Phytoremediation of Contaminated Soil in a Remote Northern Location

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Earthmaster Environmental Strategies

and the *University of Waterloo

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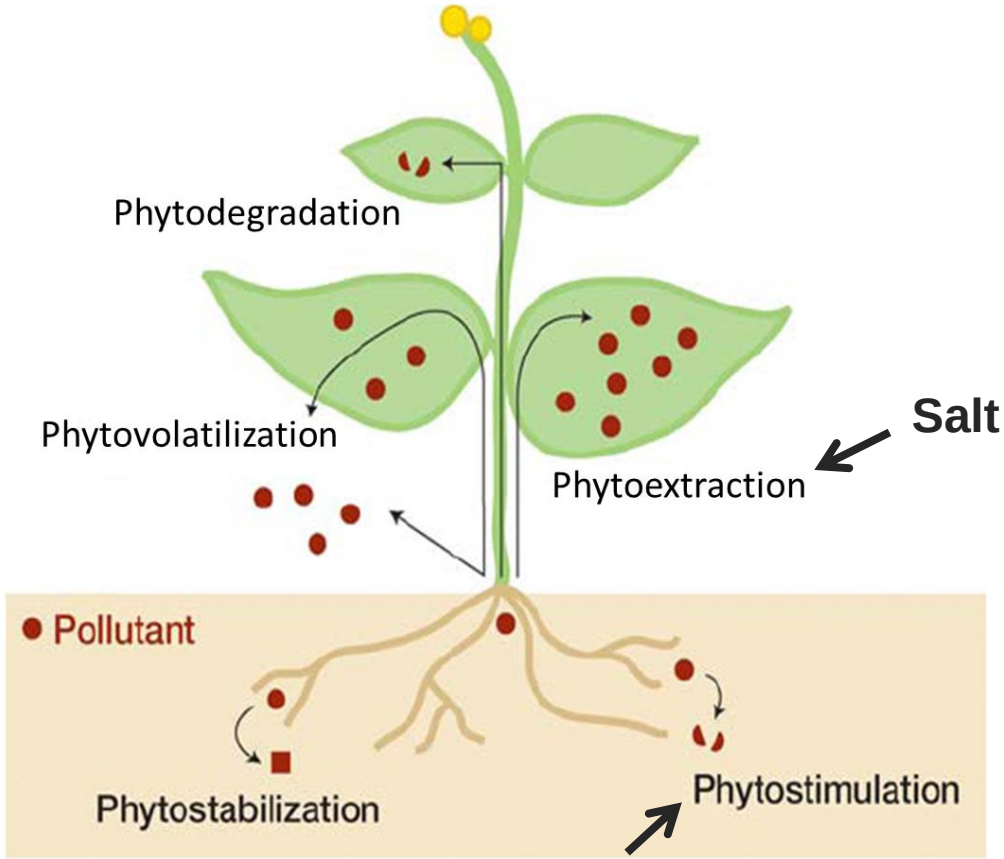
Earthmaster Environmental Strategies Inc.

A Canadian environmental technologies company:

- Based in Calgary, Alberta.
- Founded in 1998.
- Specializes in providing environmental services to the commercial/industrial and upstream oil and gas industry in Western Canada.
- Team of environmental consultants consisting of professional agrologists, biologists, chemists, ecologists, engineers, geoscientists, soil scientists, plant scientists, aquatic specialists, and foresters.
- Co-developed commercial phytoremediation systems to treat contaminated soil in an eco-friendly and responsible manner.

Phytoremediation – How it Works



Rhizodegradation – Petroleum Hydrocarbons

- Improved rhizosphere
  - Soil
  - Organic matter
  - Bacteria
  - Water
  - Roots
  - Contaminants
- Rhizodegradation
  - Petroleum Hydrocarbons
- Phytoextraction
  soil→root→foliage
  - Salts
  - Metals

Challenge – getting the plants to grow.

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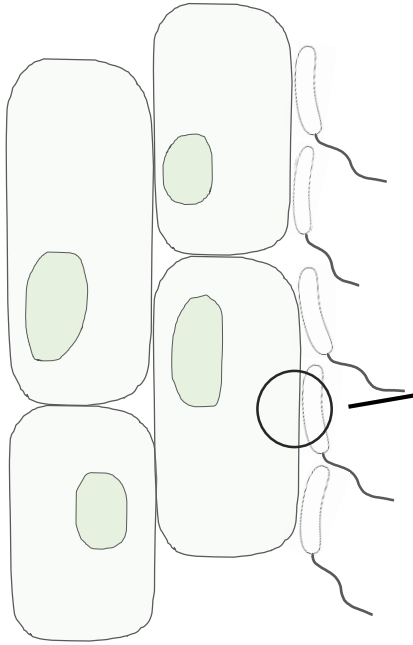
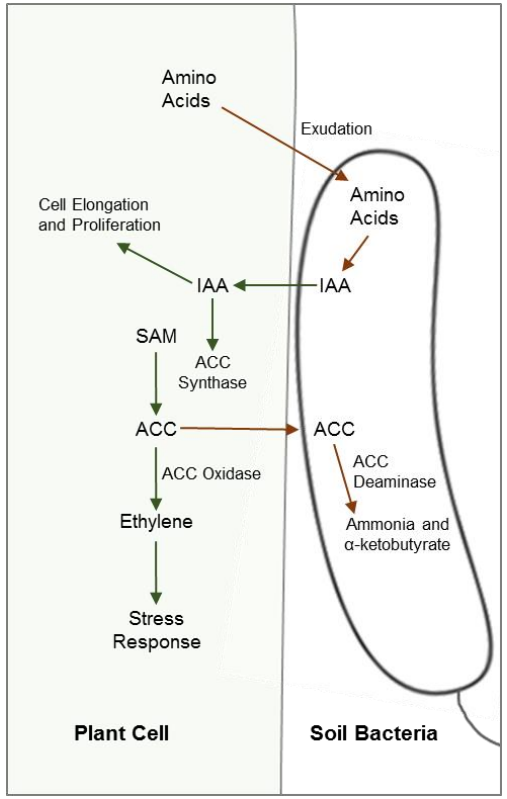
PEPSystems™ : Plant Growth Promoting Rhizobacteria (PGPR) - Enhanced Phytoremediation Systems

PEPSystems™

- Developed through collaboration between Dr. Bruce Greenberg of the University of Waterloo and Earthmaster for contaminated site clean-up.
- Earthmaster has assumed control of the PEPSystems technology and now manages all PGPR testing, selection, seed treating, and overall site specific remediation system design in Calgary. Dr. Greenberg continues to collaborate on PEPSystems.
- Earthmaster continues to conduct research on how to improve PEPSystems for remediation of contaminated sites or other applications such as to enhance plant growth on marginal or poor quality soils.

PGPR – Facilitating Plant Growth in Challenging Conditions





Active rhizosphere:
PGPR co-localize with developing roots

- Stress ethylene
- Plant vigor
- Root development
- Rhizobacteria
- Leaves
- Salt and metals uptake
- Degradation of PHC

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Remote Northern Site

Project summary:

- Salt and hydrocarbon (PHC) contaminated site in the Northwest Territories
  - Nota Creek C-17
  - Remote site located 40 km southeast of Norman Wells
  - Contaminants were from historical drilling activities in 1997
  - Surface soil contained salt and PHC contaminants
  - Numerous PHC contaminated pits/sumps were also onsite

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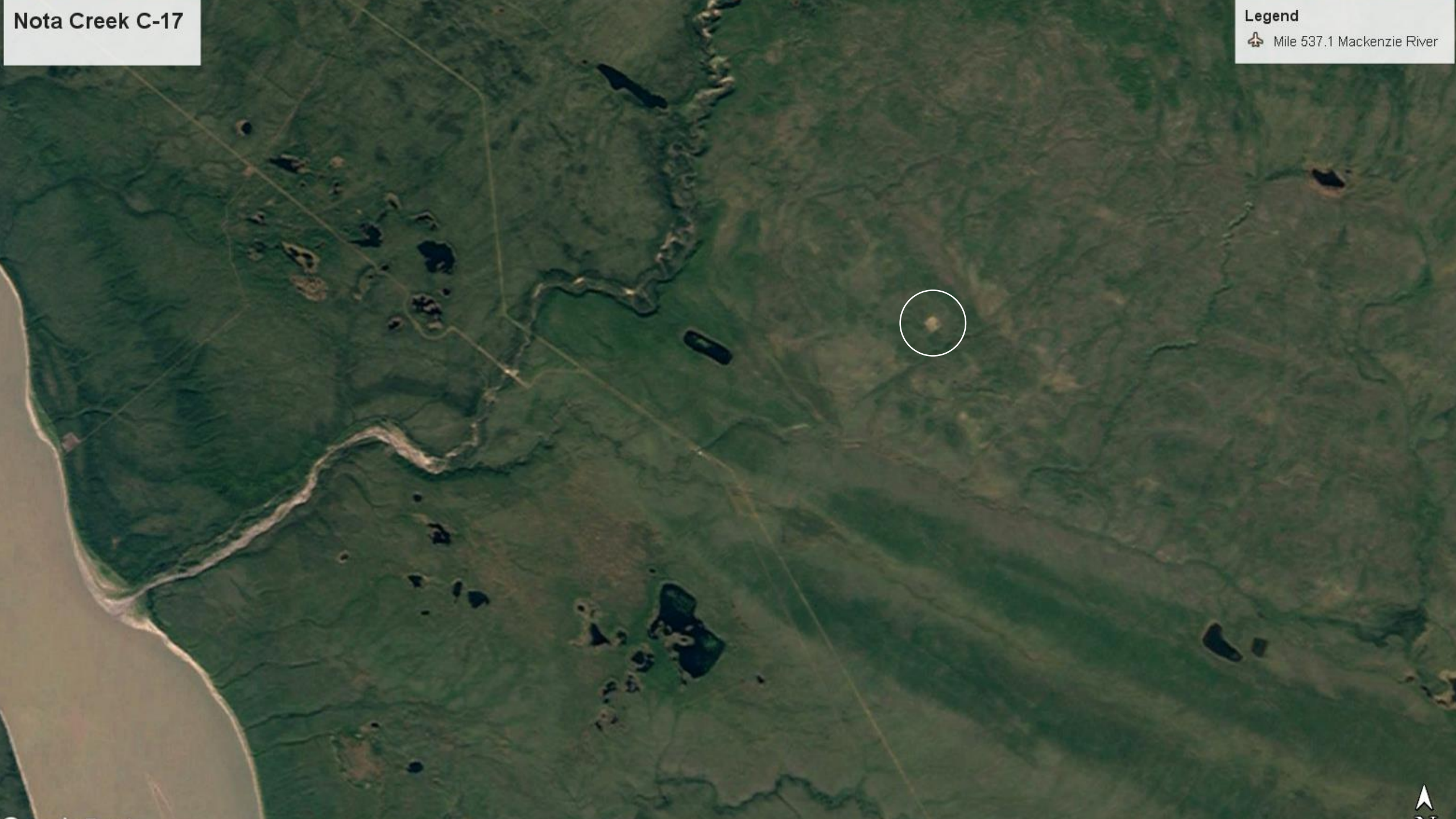

Nota Creek C-17
Legend
Mile 537.1 Mackenzie River

Nota Creek C-17 History

Well historical details:

- Construction started in December 1997, well was completed in March 1998.
- 2 invert sumps and 1 Gel-chem sump were dug onsite.
- C-17 well was drilled to a depth of 1953 m.
- Surface trench was dug from the drill rig over to invert sump #2
- Salt water was disposed downhole.
- Well was abandoned at the end of completion.
- Records show the drilling fluid was handled poorly and there was a leaking diesel tank on site.
- Drilling waste was disposed in the Gel-chem sump using mix-bury-cover.
- Invert cuttings were disposed at a remote sump.

Nota Creek C-17 History - continued

Well historical details:

- A site inspection in August 1998 identified:
  - Slumping sumps
  - Strong diesel odour from invert sumps
- Fill was added to the Gel-chem sump in March 1999 and it was re-capped.
- Invert sumps were excavated and the soil landfarmed.
  - Zeolite, fertilizer and sawdust were added
  - Chlorides were 31,200 ppm
- In 1999, the NT Government approved encapsulating the cuttings with zeolite and cement and burying them in a remote sump.
  - Work completed July/August 1999
- 2001 inspection found landfarm conditions were not being adhered to.
  - Additional assessment of the site was completed.

Nota Creek C-17 History - continued

2002 assessment details:

- EM survey showed 5 anomalies.
- PHC, EC and SAR exceedances were found in the soil near 2 of the anomalies.

April 2004:

- A pilot bioremediation program was initiated for PHC contaminated soil from the 2 invert sumps.
  - Soil was spread to a depth of 0.3 m across the northwest portion of the site.
  - Salinity contamination was discovered in the soil so further assessment was required.

2004 - 2007:

- 60 boreholes were advanced to further assess the excavations on the site.

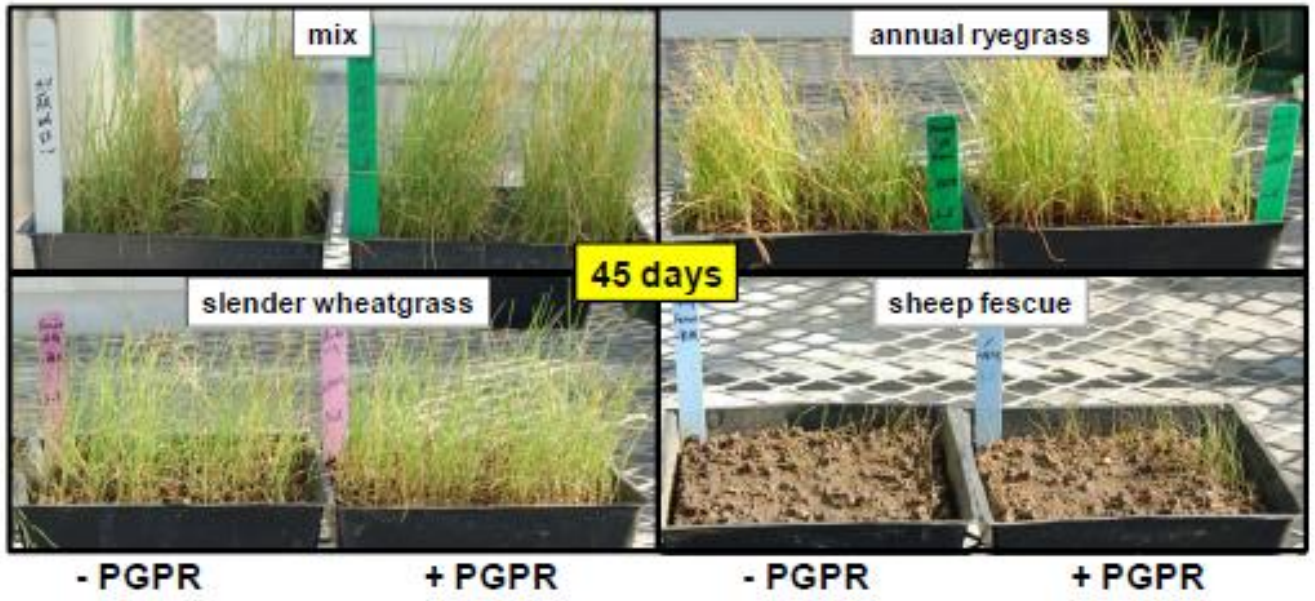
Nota Creek C-17 Pre-deployment 2008

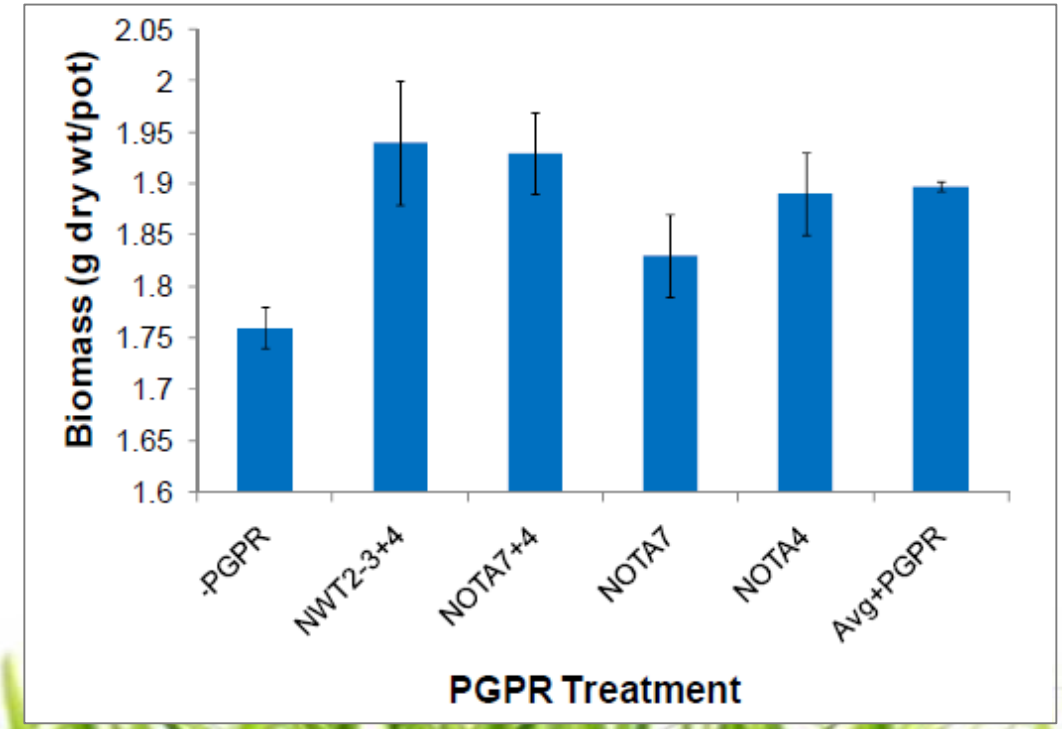
Site details:

- Summer access – fly in
- Winter access – frozen road
- Land use – industrial
- Soil texture – coarse
- Alberta Tier 1 EC guideline value
  - 4.0 dS/m
- CCME remediation guideline values F2:
  - surface soil – 260 mg/kg
  - subsoil – 320 mg/kg
- Invert sumps were left open after excavating in April 2004 for landfarming.
- Middle area of the surface soil was contaminated with salt. Soil in the pits and sumps was contaminated with PHC.
- White bags were old soil amendments.
- Initial remediation work on the site was done by University of Waterloo.

University of Waterloo Benchtop Studies

- Conducted in 2007/2008
- Soil collected from high (EC 14 dS/m) and medium salt (EC 5 dS/m) areas was shipped to UWO.
- 12 PGPR were isolated from the soil – 6 were selected for greenhouse tests.





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Nota Creek C-17 Lift #1

Phytoremediation details:

- **Lift #1** T=0 June 2008
  - Surface soil treated for salt.
  - Salt levels inhibited natural vegetation growth.
  - 2008 work consisted of test plots – full treatment started in 2009.
  - Work was completed by University of Waterloo
- Seed – ARG, SWG, CRF
- PGPR – *Pseudomonas corrugata* and *P. marginalis* isolated from the site (Nota 4/7).

University of Waterloo Field Set-up

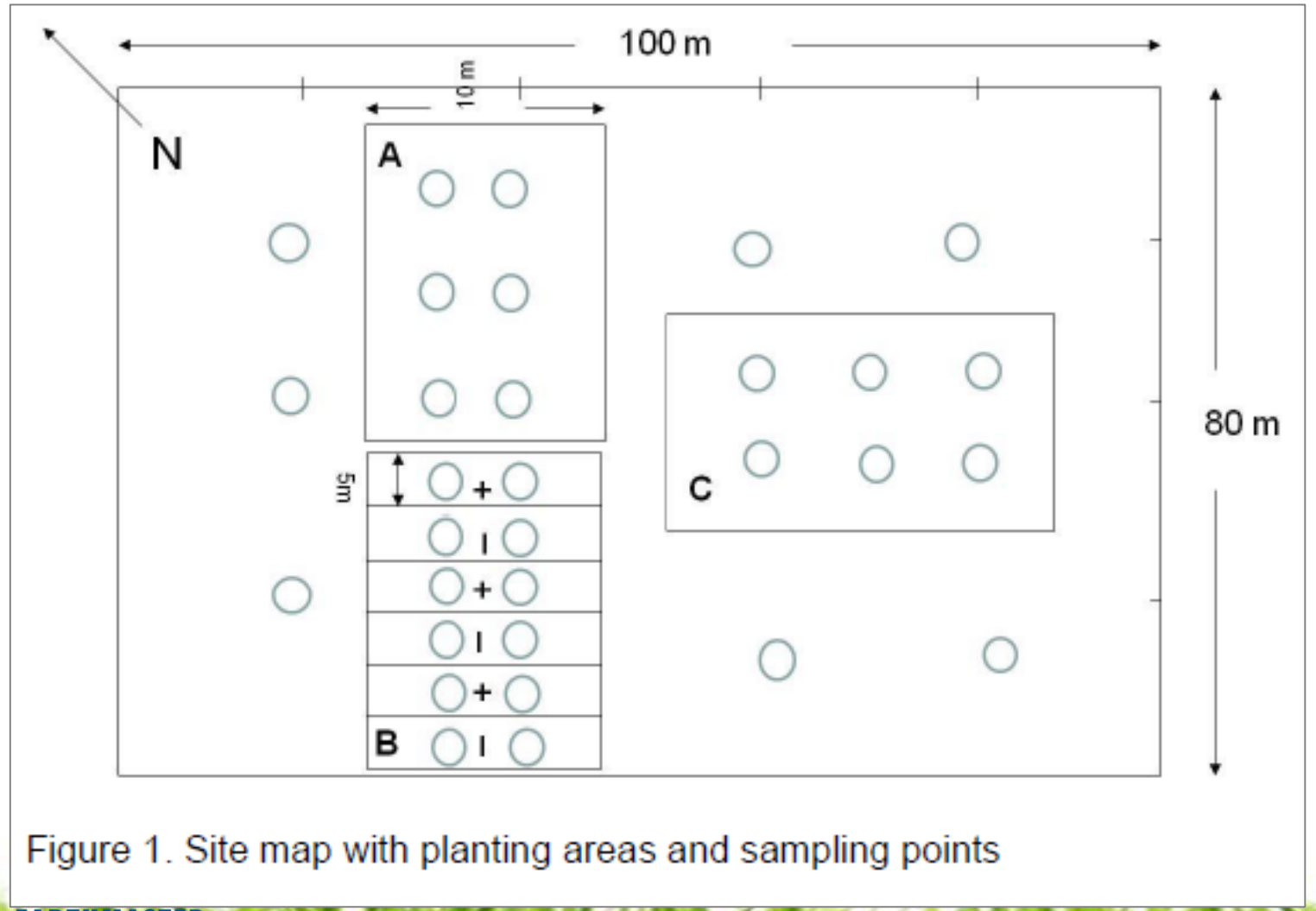

Figure 1. Site map with planting areas and sampling points

Area A – high salt (14 dS/m)

Area B – medium salt (5.33 dS/m)

Area C – low salt (3.65 dS/m)

Field work was preceded by laboratory/greenhouse studies to develop suitable bacteria and plant species.

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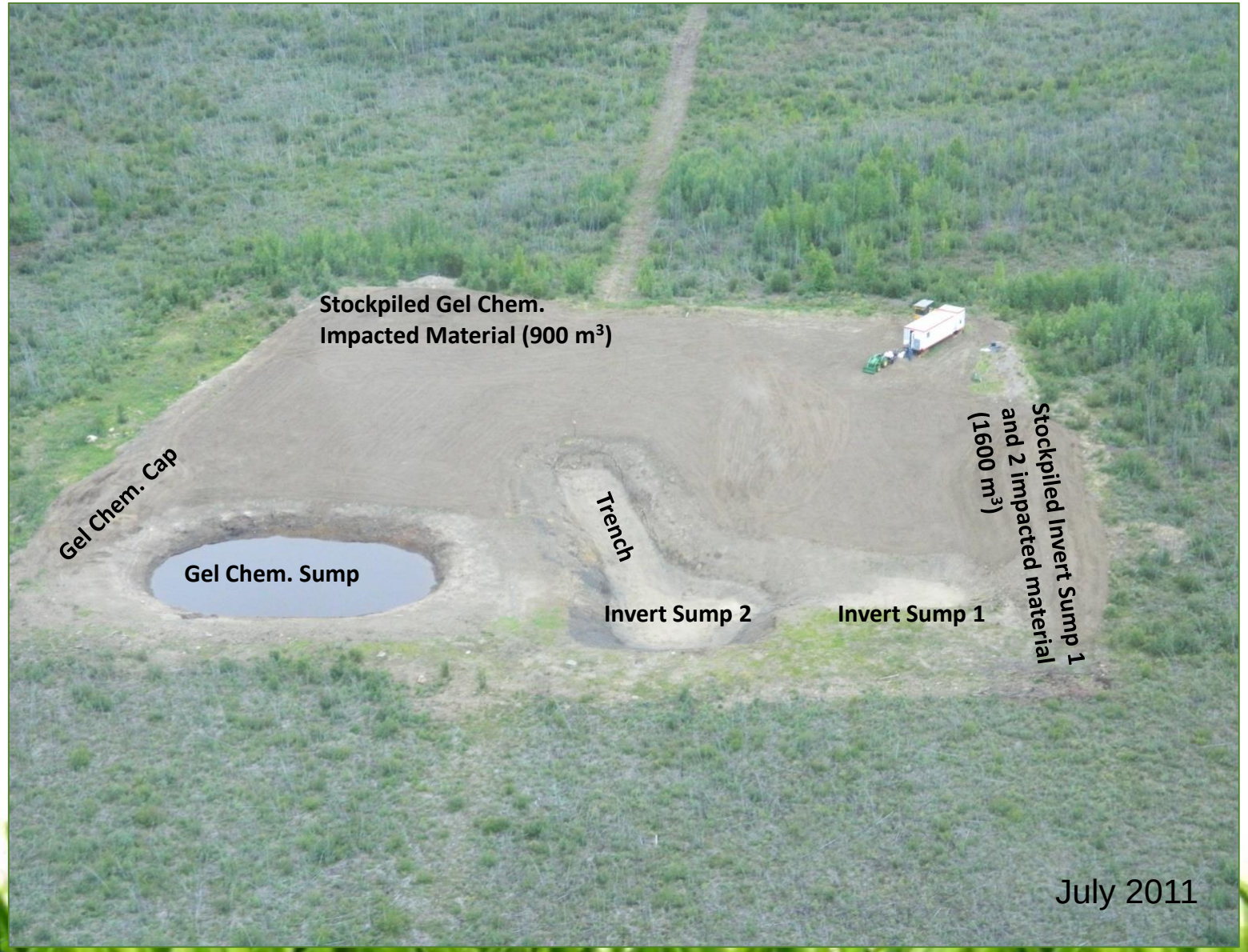
Summary for Treatment Lift #1

Phytoremediation summary:

- Treatment of lift #1 was from June 2008 – early 2011.
- Seed was planted each spring and grasses were harvested from the site each fall and disposed in a landfill.
- Middle area only had elevated salt concentrations.
- June – September 2008 had EC decrease of 29%.
- June – September 2009 had EC decrease of 13%.
- Sep 2009 – Sep 2010 had EC decrease of 18%.
- From 2008 to 2009 the highest salinity area had average ECs drop from 14.5 to 6.3 dS/m.
- Portion of the soil with elevated salt concentrations was incorporated into lift #2.
- Additional material was excavated from the pits and sumps in February 2011.

Treatment of Lift #2



Phytoremediation details:

- **Lift #2** T=0 July 2011
  - Material (2,125 m³) excavated from pits and sumps placed on top of lift #1 for treatment.
  - Additional excavated material was placed in stockpiles for future treatment.
  - Contaminated soil was left in the pits and sumps due to space constraints
  - One area had elevated salts
  - Average F2 concentration of lift #2 = 549 mg/kg
- Seed – ARG, SWG, CRF
- PGPR – *Pseudomonas corrugata* and *P. marginalis*
- Work was completed by the University of Waterloo.

Treatment of Lift #2

Phytoremediation summary:

- Treatment for PHC F2 contamination was completed in June 2013 and left in place.
- Salinity was low on this lift – just 3 points exceeded EC guideline value at T=0 (~ 5.5 dS/m).
- Grass in the elevated salinity area was harvested and disposed.
- July – September 2011 had F2 decrease of 30% (avg. 549 mg/kg to 370 mg/kg).
- July – September 2012 had F2 decrease of 26% (avg. 330 mg/kg to 244 mg/kg). 1 point >260 mg/kg.
- Avg. EC in September 2012 was 3.3 dS/m (decreased 52% from July).
- 1 sample point had EC above guideline value.

Harvesting

Treatment Lift #2

As of June 2013, all parameters complied with guideline values. Overall, F2 decreased from 549 mg/kg in June 2011 to 84 mg/kg in June 2013 (84% decrease). Average EC was 2.9 dS/m.

Treatment Lift #3

Phytoremediation details:

- **Lift #3** T=0 September 2013
  - Gel Chem. sump stockpile (900 m^3) was spread across lift #2.
  - Treatment was for PHC F2 contamination.
  - EC values complied with guideline value.
  - Work was initiated by the University of Waterloo.
- Seed – ARG, SWG, CRF
- PGPR – *Pseudomonas corrugata* and *P. marginalis.*

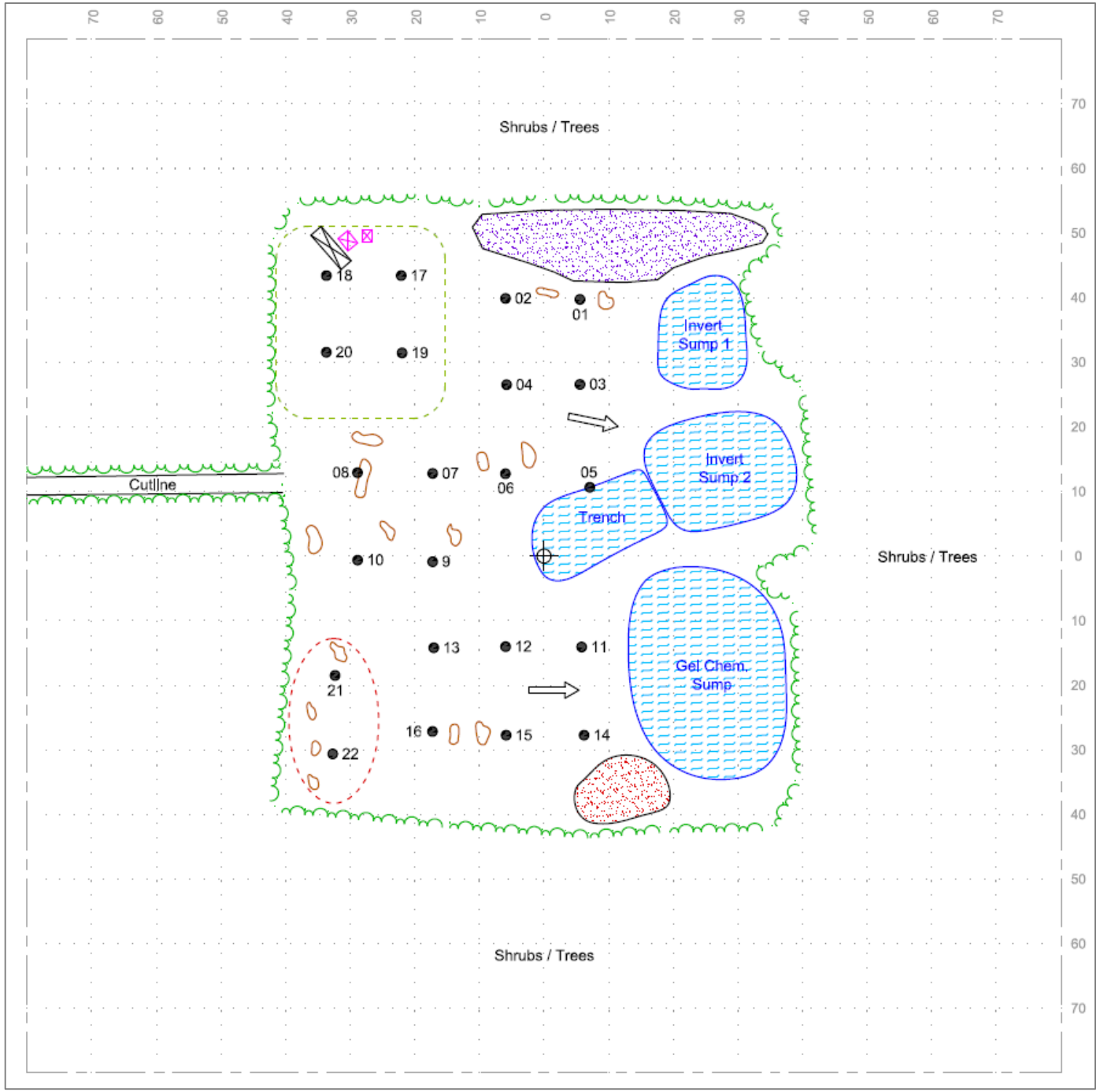
Lift #3 Sample Chemistry T = 0				
Depth	PHC	Sep 2013		
		# samples	range	average*
0.00-0.30 m	F2	17 of 17	830-1900	1418±90

samples exceeding surface soil guideline value

*average mg/kg ± standard error

LEGEND

- Wellbore
- Sample Location
- Control Area
- Bare Area
- Former Gel Chem. Impacted Material Area
- Invert Sump 1 & 2 Impacted Materlal Stockplle
- Gel Chem. Cap Material Stockpile
- Sump
- Shrubs / Trees Edge
- Field Trailer
- Field Equipment
- Slope Direction



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Treatment Lift #3

June 2015

Phytoremediation summary:

- Treatment lift #3 was from September 2013 – June 2016.
- Lift was treated for PHC F2 only.
- September 2013 to June 2014 had F2 decrease of 60% (1417 mg/kg to 610 mg/kg).
- June 2014– September 2014 had F2 decrease of 50% (610 mg/kg to 307 mg/kg).
- 2015 – Earthmaster was onsite.
- June 2015 – September 2015 had F2 decrease of 7% (296 mg/kg to 276 mg/kg).
- Lift #3 was targeted to be placed in the excavations at subsoil depth.

Treatment Lift #3

September 2015

Treatment Lift #3

- End of growing season (September 2015) for treatment lift #3.
- Treatment lift #3 was ripped to incorporate organics.
- Soil samples were collected from the assessment points.
- The site was not seeded.
- Soil would be stripped in the spring based on laboratory results.

Treatment Lift #4

- Grids corresponding to sample points 06, 12, 13, 15, 21, and 22 were stripped
- Stripped soil was homogenized with the remaining invert 1 and 2 stockpile.
- Treatment area was re-contoured.
- Homogenized pile (1,600 m³) was spread over the treatment area to form lift #4.
- Excavations were sampled to evaluate remaining contamination.

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Treatment Lift #4 – Challenges

June 2016

Treatment Lift #4

Phytoremediation details:

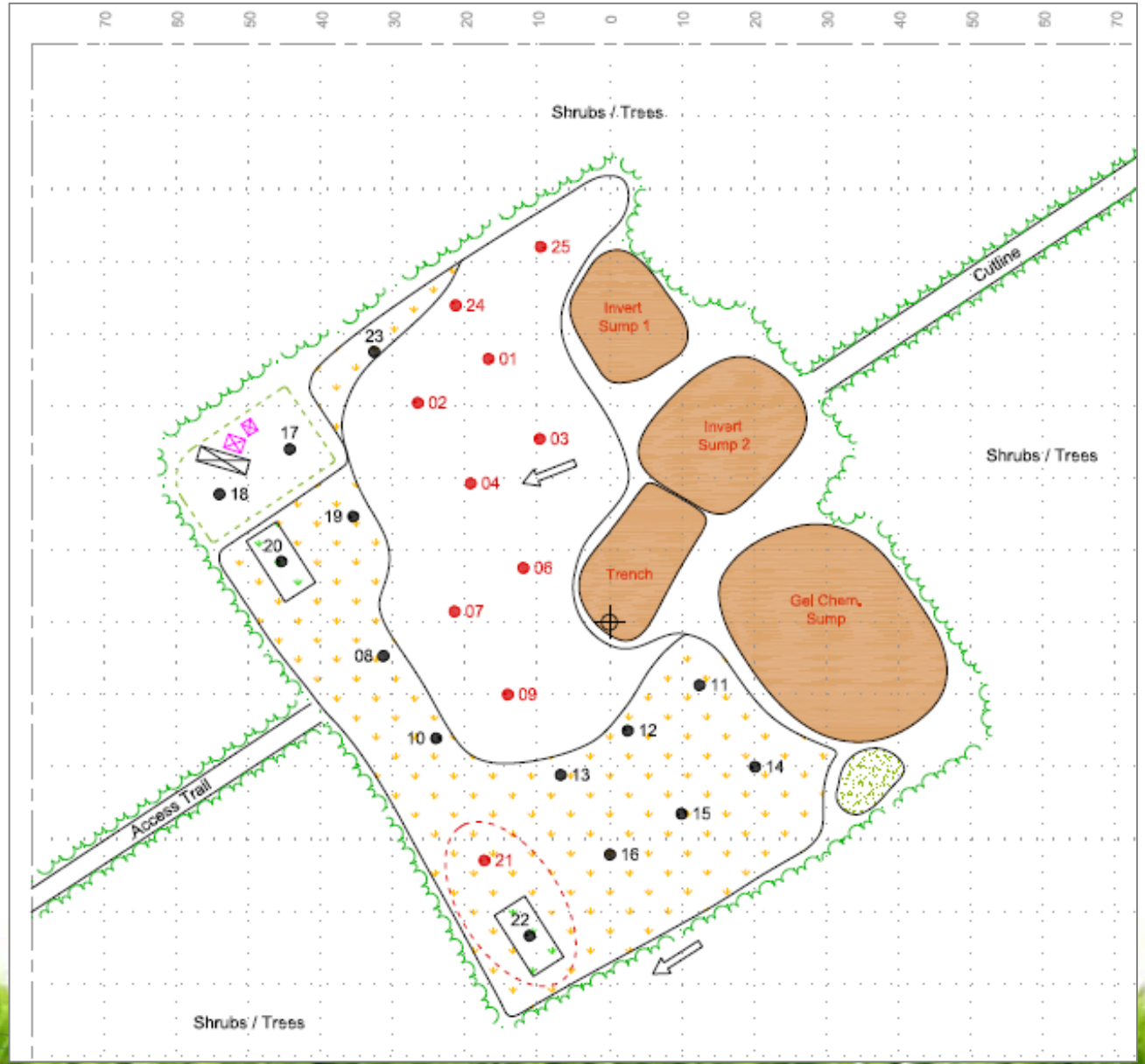
- **Lift #4** T=0 July 2016
  - Invert 1 and 2 stockpile mixed with grids from lift #3 (1,600 m^3) was spread across re-contoured lift #3.
  - Treatment was for PHC F2 contamination.
  - 1,250 m^3 were stripped in June 2017 and placed in an excavation.
- Seed – ARG, SWG, CRF
- PGPR – *Pseudomonas corrugata* and *P. marginalis.*

Lift #4 Sample Chemistry T = 0				
Depth	PHC	Jul 2016		
		# samples	range	average*
0.00-0.30 m	F2	23 of 25	268-1350	644±73

samples exceeding surface soil guideline value

*average mg/kg ± standard error

Treatment Lift #4 - Challenges



LEGEND

- Wellbore
- Sample Location (Remediated)
- Sample Location (Exceedance)
- Control Area
- Former Gel Chem. Impacted Material Area
- Topsoil Stockpile
- Historical Excavation
- Plant Growth Area
- CFIA Control Area
- Field Trailer
- Field Equipment
- Shrubs / Trees Edge
- Slope Direction

Treatment Lift #4

Phytoremediation summary:

- Treatment lift #4 was from June 2016 – June 2017.
- Lift was treated for PHC F2 only.
- June 2016 to September 2016 had F2 decrease of 44% (644 mg/kg to 360 mg/kg).
- 1250 m^3 of soil was stripped in June 2017 and placed back in the excavations.
- Grids associated with sample points that had guideline value exceedances were stockpile (350 m^3) for incorporation into lift #5.

Treatment Lift #5

January 2017

Treatment Lift #5

Phytoremediation summary:

- Treatment lift #5 was from June 2017 – September 2017.
- Lift was treated for PHC F2 only.
- New material excavated from pits and sumps (750 m³).
- Add to grids from lift #4 (350 m³)
- Lift #5 was spread on top of lift #3.

Lift #5 Sample Chemistry T = 0				
Depth	PHC	Jun 2017		
		# samples	range	average*
0.00-0.30 m	F2	21 of 25	263-826	385±41

samples exceeding surface soil guideline value
*average mg/kg ± standard error

- June 2017 to September 2017 had F2 decrease of 60% (385 mg/kg to 152 mg/kg).

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Treatment Lift #5 – September 2017

Treatment Lift #5

September 2017

Site Reclamation

July 2018

Site Reclamation

July 2018

Nota C-17 Site Summary

- 5,375 m³ of impacted soil have been treated in 5 soil treatment lifts.
- Impacted soil contained BTEX, PHC F1 to F4, salts (sodium and chloride), and some metals.
- Following treatment all soil met applicable remediation criteria.
- Final site restoration was completed in 2018 (i.e. contouring and re-vegetation).

Advantages of PEPSystems

Environmentally Responsible

- Green technology, driven by solar energy.
- Soil is conserved and reused, quality is improved.
- Small carbon footprint (no offsite disposal; minimal heavy equipment usage).

Suitable for remote locations

- Fly in seed and amendments, etc.
- No large scale equipment requirements or hauling requirements reducing truck traffic on roads.

Effective for challenging contaminants

- PHC fractions F3 and F4.
- Salts and metals.

Economic advantages

- Low cost as compared to other technologies.
- Overall remediation cost spread out over a number of years.

Economics of PEPSystems

Remote Site – PHC and Salt Contamination

- 5,375 m^3 of impacted soil was treated in 5 soil treatment layers.
- Phytoremediation costs have been $540,000 (not including excavation costs or equipment rental costs).
- Landfilling costs were estimated at $3.0 million.

Predictive Modeling for PHC Remediation

Goal: to predict the amount of time it takes PEPSystems to degrade PHC in soil based on starting concentrations and desired end point.

- Original models were developed by Dr. Bruce Greenberg using data from six phytoremediation sites in Alberta.
- Models have been updated based on additional sites in a variety of geographical locations in western Canada.
- Based on PHC fractions F2(C_{10-16}) & F3(C_{16-34}) remediation kinetic data.
- Observed 25-35 % remediation per year for both PHC fractions.
- The remediation rates followed first order exponential decay kinetics.

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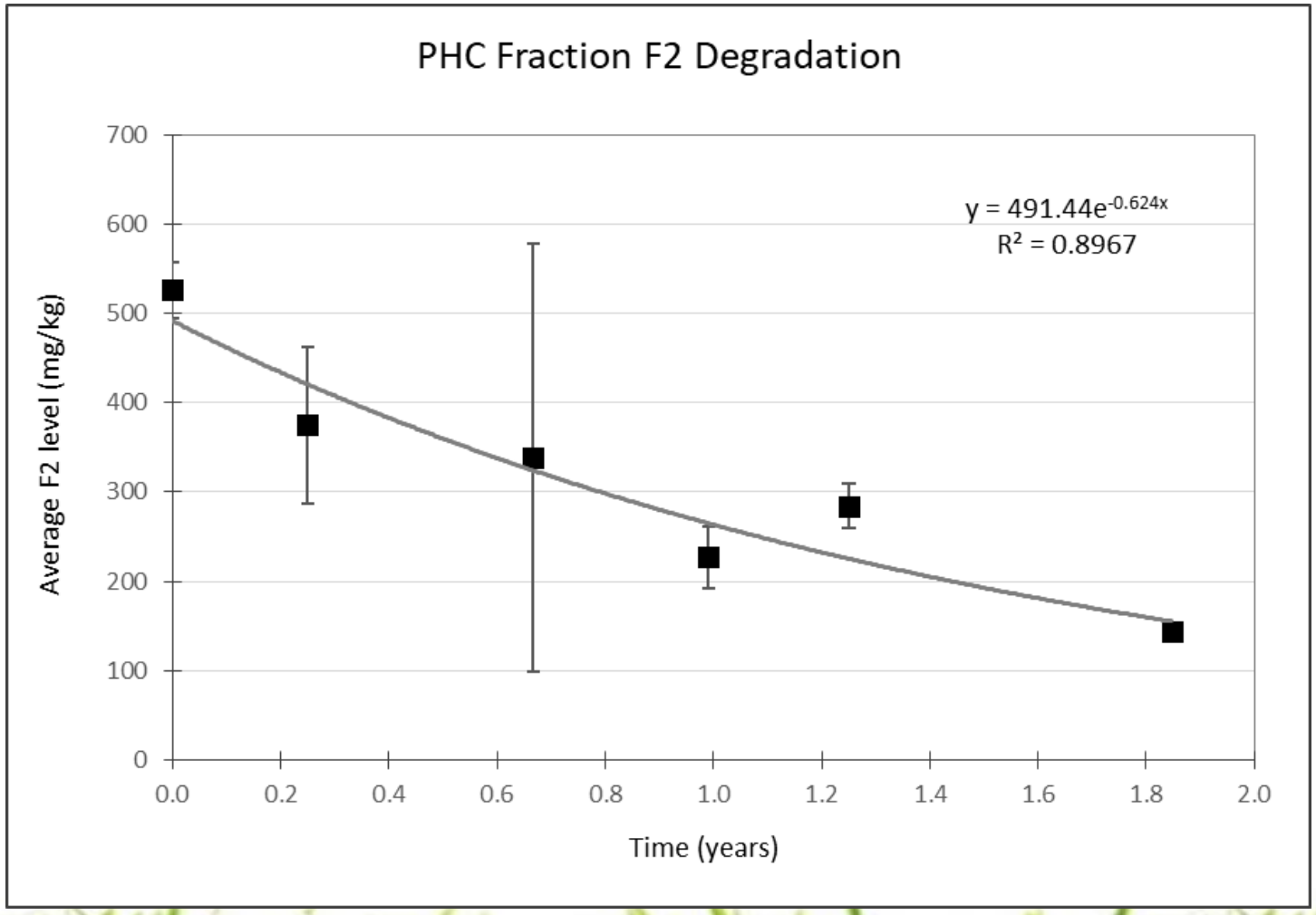
F2 Remediation Trend



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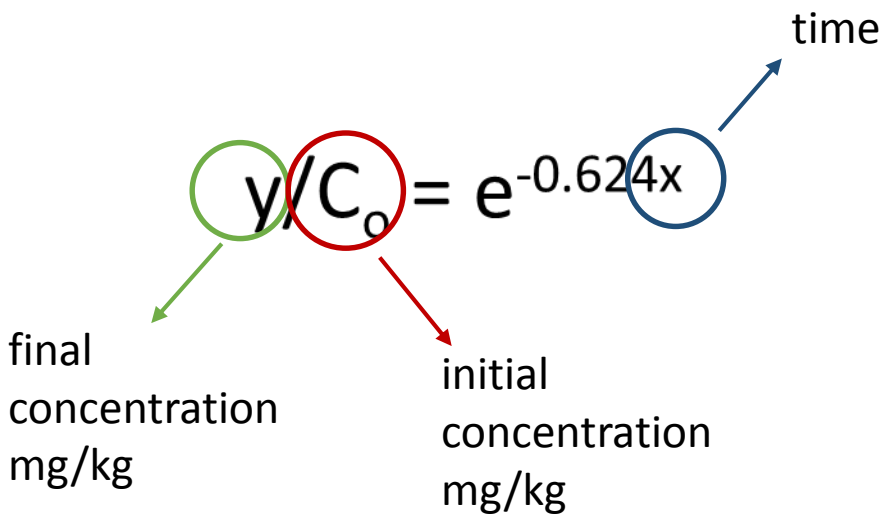
Limitations of the Model

Predictive models are based on whole site averages. Limitations include:

- Heterogeneous soil containing ‘hot spots’ which may require additional treatment time
- Lack of precipitation or very low soil moisture
- Poor agronomic practices
- Treatment zone thickness of 0.30 m
- Rooting depth of 0.30 m
- Extremely high PHC levels (F3 of >10,000 mg/kg) not tested

Predicting PHC Remediation Times



Lift #2

Depth	T=0 C_0	x yrs	$C_{2.0\ yrs}$
0.00-0.30 m	549	1.2	84

Lift #3

Depth	T=0 C_0	x yrs	$C_{2.1\ yrs}$
0.00-0.30 m	1418	2.7	275

Lift #4

Depth	T=0 C_0	x yrs	$C_{0.3\ yrs}$
0.00-0.30 m	644	1.5	360

Lift #5

Depth	T=0 C_0	x yrs	$C_{0.3\ yrs}$
0.00-0.30 m	644	0.6	152

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Taylor & Francis
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Check for updates

Kinetics of phytoremediation of petroleum hydrocarbon contaminated soil

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Ongoing PEPSystems Research

Improved Efficacy of Salt Impacted Soil

- Use commercial seed treatments in combination with PEPSystems to increase remediation efficiency.
- Three commercial seed treatments were tested in laboratory studies.
- One has gone on to field trials this past growing season.

Enhanced Reclamation

- Speed the re-vegetation of marginal soil.
- One field trial site in 2018 (±PGPR).

Phytoremediation of Trace Metals

- Suitability of PEPSystems for metal uptake.
- If it's bioavailable it can be phytoremediation.
- Working on securing industrial partners.

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Ongoing PEPSystems Research

Alternative Plant Species

- Flowering plants for road median work.
- Salt tolerant plant seeds treated with PGPR.

Alternative Bacteria Species

- Collaborations with other academic partners.

Bear Rock Sinkhole, NT

Acknowledgements

National Research Council – Industrial Research Assistance Program (IRAP).

Thank You

Questions?

Background Soil Sample Chemistry

Background Surface Soil Sample Chemistry 2004-2008	
F1	<12-<36 mg/kg
F2	<10-439 mg/kg
F3	18-822 mg/kg
F4	<10-375 mg/kg
Benzene	<0.004-<0.012 mg/kg
Toluene	<0.005-0.017 mg/kg
Ethylbenzene	<0.010-<0.030 mg/kg
Xylenes	<0.010-0.04 mg/kg

Background Sample Chemistry 2004-2008	
pH	7.4-8.0
EC	0.21-1.88 dS/m
SAR	<0.1-0.5
Na	2-16 mg/kg
Cl	<2.4-82 mg/kg

Background Subsoil Sample Chemistry 2004-2008	
F1	<12-4 mg/kg
F2	301-316 mg/kg
F3	563-699 mg/kg
F4	234-428 mg/kg
Benzene	<0.004 or <0.02 mg/kg
Toluene	<0.005 or 0.02 mg/kg
Ethylbenzene	<0.010 or <0.02 mg/kg
Xylenes	<0.010 or 0.03 mg/kg