Biological debris	-metals adsorb to negatively charged organic particle surfaces esp .–COOH -NH_3 -OH groups -metals also attach to cation/anion ligands already attached to the surface of the particles
$CaCO_3$	- Heavy metals and phosphates are adsorbed as calcium carbonate crystals grow. Their large size and therefore small surface area limits the amount of metal $CaCO_3$ co-precipitates.
Fe(III) hydroxides and oxides	-pH dependent, ferric hydroxides/oxides have a strong affinity for heavy metals, phosphates, silicates and oxyanions of As Se Fe(III) oxides -even if ferric hydroxides/oxides are present in small proportions they can exert significant removal of trace metals -at an oxic/anoxic boundary, Fe(III) can represent a large part of settling particles
Mn(III,IV) oxides	-pH & redox-dependent, manganese oxides have a high affinity for metals and high specific surface area and is usually important in regulating trace metals in the lower portions of lakes and sediments
Aluminum Silicates Clays, oxides	-Ion exchange, binding of phosphates and metal ions (usually minor)

Freshwater Microfloral Surfaces and Exudates that Adsorb Aqueous Metal Ions

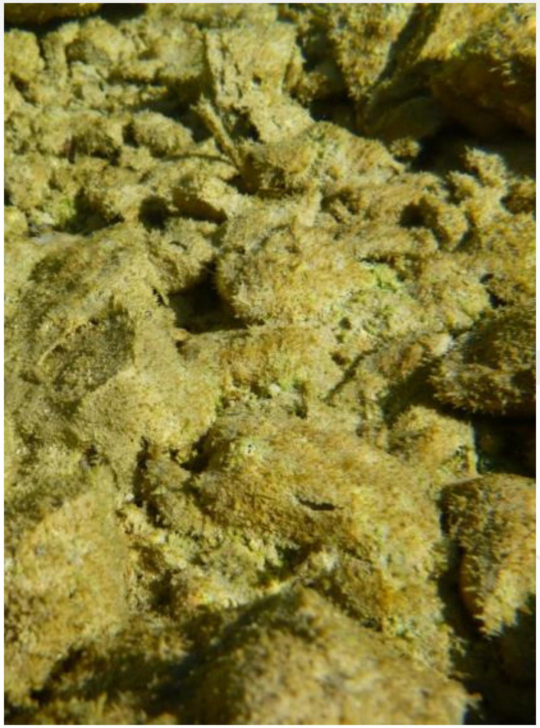
- Gram +ve bacteria   Lipid sheath
- Gram –ve bacteria   Peptidoglycan cell walls
- Cyanobacteria Mucilage sheath in filamentous types, excrete complex protein-based toxins
- Euglenoid algae Mucous coatings
- Chrysophyte algae External gelatinous matrix
- Diatom algae Frustules (shells) made of silica dioxide, excrete organic molecules
- Desmid algae Silicate surfaces, some species form calcareous coatings as well
- Dinoflagellates Cellulose walls
- Cryptomonad algae Periplast protein coat with mucous

Goal = Grown-in-place biological amendments (comes in two styles)

Plankton blooms

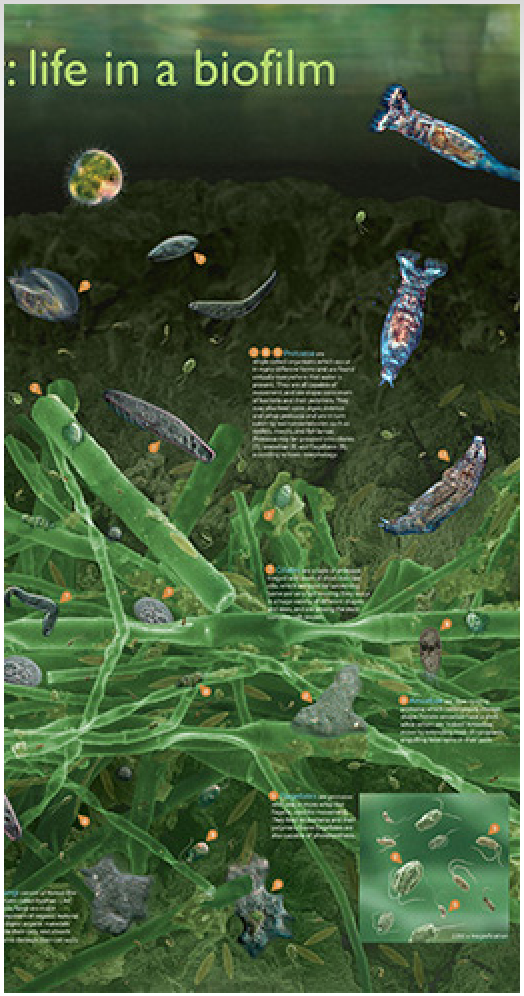


Periphyton



Periphyton biofilms are complex and amazing

- Structure of biofilm



invertebrates (fish food)

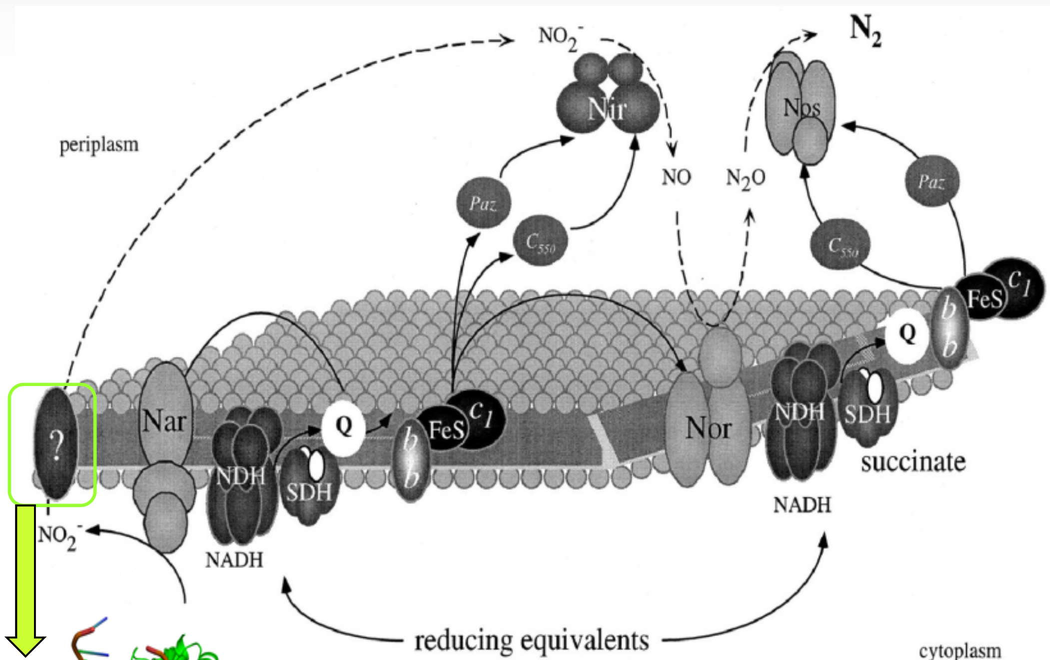
zooplankton (fish food)

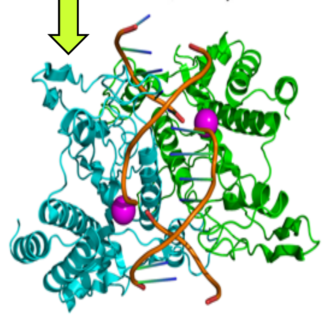
algae

cyanobacteria

bacteria

- Bacteria mediate otherwise impossible chemical reactions with enzymes





, Ludwig, B., Page, M.D., Richter, O.-M.H., van Spanning, R.J.M.:
enus Paracoccus: Metabolically versatile bacteria with bioenergetic flexibility
998, 62, 1046-1078.

What's wrong with a pit lake?

Crater Lake Pit Lake

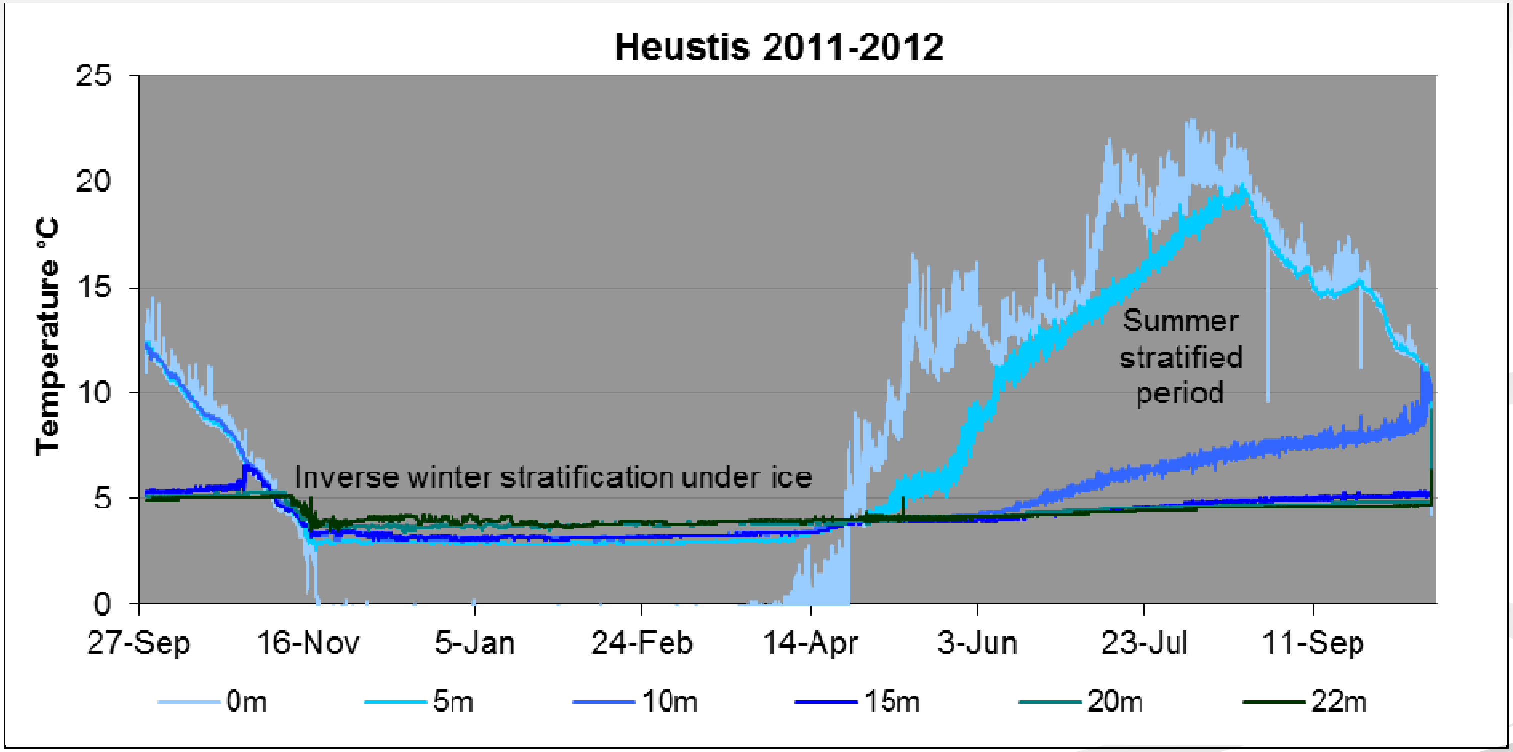
Both lakes naturally have crystal-clear water

What are the limitations on crater and pit lake productivity?

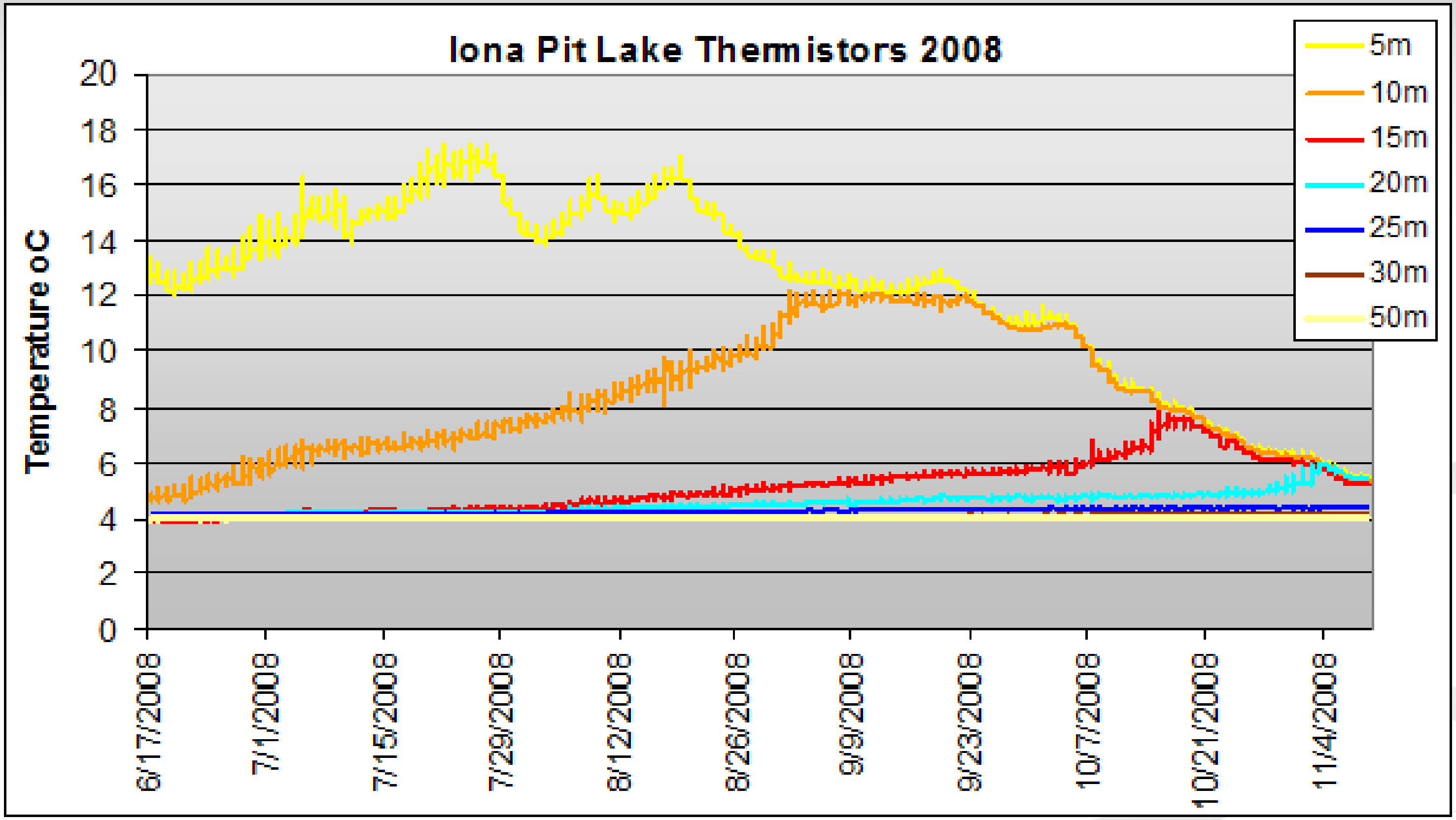
- Major (e.g. N P C Si) and/or minor (e.g. Fe Mn Cu S) nutrient limitations
- Limited substrate-water column interaction due to basin shape
- Limited shoreline for recuitment of benthic/planktonic microflora and growth of rooted aquatic macrophytes
- Lack of turbulence for nutrient upwelling, cell suspension
- Homogenous environment compared to natural lakes thus a restricted potential species pool.

Inside a pit lake

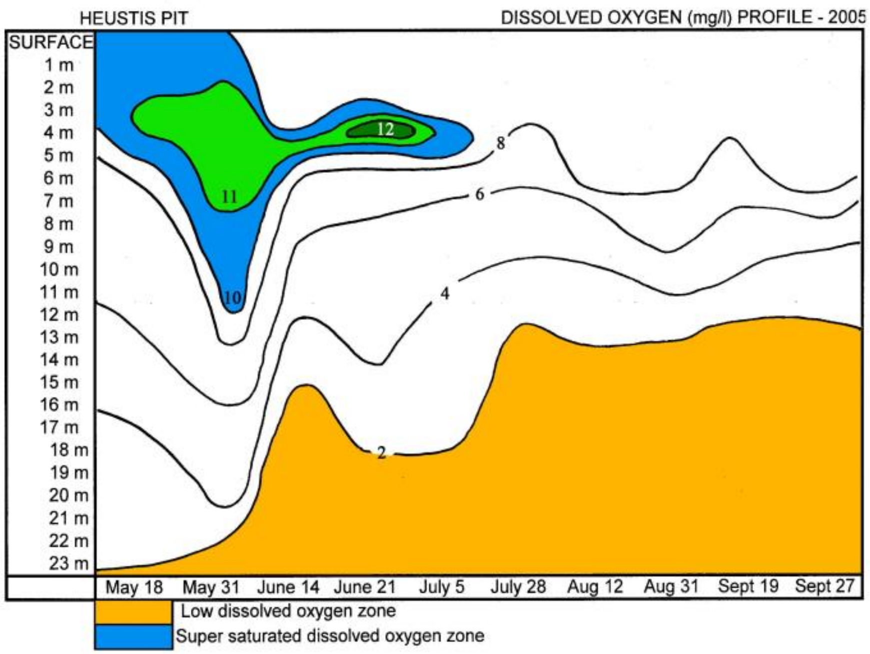
Inner workings: Thermal behavior – shallow <50 m pit lake

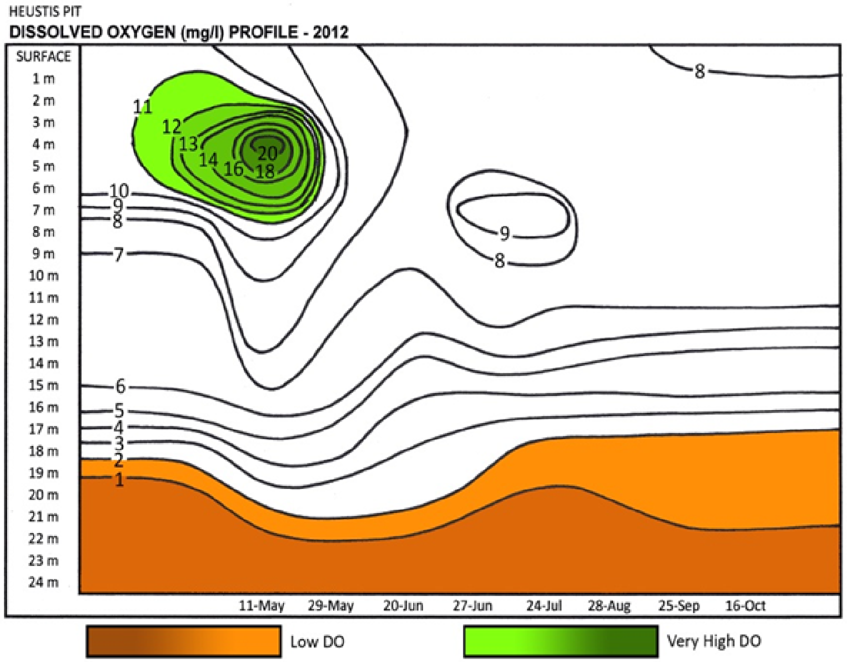


Thermal behavior – deep >50 m pit lake

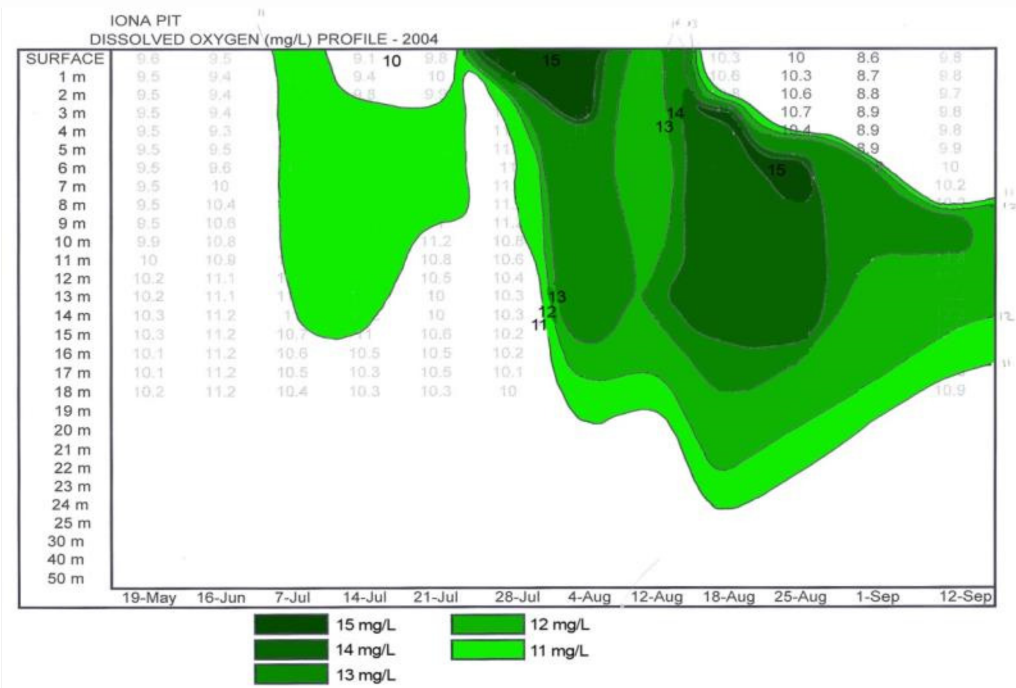


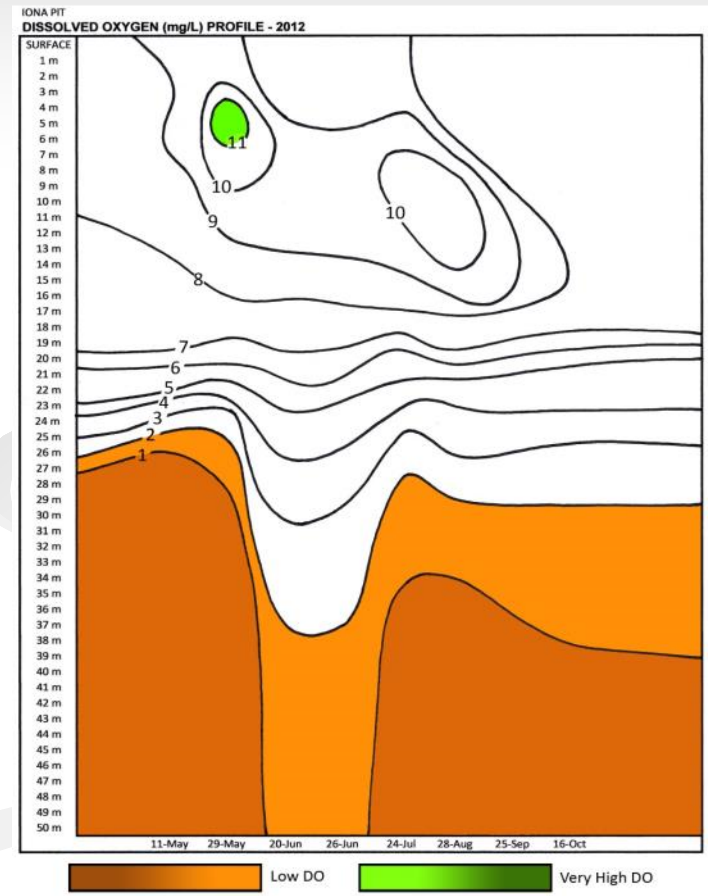
Dissolved oxygen
– shallow pit lake
(year 5 vs year 12, fertilized most years)



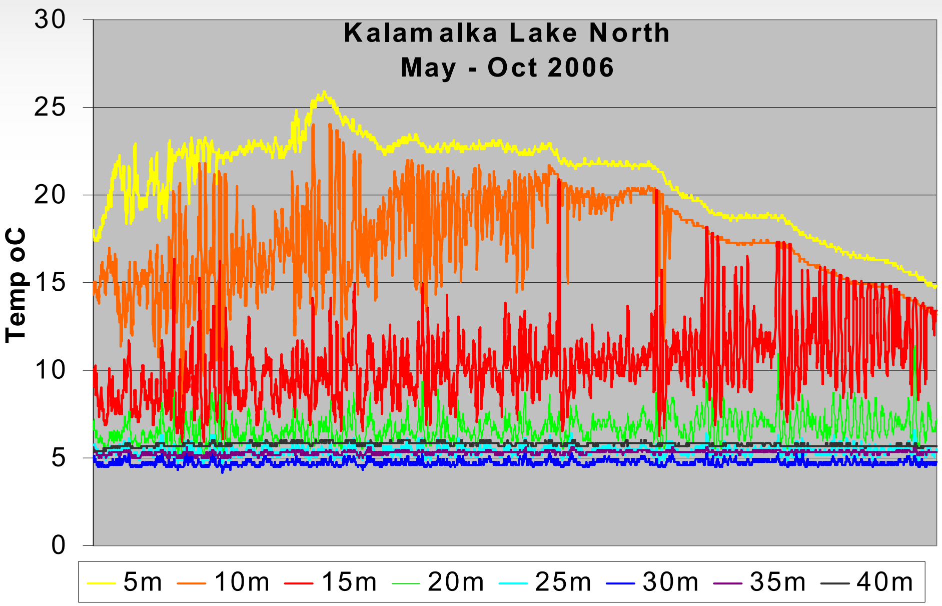


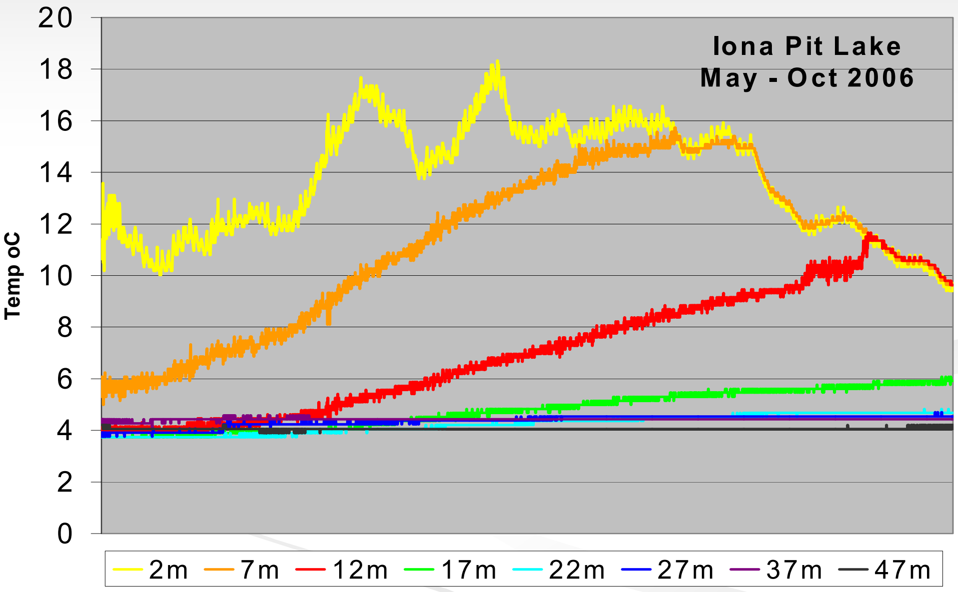
Dissolved Oxygen
– deep pit lake
(year 1 fertilized vs year 8 not fertilized)





Turbulence and seiches show as jogs in the 5 – 25 m lines





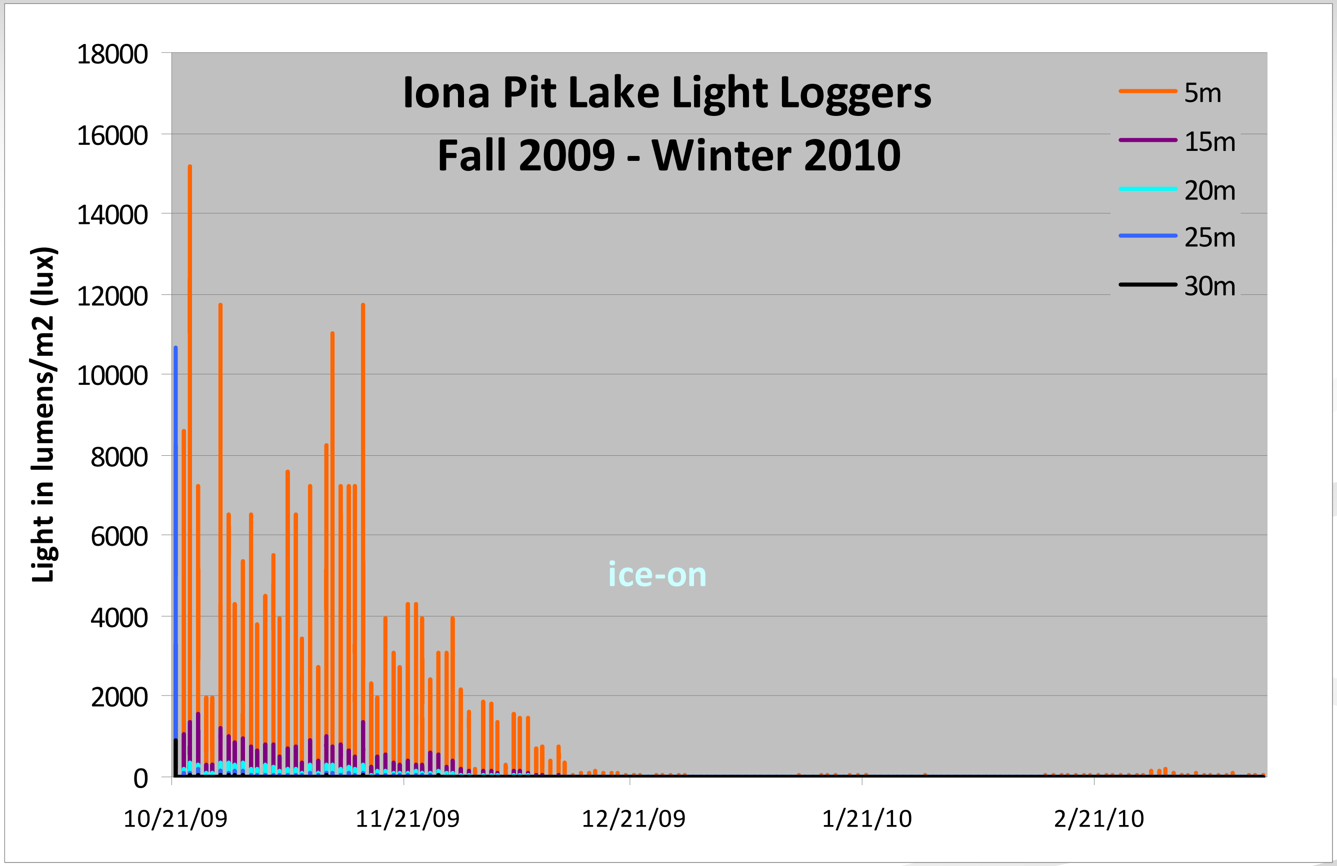
Surface water is transported down with ice melt thermals and with sediment density plumes; upwelling is restricted

Sporadic mixing of surface water into deep water can occur in a non-mixing pit via:

- **Fall Overturn Turbulence** During the fall overturn, turbulent energy fluxes penetrate deep into the hypolimnion, eroding the monimolimnion and potentially re-distributing water throughout the water column, which lowers the developing chemocline.
- **Ice Melt Thermals** In the spring, cold water from freshly melted ice is near the temperature of maximum density (4°C) and tends to sink, carrying dissolved oxygen and solutes with it.
- **Density Plumes** Density plumes of silt-laden rainwater are observed during storms Density plumes carry warmer surface water into deeper water.
- **Pit Wall Seepage** Groundwater seepage through the pit walls accumulates in a bottom pool. Groundwater seepage affects pit water chemistry directly or through dissolution from fines lining the pit benches. For seepage to be considered a significant influence, water chemistry in the deepest water should move toward the chemistry of local groundwater.

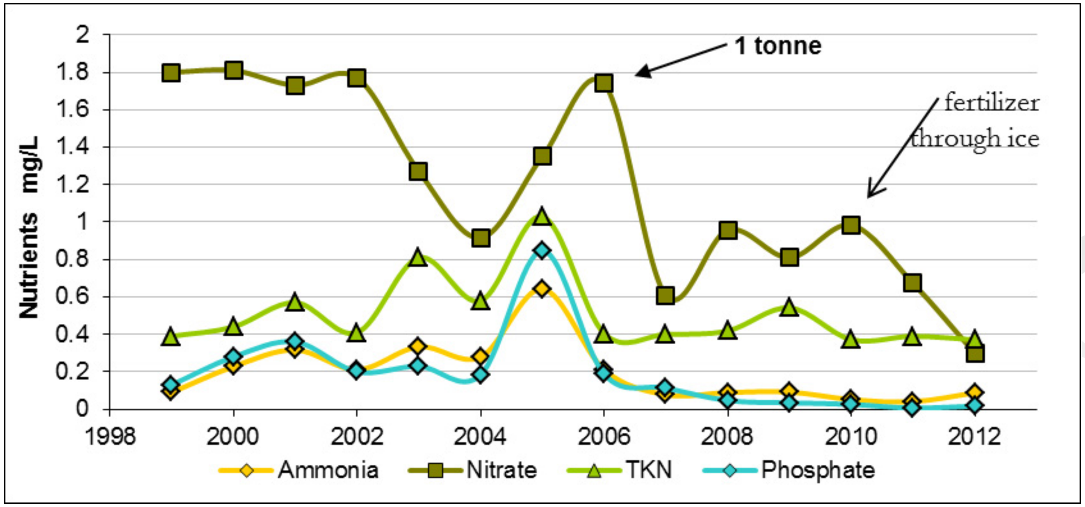
- **BUT RETURN OF DEEP WATER TO THE SURFACE IS RESTRICTED**

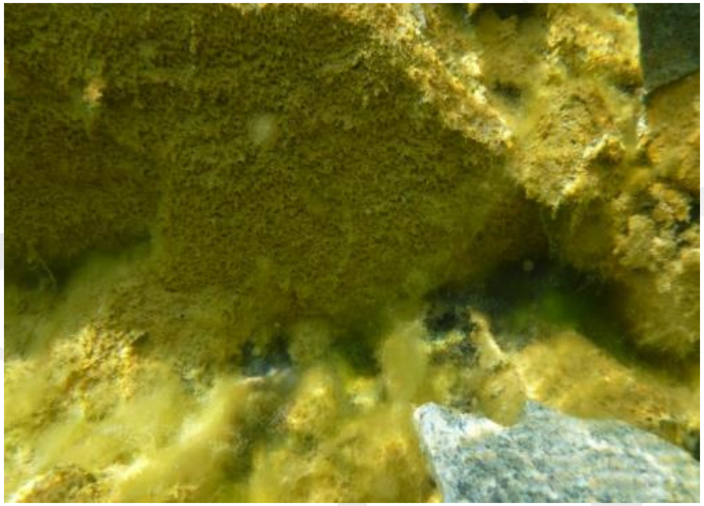
Loss of light with depth and season; photosynthesis ends at 30m and under ice



Let the reclamation begin!

HVC pit lakes reclamation has the same starting point as tailings ponds – develop them as fishery habitat and as bioreactors by adding the nutrient in short supply - P





Year 1 Iona algae bloom: but no more blooms after that, no matter how or in what proportions, the major nutrients (NPK) were added after year 1

What did we know about fertilizing pit lakes:

- Tailings ponds fertilized (liquid agrium N+P) to high nutrient levels have algae blooms while the same water in a pit lake is crystal clear
- Non-mixing deep HVC pit lakes bloom for one year *only*, no matter how or when additional nutrients are supplied, but if they are mixed by pumping, intense blooms result
- Shallow HVC pit lakes have ice-off algae blooms as soon as the ice comes off but the blooms stall during June despite luxuriant macro and micro nutrient supplies
- Periphyton growth is invariably excellent and grows on many surfaces after P is added, even when no phytoplankton growth can be induced

- What was missing from the pit lake water column?

Missing…

- The big difference between tailings ponds and pit lakes is water column interaction with the sediments, and the sediments are a huge bacterial reservoir.

- So a bacterial product could be missing from the pit lake water columns, but which one?....

Shortage of B-vitamins hypothesized

We re-tried the experiment with an assortment of B-vitamin from pills

- B1
- B6
- B12
- Biotin
- Multi-B
- Vitamin B1 (thiamine)
- Vitamin B2 (riboflavin)
- Vitamin B3 (niacin)
- Vitamin B5 (pantothenic acid)
- Vitamin B6 (pyridoxine)
- Vitamin B7 (biotin),
- Vitamin B9 (folic acid)
- Vitamin B12 (various cobalamins)

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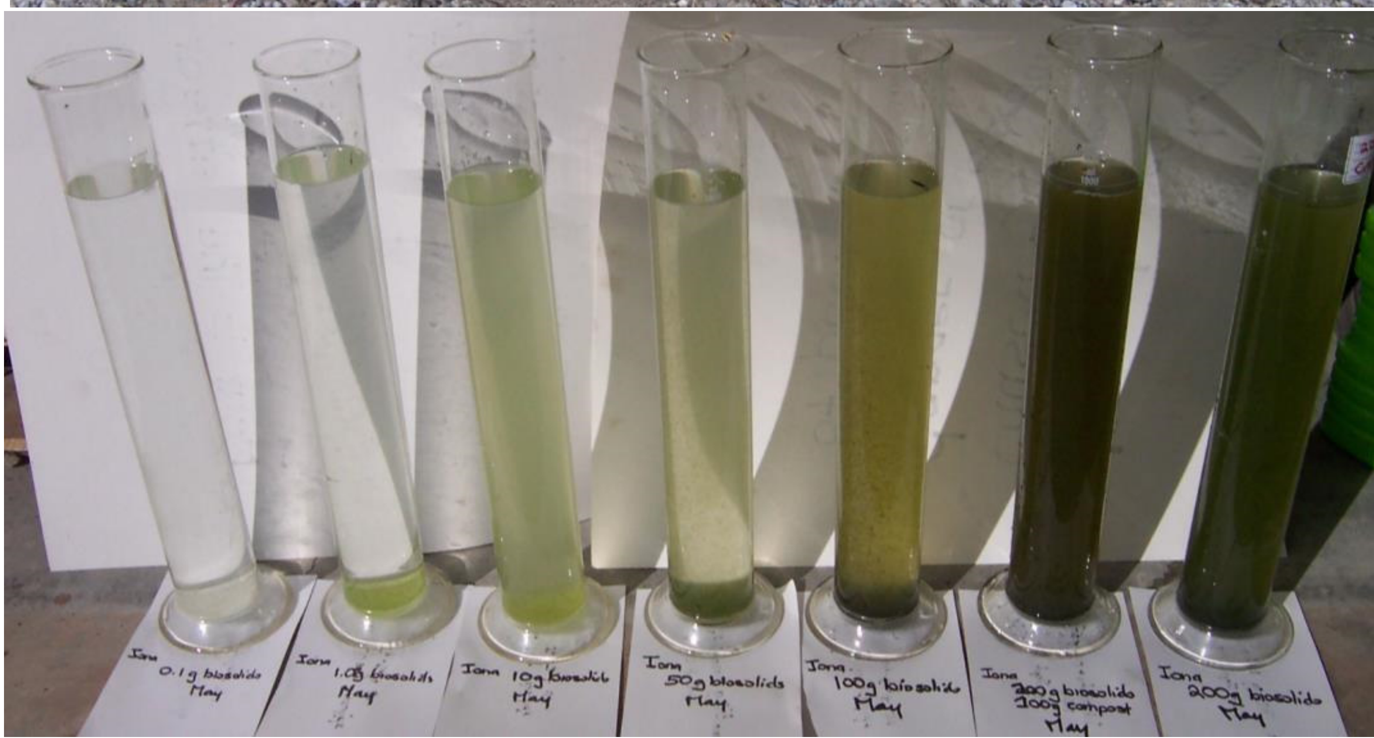
- Vitamin B12 (various cobalamins)

The Missing Factor

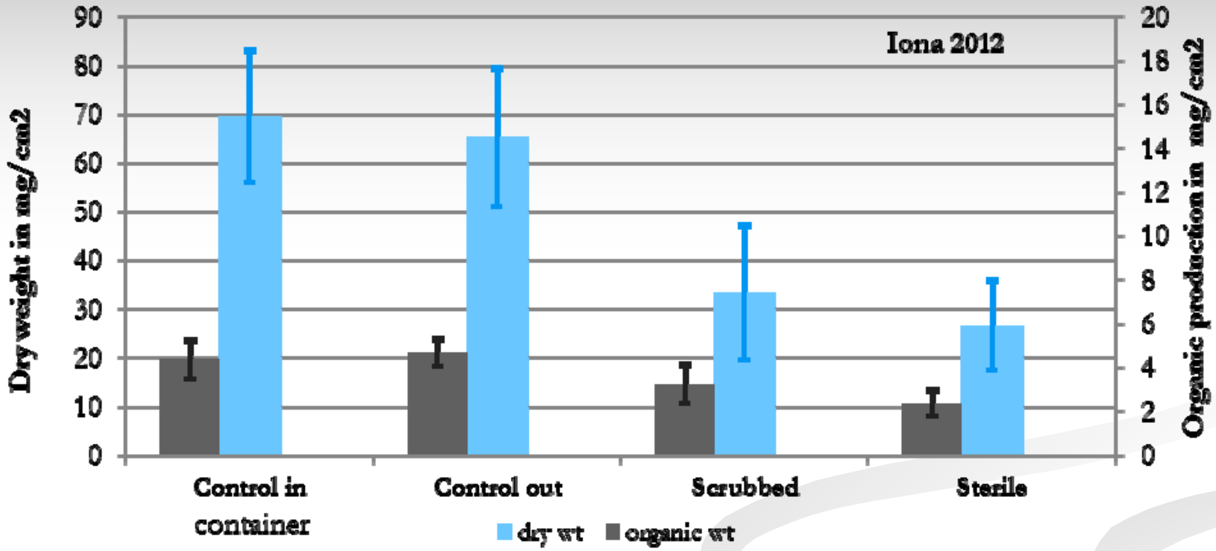
- Many algae supplement their growth by taking in organic substrates, particularly the made-by-bacteria B vitamins: especially B12, as well as thiamine (B1) and biotin (B7).
- Adsoprtion and removal of B12 by particulate calcium occurs in natural lakes and marling pit lakes, thus a steady supply of vitamins is needed.

Other well-known sources of B-vitamins…

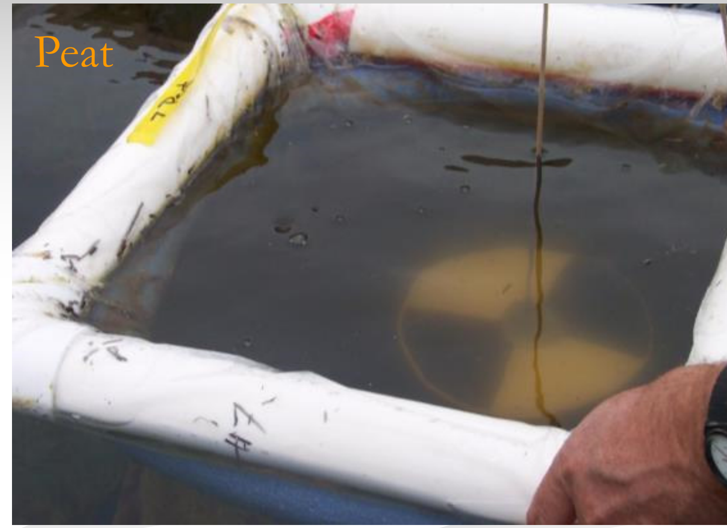
Iona and Heustis dose trials – biosolids as B vitamin source

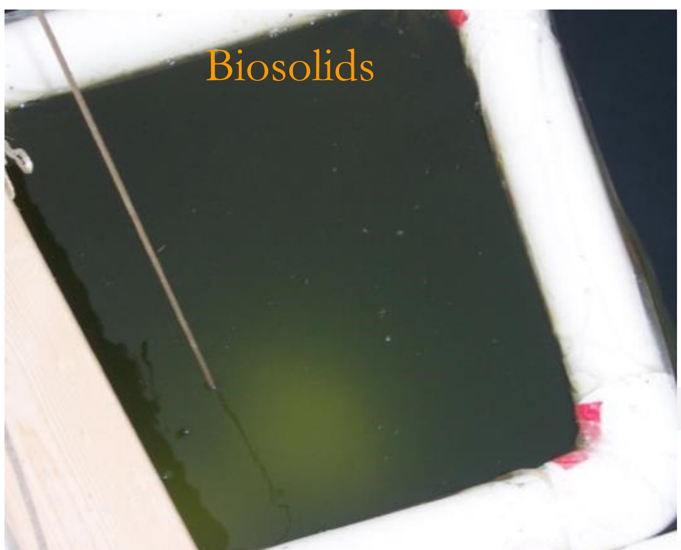


Experiment showed that substrates pre-conditioned with bacteria gave the periphyton a small head-start



Enclosure testing of substrates to enhance periphyton growth



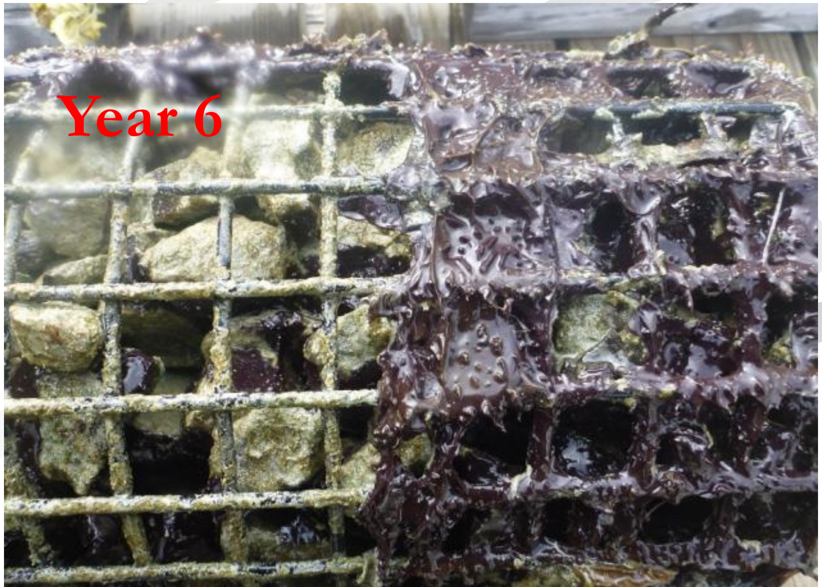


Enhancing pit lake periphyton

- Various introduced substrates grew 17 benthic algae in varying combinations.
- Aquatic macrophytes grew 30 periphytic algae species in the Iona enclosure.
- Enclosures with intense photosynthesis precipitated calcium carbonate (marl).

$$H_2O + CO_2$$
$$||$$
$$CaCO_3 + H_2CO_3 = Ca^{+2} + 2HCO^-_3$$
$$\Leftarrow$$

Rock basket trial

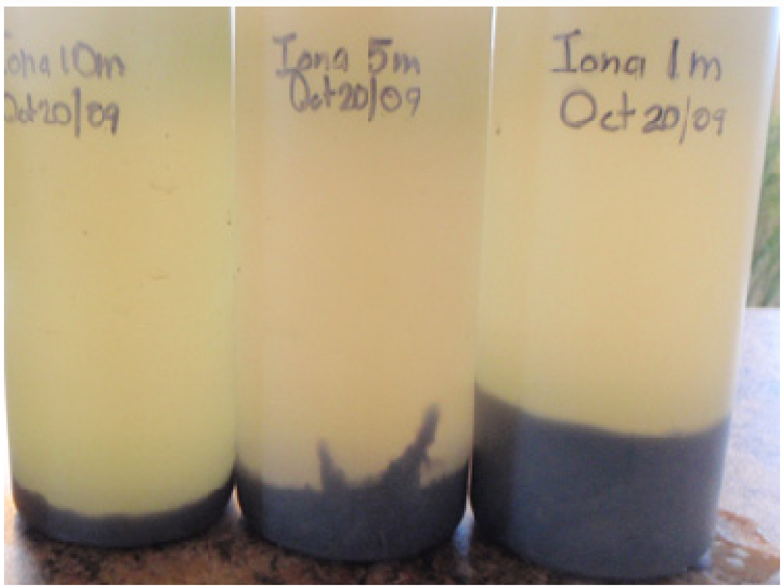


- Only lighted surfaces grow periphyton
- Interior is bare, even after 6 yrs
- Bacteria need algae, algae need bacteria *and sunlight*

Photic Zone

diminishing growth with depth is normal in all lakes

Photic Zone: Periphyton biomass decreases with depth



Artificial Substrate	IONA -2009		
Parameter mg/kg (ppm)	1m	5m	10m
pH	6.7	6.7	6.9
Solids, Fixed %	78.3	67.9	72.1
Solids, Total Volatile %	21.7	32.1	27.9
Aluminum	1000	4100	5600
Barium	55	72	87
Boron	16	22	16
Calcium	230000	180000	180000
Cobalt	0.9	2.1	2.6
Copper	870	1700	2200
Iron	1500	4600	15000
Magnesium	1200	2300	2700
Manganese	46	92	110
Molybdenum	86	100	1200
Nickel	6.6	11	9.6
Phosphorus	591	1720	2030
Potassium	880	1700	1800
Sodium	300	400	370
Strontium	1100	930	960
Zinc	67	130	150

Metals content of periphyton tissue varies between years and between pit lakes, but always demonstrates that water column metals are accumulating in the periphyton

What did we learn?

- Bacteria resident on fines provided the initial bloom with their missing growth factors – probably B vitamins.
- These bacteria apparently grow on all substrates and supply the benthic microflora.
- Returning bottom water to the surface replenishes these growth factors.
- Supplementing with B vitamins in biosolids allows excellent algae growth.

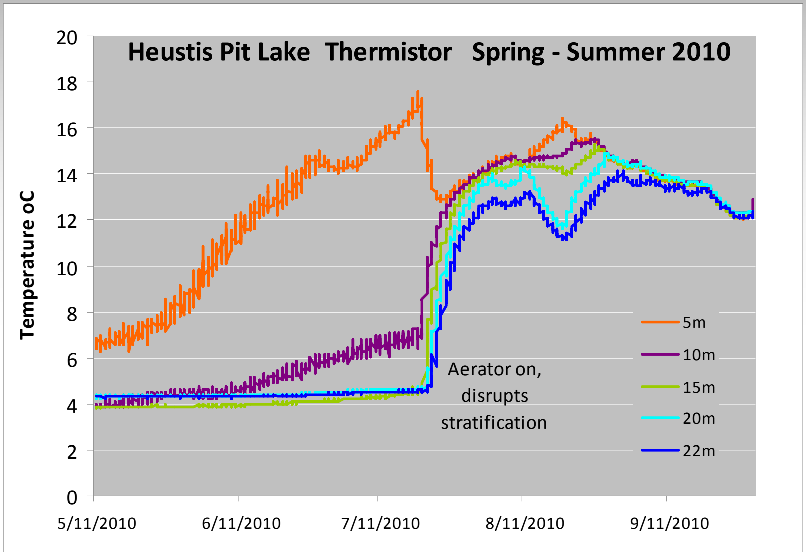
Solutions to Crater-ish Pit Lakes

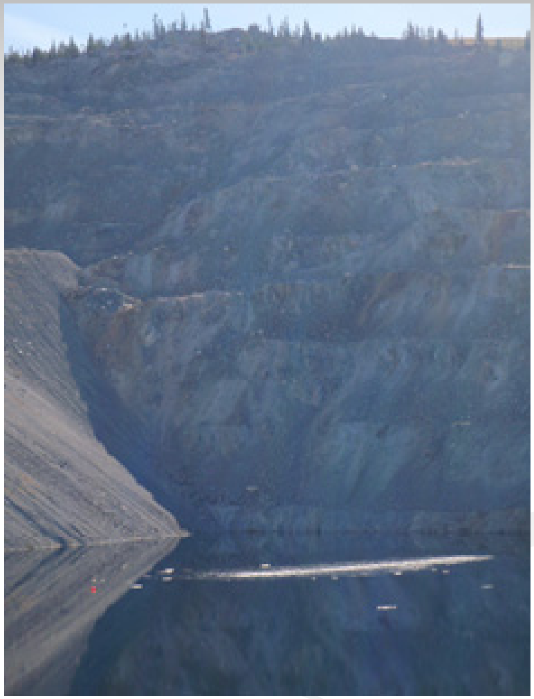
In addition to adding limiting nutrients most years…

Solution 1: add B vitamins and nutrients from biosolids by:

- Dumping biosolids on submerged ramp
- Construct a "biosolids raft" with permeable floor
- Create a channel that is periodically dosed with biosolids and let ramp drainage flow through it (or pump pit lake water through it)

Solution 2: provide nutrients and B vitamins by destratifying the water column

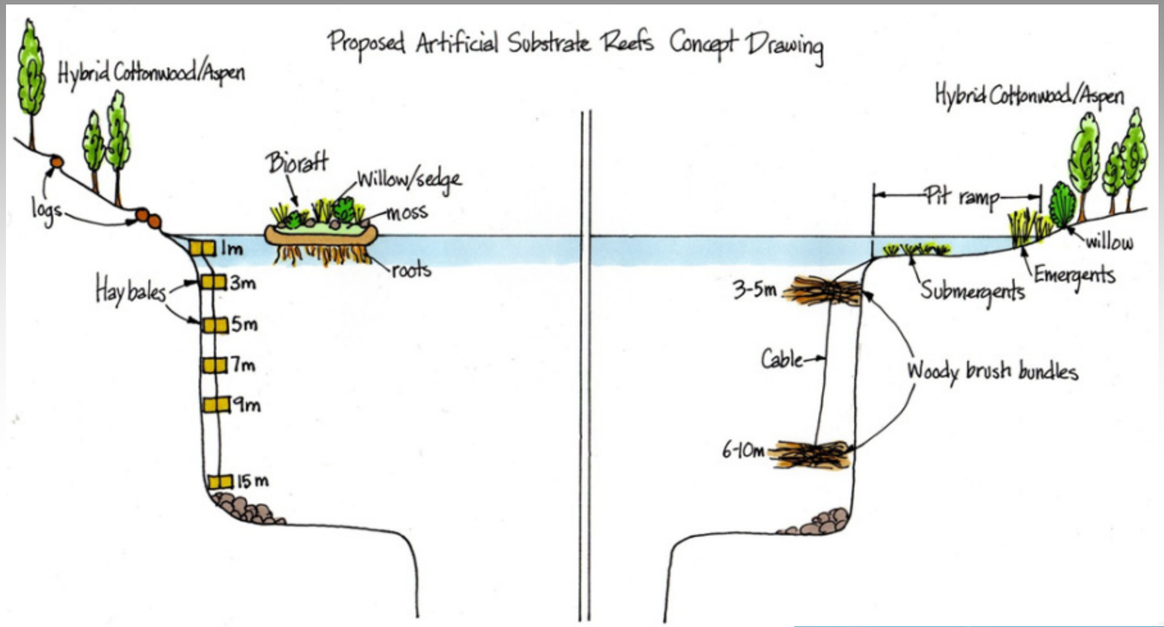


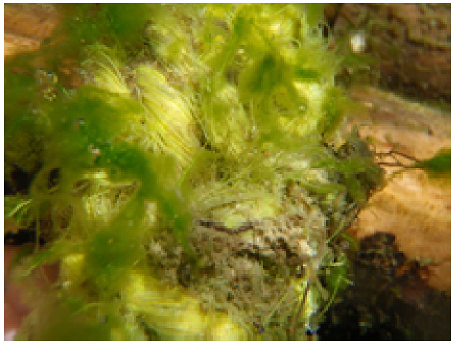


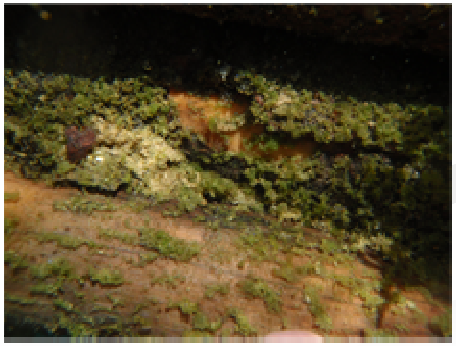
Solution 3: Diversify pit habitats: add nutrients, plants & substrates

Benthic microflora / Aquatic macrophytes / Duckweed

Solution 4: Pit lake artificial reef concept







Contributions to annual Heustis pit lake production

Component	Est. Annual Production	Controlling factors and influences on production (from most influential to least influential)
Plankton bloom phase	21–231 kg/yr wet wt	Circulating B vitamins, nutrients, co-precipitation of P, vitamins TIC with marl, turbulent upwelling from aerator (Using an estimate of algae cell loss/replacement of 1 kg/ha/day and a 1 week life-span of a cell
Plankton clear phase	2 kg/yr wet wt	Circulating B vitamins, nutrients, excessive light intensity
Periphyton	860 – 1010 kg/yr wet wt	Nutrients, available substrate in 0 – 10 m depth, diversity of substrates, available substrate in 10 – 20 m depth
Bacteria		Nutrients, organic substrate
Macrophytes	420 kg/yr wet wt	Pore water nutrients and metals, overgrowth of cyanobacteria coatings, coating with marl (0.1–0.5 kg/m^2/yr)





So what did the reclamation efforts achieve at HVC pit lakes?

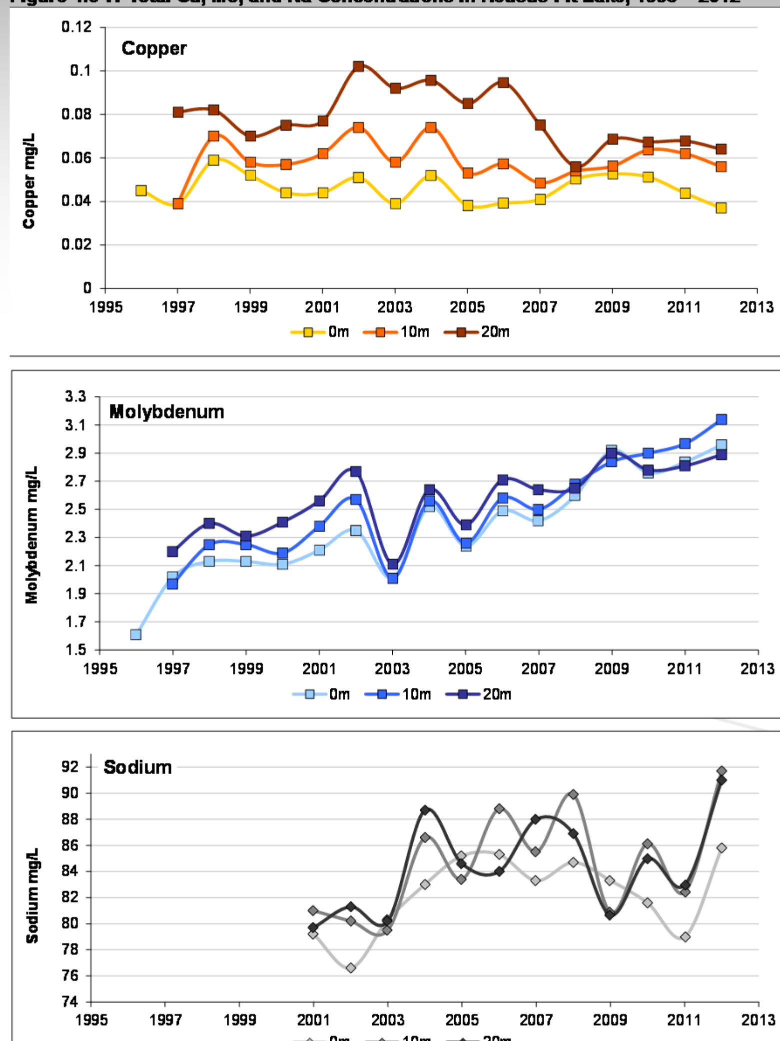


Iona (fertilized) with ice-off spring bloom, versus Jersey (control)

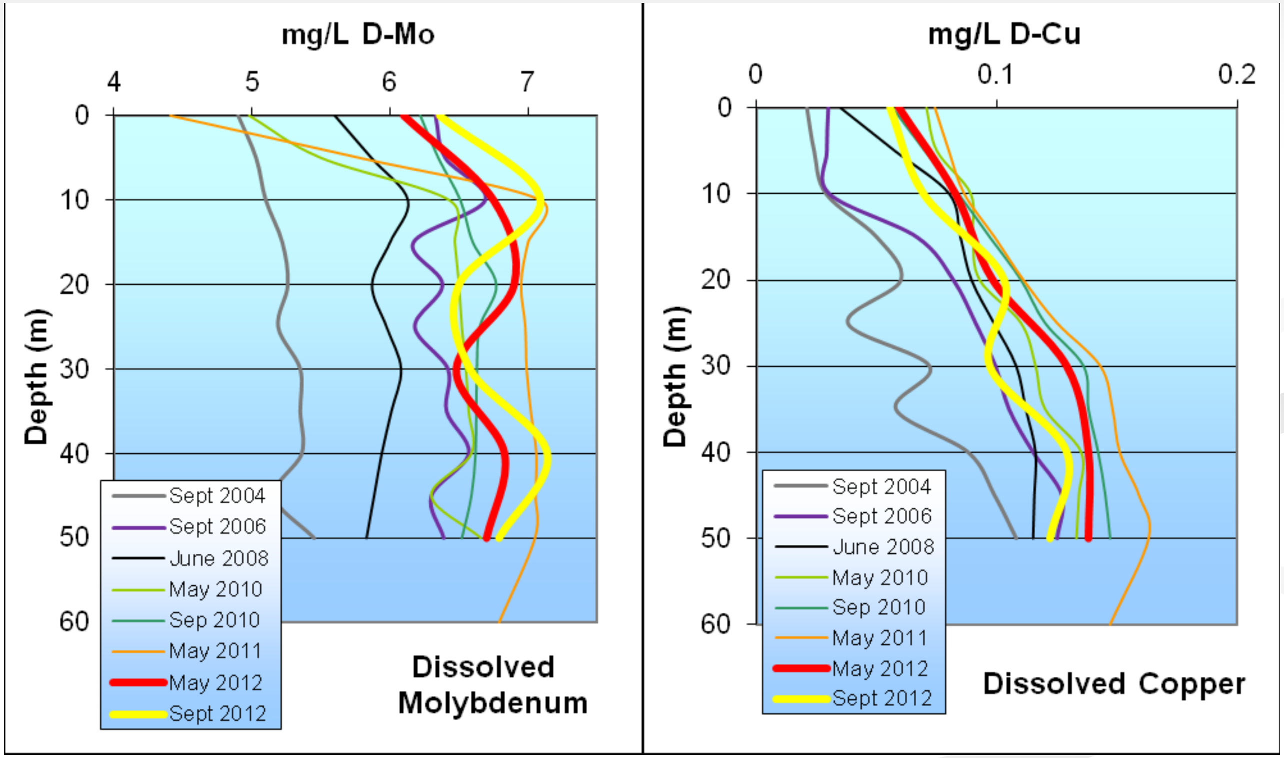
As bioreactors, summer-long plankton and benthic algae growth removed as much as 10% of the dissolved molybdenum and 4% of the dissolved copper from Iona pit surface layer in a single season. Metal removal measured within a bloom phase reached 30% in surface water for Mo and Cu at HVC.

Pit lakes removed dissolved metals from the water column, but may not keep pace with influx

Figure 4.6-7: Total Cu, Mo, and Na Concentrations in Heustis Pit Lake, 1995 – 2012



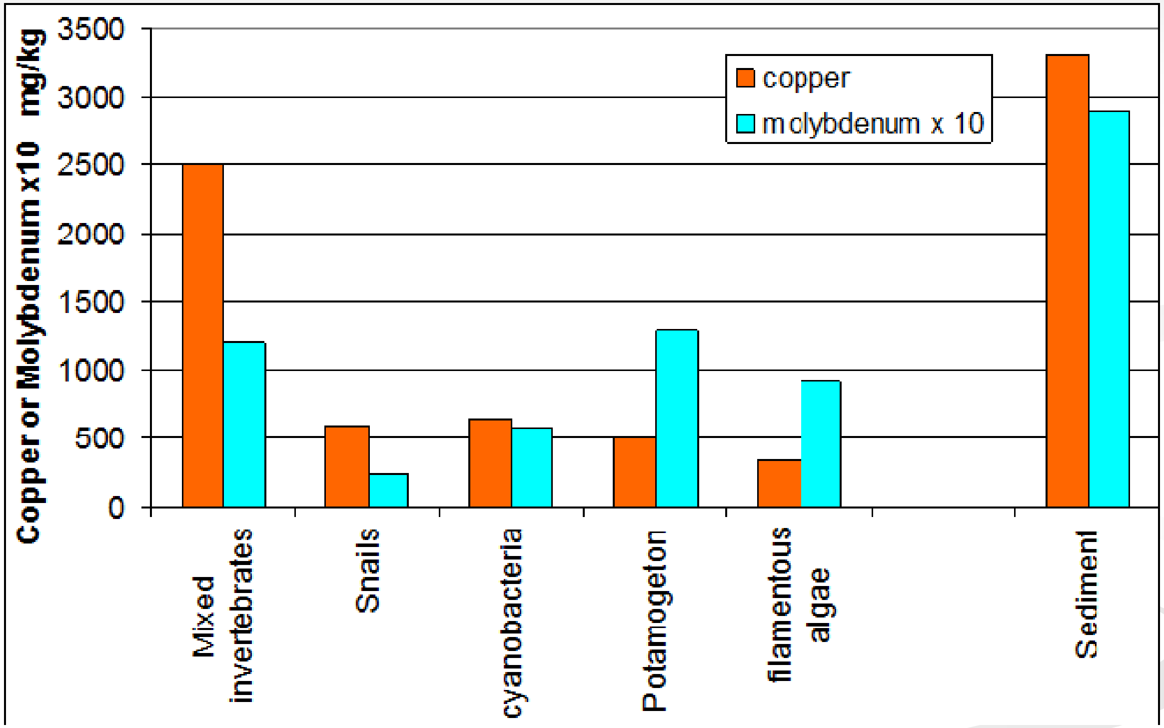
Metal profiles show change with depth, season and year



Grown-in-place biological amendments add to bioreactor and to fishery habitat values.

Peripheral vegetation adds organic carbon as leaves, while pollen contributes some B vitamins

Bioaccumulation of metals in Heustis pit lake food chains



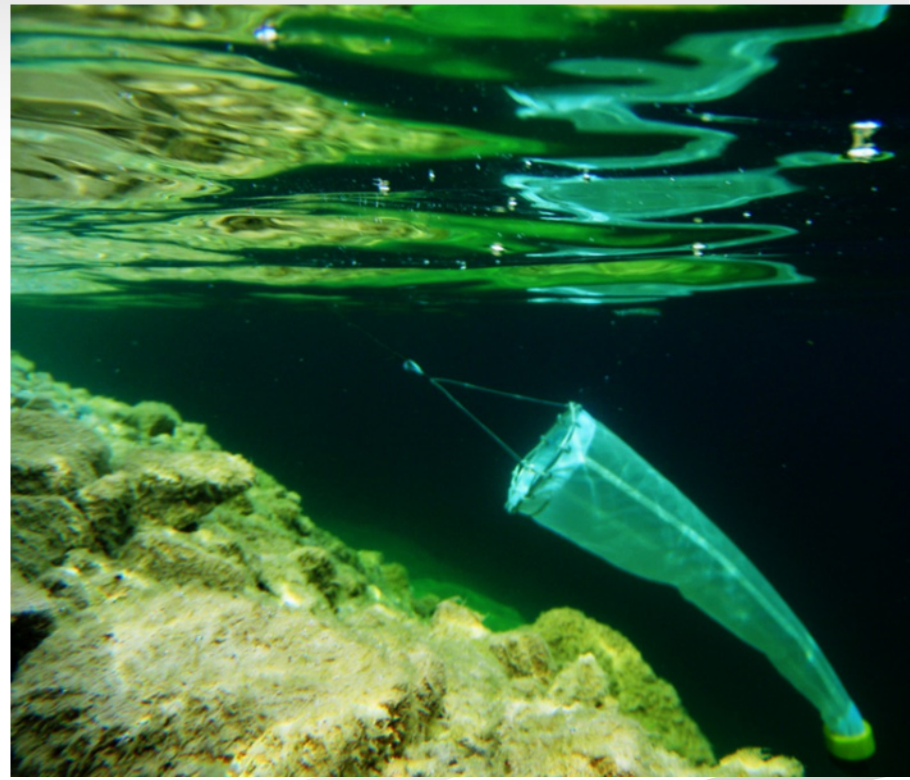
Kokanee introductions to augment Rainbow trout fishery

Heustis Pit Lake 2011 - No Aeration

Temperature oC

Depth (m)	24-May	11-Jun	21-Jun	6-Jul	20-Jul	2-Aug	6-Sep	28-Sep	Benthic Algae
	Temp (°C)								
0	12.36	15.22	14.57	14.61	16.03	16.69	16.98	12.99	
1	11.92	15.01	14.41	14.39	16.06	16.66	16.02	12.44	
2	10.88	14.89	13.92	14.19	16.04	16.37	16.02	12.33	
3	9.24	12.33	13.38	14.06	15.62	16.29	16.02	12.26	
4	6.46	9.61	11.12	13.86	15.34	16.24	16.02	12.18	
5	4.64	6.86	7.86	10.76	13.66	15.13	16.01	12.13	
6	4.16	5.22	6.15	7.83	11.49	13.49	16.01	12.12	
7	3.81	4.39	4.98	6.57	8.23	10.29	13.03	12.09	
8	3.83	4.17	4.62	5.74	6.49	8.38	10.07	12.07	
9	3.81	4.08	4.29	5.23	5.54	6.39	8.19	12.03	
10	3.79	4.04	4.17	4.61	5.08	5.48	6.76	8.06	
11	3.81	4.02	4.08	4.62	4.66	4.67	5.96	6.52	
12	3.79	3.98	4.04	4.36	4.61	4.62	5.37	5.81	
13	3.78	3.93	4.02	4.21	4.31	4.36	5.08	5.44	
14	3.78	3.97	4	4.13	4.26	4.29	4.61	5.16	
15	3.81	3.93	3.96	4.06	4.16	4.26	4.78	4.99	
16	3.86	3.96	4.02	4.09	4.23	4.36	4.69	4.83	
17	3.9	4.01	thermocline zone			4.4	4.83	4.79	
18	3.97	4.02	ideal kokanee T/DO zone			4.39	4.83	4.83	
19	4.06	4.09	High	moderate	low	4.36	4.84	4.79	
20	4.14	4.23	plankton/benthic algae producti			4.42	4.86	4.76	
21	4.2	4.27	4.26	4.3	4.36	4.43	4.84	4.81	
22	4.26	4.26	4.32	4.32	4.4	4.46	4.86	4.84	
23	4.26	4.32	4.36	4.36	4.41	4.46	4.86	4.86	
Bottom (m)			4.36	4.42	4.46				
Secchi (m)	1.7	1.6	5.62	6.3	9.27	14.6	13.4	13.4	

Plankton Algae



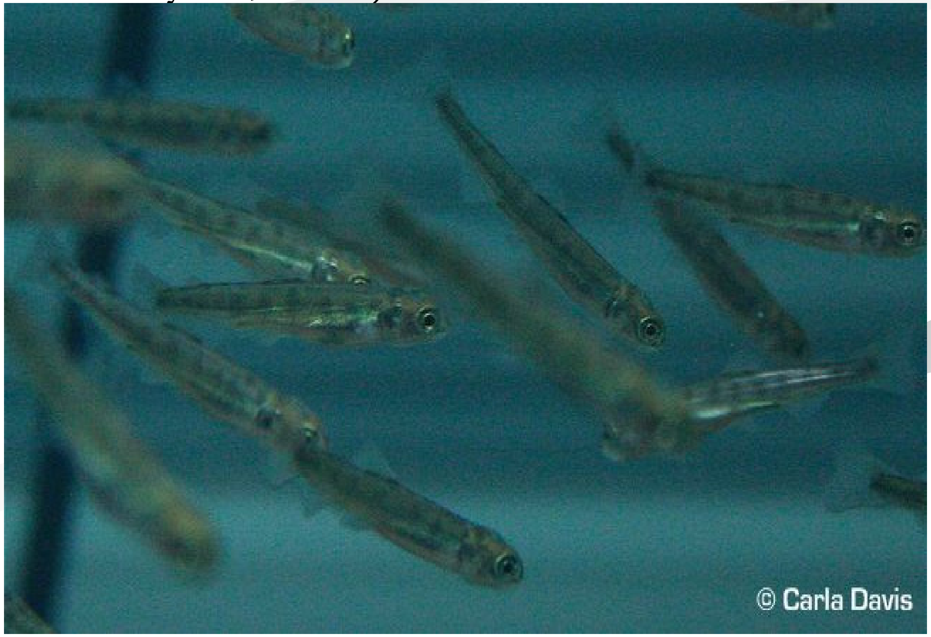
Proven Pit Lake Fisheries at Heustis

Rainbow trout

- Feeding – benthic invertebrates, sm fish
- Benefits – FISHING!
- Growth rates – fast, ranged from 45.7 – 63.5 cm (3 – 5 lb) with an average of 56 cm in 2012

Kokanee

- Feeding – plankivors sm zoops
- Benefits - food for RBT, lowered zoop population (2013 fall bloom!)
- Growth rates- great (from 10-20 g introduced size to 326 – 501 g in first year, 2012)



Summary

- Periphyton and photosynthetic bacteria provide much of the primary production in HVC pit lakes
- Spring ice-off HVC pit blooms tend to become more diverse over time
- SRB colonize the substrate once organic carbon from microflora accumulates (1-3 years into reclamation)

- After 2 years of fertilization + B vitamins, the periphyton hosted chironomids sufficient to support a limited fishery in every HVC pit lake.
- Fishermen, eagles, osprey and goldeneyes now utilize HVC pit lakes.

Can you ever walk away??

No

- Productivity declines
- Bioreactor and habitat values decline

Yes, but

- but productivity never returns to 0
- but it takes 3-5 years for the slow-down to be significant

Thank you, Questions?