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BC MEND Metal Leaching/Acid Rock Drainage Workshop
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UNIVERSITÉ DU QUÉBEC EN ABITIBI-TÉMISCAMINGUE
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Investigating the evolution of cover systems after vegetation colonization
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CONTENTS

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CONTENTS

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3

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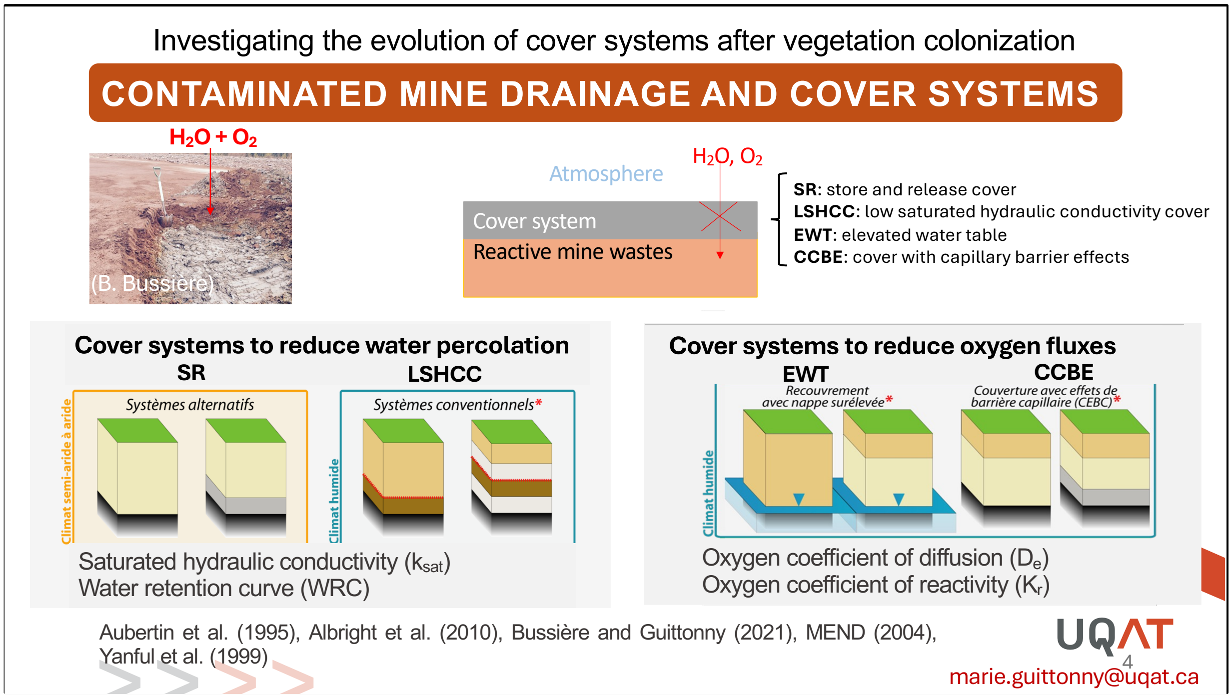

Cover systems are engineered works designed to control the oxygen and/or water fluxes that feed reactive waste oxidation. Their effective design ensures that the important hydrogeotechnical properties on which relies their efficiency remain adequate even in case of changes in boundary conditions of the cover system like fluctuations in precipitation and water table level, or **<u>vegetation presence</u>**.

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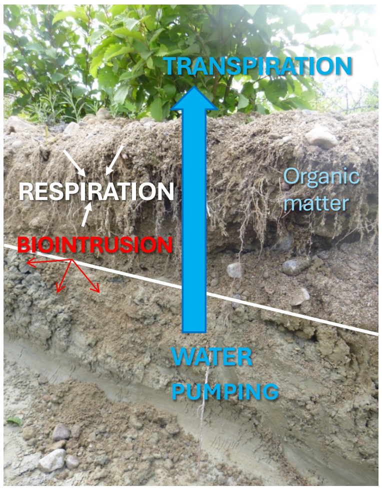
VEGETATION AND COVER SYSTEMS



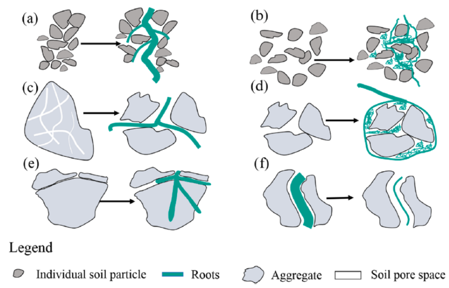


Fig. 1. Conceptualization of dominant processes involved in RIM of SHP: (a) re-orientation of the soil particles; (b) pore clogging; (c) macro-aggregate cracking; (d) micro-aggregate amalgamation; (e) root penetration and expansion; (f) root shrinkage and/or decay forming macro-pores.

→ Changes associated to vegetation still need work to be appropriately considered

Bussière and Guittonny (2021), Lu et al. (2020), Bodner et al. (2014), Ng et al. (2016), Ni et al. (2019), Grevers and De Jong (1990), Scanlon and Goldsmith (1999), Wick et al. (2007), Proteau et al. (2020)

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5

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Cover systems are inevitably colonized by vegetation with time. Vegetation presence modifies cover efficiency to control fluid migration by affecting water balance and material properties.
Plants intercept, pump and transpire water, shadow the soil. Roots reorganize the pore size distribution, shape and connectivity, by enhancing wetting-drying cycles and creating cracks, by exuding hydrophilic or hydrophobic organic components attracting soil organisms, and consume O_2 and produce CO_2.
Nevertheless, few studies have investigated root development in the specific material configurations of mine cover systems.
Moreover, root effects are rarely quantified, especially the associated hydrogeotechnical changes in material properties that can affect the performance.

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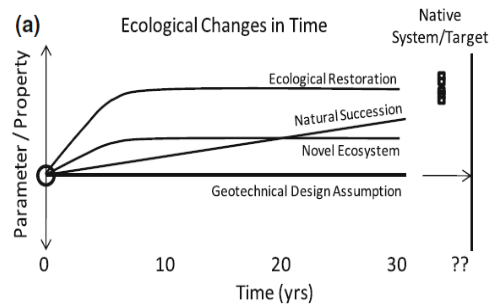
CHALLENGES TO OVERCOME TO CONSIDER VEGETATION EFFECTS

Statements

- Cover systems are young engineered works
- Vegetation development is particular in cover system environment
- The trajectory of plant community evolution in space and time is uncertain



DeJong et al. (2015)

Associated challenges

→ Anticipate the long-term evolution of vegetation effects on cover systems
→ Obtain representative vegetation input parameters for modeling
→ Overcome disciplinary barriers

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PRESENTATION OBJECTIVES

Present several approaches to integrate potential vegetation effects in the evaluation of cover system performance through research case studies:

1) Quantifying evolving material properties: root effects on saturated hydraulic conductivity
2) Using unsaturated hydrogeological modeling: including water transpiration
3) Using natural analogues: obtaining long-term rooting parameters

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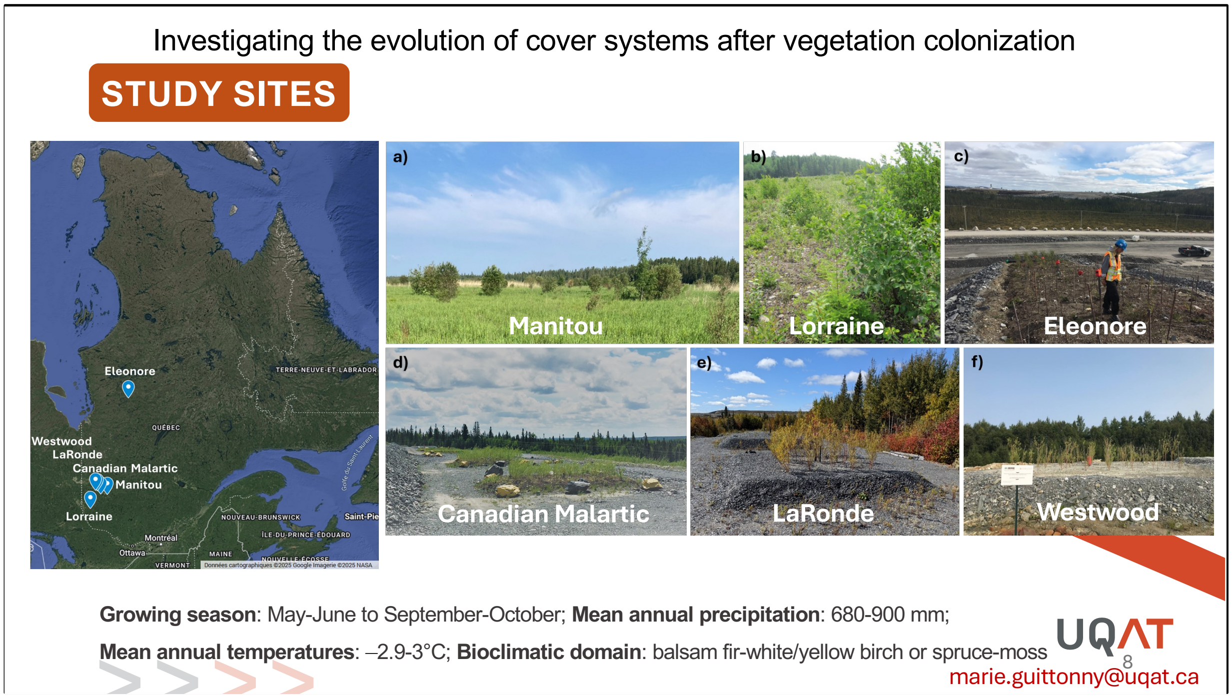
Travaux des 10 dernières années



The investigated regions (Abitibi-Temiscamingue and Eeyou Istchee in north-western Quebec) were dominated by boreal or northern temperate forests.

The investigations took place in constructed cover systems at the site scale, intermediate scale in field experimental cells, or in the laboratory.

Vegetation age varied from 1 season (laboratory), 3-4 years (experimental cells) to 12-17 years (reclaimed sites).

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9

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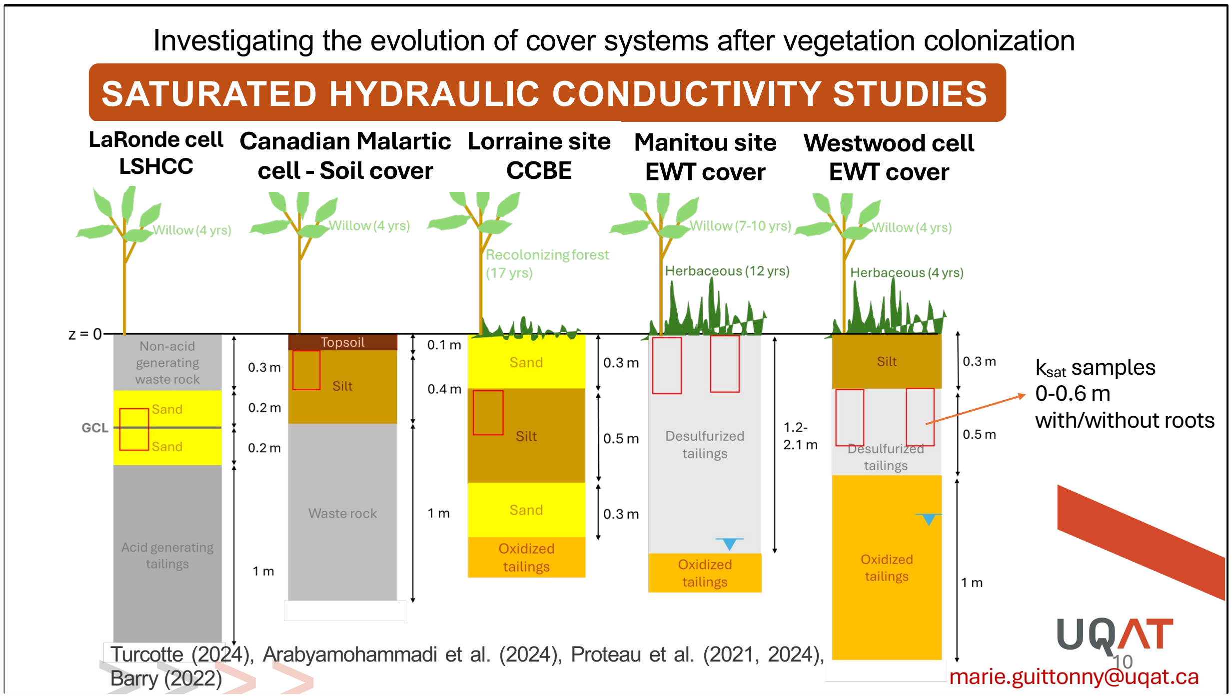
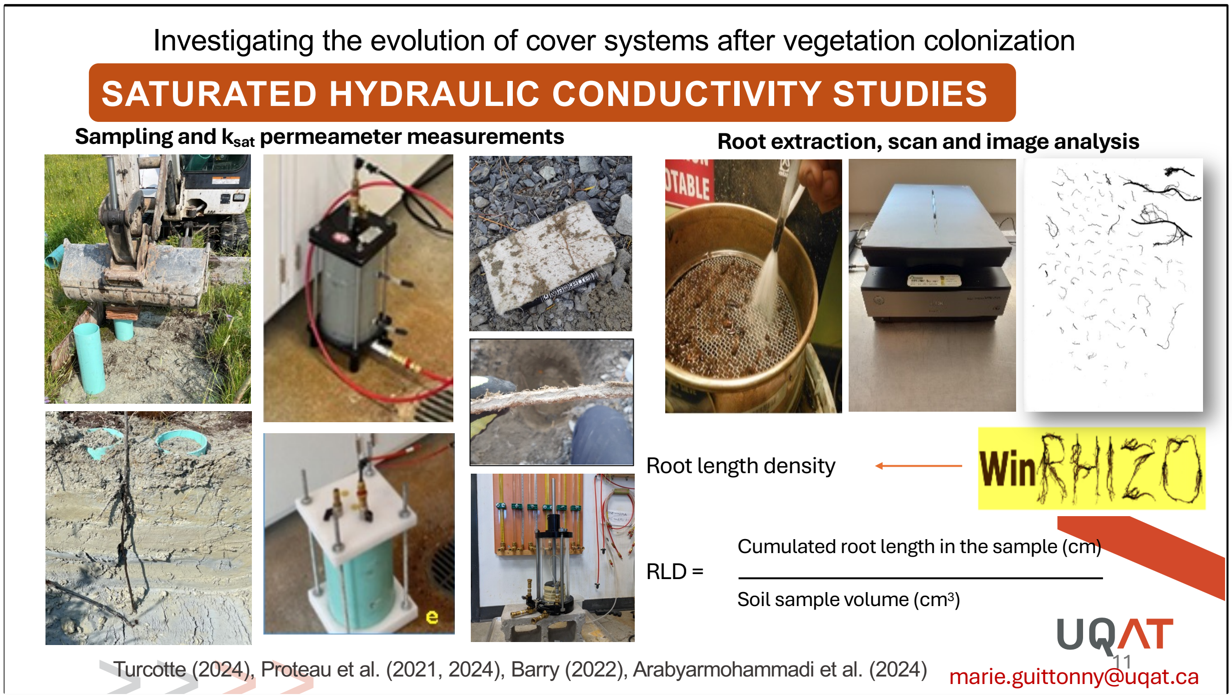
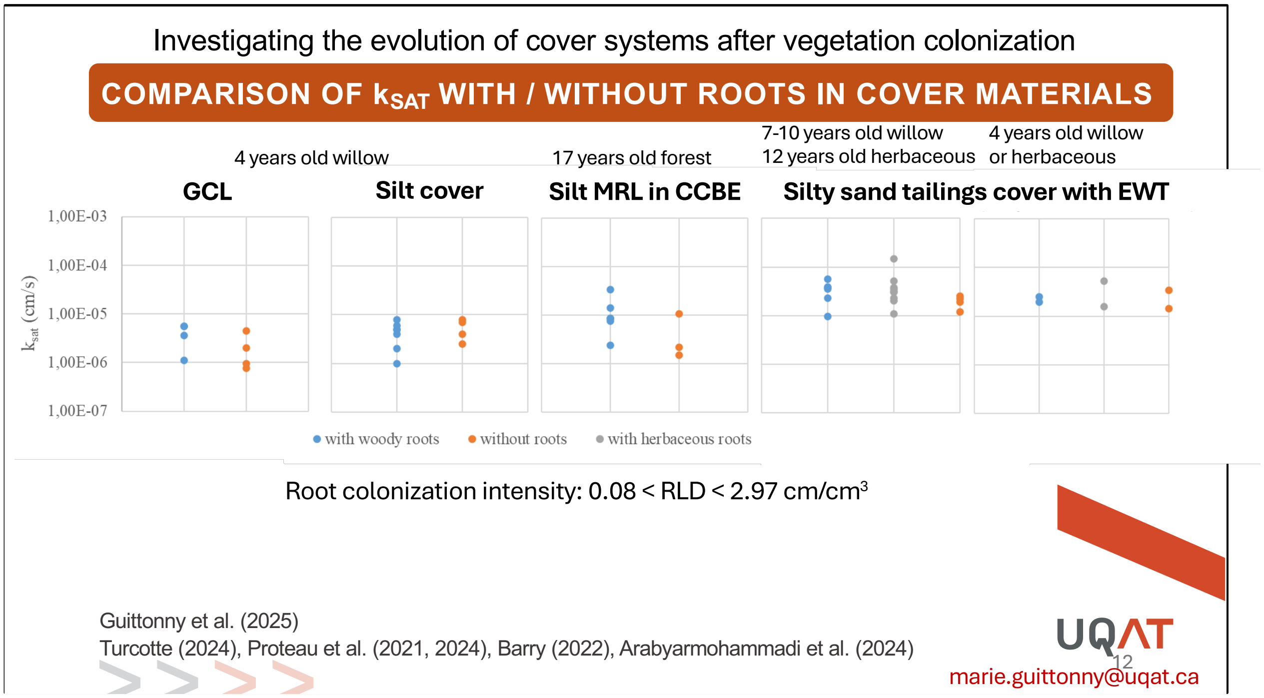


Case studies mainly investigated woody plants, but also agronomic herbaceous plants typically used to revegetate mine sites. Age.
Cover systems spanned from low saturated hydraulic conductivity cover systems to oxygen barrier like covers with capillary barrier effects and covers combined to elevated water table.
Various materials (GCL, natural silt, recycled tailings) colonized by roots from 0 to 0.6 m deep were collected to measure ksat in the lab and compared to controls without roots.



Undisturbed samples were collected in each barrier material layer, then transfered in a rigid wall or flexible wall permeameter to measure ksat in the lab. Then, root colonization in terms of RLDs in each material were measured by image analysis after root extraction.



Comparisons of saturated hydraulic conductivities (k_{sat}) measured with and without roots in the core material layers achieving the barrier effects in the tested cover systems in five case studies. The tested materials spanned k_{sat} values from 10^{-7} to 10^{-4} cm.s^{-1} from clay (GCL) to silty sand (tailings).
there was little difference (< 10^{-1} cm.s^{-1}) between k_{sat} values measured on materials colonized or not by roots considering that the precision of measurements with permeameters is around half an order of magnitude (Khirevich et al. 2022). Moreover, the difference between the values in two sets of samples (with or without roots) for each material was similar to the range of variability among measured values inside each set of samples.
The measured k_{sat} values in the in situ GCL were high, whether colonized by roots or not, compared to the k_{sat} measured in new intact samples of the same GCL (5.4×10^{-8} cm.s^{-1}, results not shown). Several in situ factors can be responsible of these higher values like cationic exchanges with infiltrating water and freeze-thaw cycles that can affect the GCB integrity with time (Chevé 2019, Rowe 2020) and should be further investigated.

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COMPARISON OF k_{SAT} WITH / WITHOUT ROOTS IN COVER MATERIALS

Some lessons learned

- At the young stages of woody vegetation that were investigated (4-17 years), **fine roots** (diameter < 2 mm) are still **dominating** the colonization of the barrier layers. They have limited impact on **measured k_{sat}** values, which remained in the range of values at the **construction stage**.

- Results were obtained with **willows** and **poplars** with rapid and extensive root colonization and tolerance to temporary soil saturated conditions (Kuzovkina and Volk, 2009). It may fall among the **worst-case scenarios** of root deep colonization in cover systems compared to other boreal plant species.

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13

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k_{sat} values remained in the range of values at the construction stage, which is encouraging regarding the preservation of cover performance over years despite vegetation presence

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INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

Vegetation parameters in hydrogeological numerical modelling

- Unsaturated hydrogeological models (like SEEP/W, HYDRUS, SWIM, LEACHM, UNSAT-H, SHAW) can include vegetation effects on the transpiration and storage variation components of a cover system.

- Growing season length

- **Leaf area index (LAI)** = total leaf area (one side) by unit of soil surface
- Vegetation height
- Vegetation cover

- **Maximum rooting depth (Rt_{max})**
- **Root length density (RLD)** = cumulated root length by unit of soil volume
- Reduction factors

Bussière and Guittonny (2021)

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15

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Several vegetation parameters used as inputs.

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INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

Long-term vegetation parameters in hydrogeological numerical modelling

1) Vegetation scenario formalization

- Conservative approach: maximal values for the parameters potentially negatively influencing the performance (LAI, Rt_{max})
- Realistic approach: mean or representative values of the whole plant community
- Combine parameters to build scenari

2) Sensitivity analysis

- Range of parameter values to be sequentially input in the model

Botula et al. (2021)

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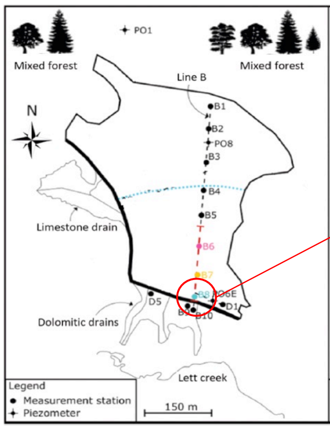
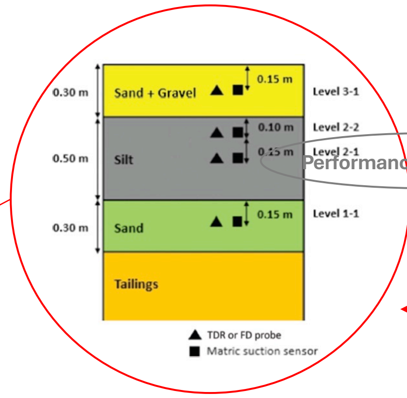
INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

Lorraine CCBE case study



Botula et al. (2024)

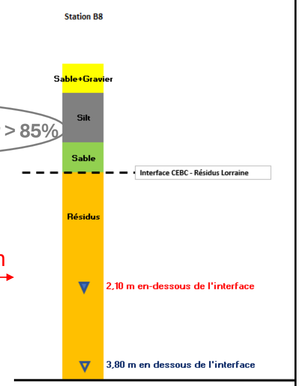
In situ instrumented station



Performance criterion: Sr > 85%

Calibration

Conceptual 1D model SEEP/W
(GeoStudio 2021 R2)



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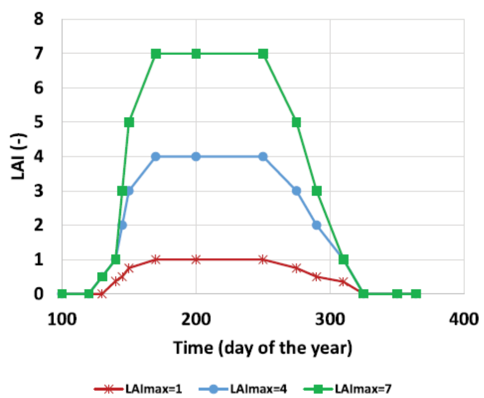
INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

Lorraine CCBE case study

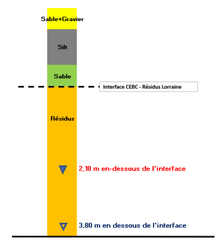


Vegetation scenari

Sparse forest (recolonizing)	Dense mature forest (poplar dominance)	Dense mature forest (maple dominance)
LAI = 1	LAI = 4	LAI = 7

Rt_{max} = 50 cm or 80 cm

Model top boundary conditions



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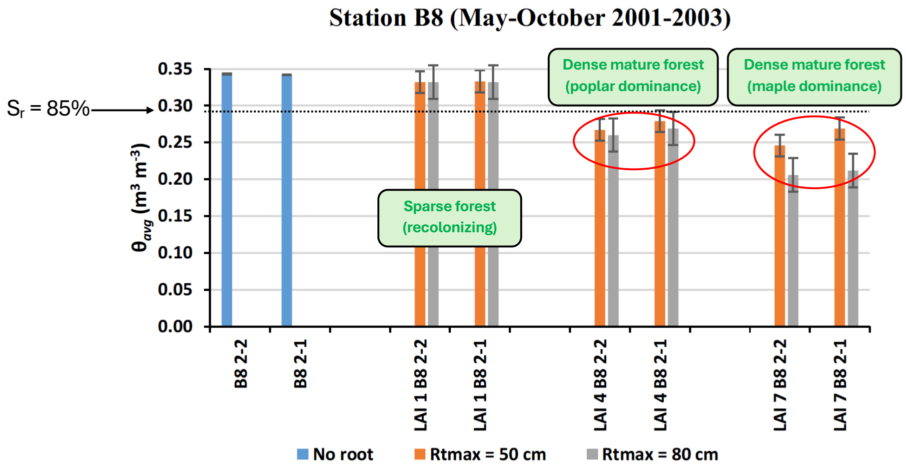
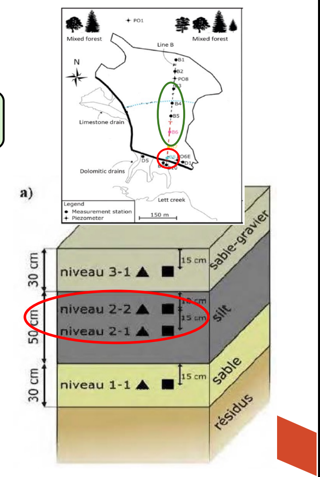
INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

Lorraine CCBE case study





Botula et al. (2024)

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19

This negative effect of vegetation evolution on the performance was observed for the B8 station only, which is the closest to the southern dike, with the lowest level of the water table.

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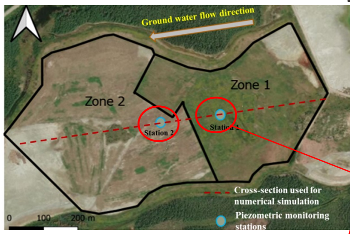
INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

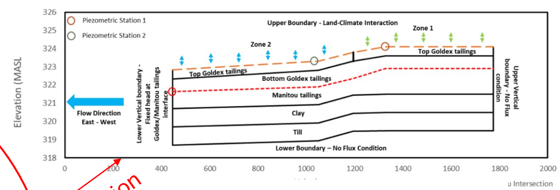
Manitou EWT case study



In situ instrumented stations

▲ VWC sensor
■ Suction sensor
▌ Well point

Calibration



2D conceptual model SEEP/W
(GeoStudio 2021 R2)

Performance criterion : EWT above reactive tailings interface

Mujtaba et al. (2025)

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20

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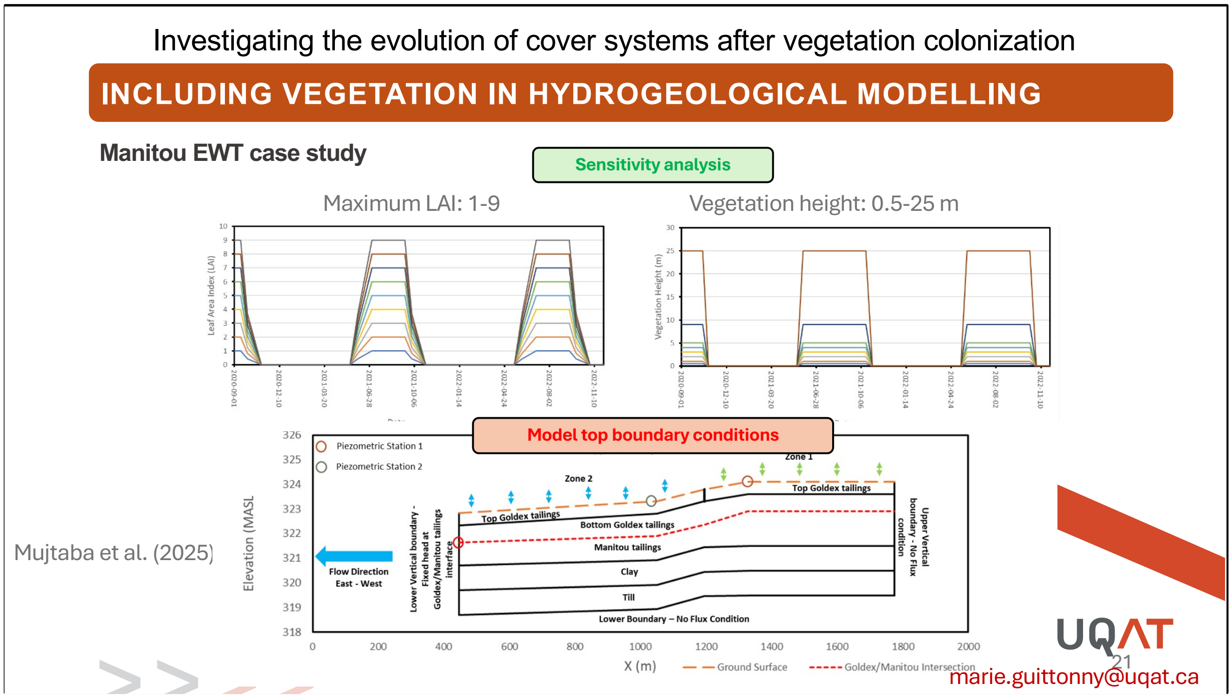
Several vegetation parameters used as inputs.



Severeal vegetation parameters used as inputs.

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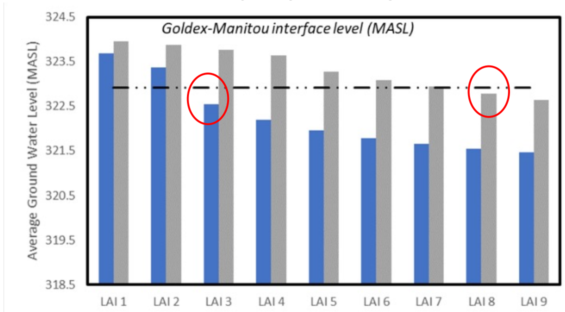
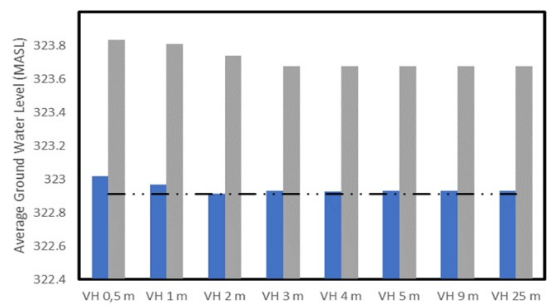
INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

Manitou EWT case study

Maximum LAI: 1-9



Vegetation height: 0.5-25 m



LAI ≥3 → below the design criterion for a dry season (2021)
LAI ≥8 → below the design criterion for a normal season (2022)

Height → low influence on the performance

Mujtaba et al. (2025)

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INCLUDING VEGETATION IN HYDROGEOLOGICAL MODELLING

Some lessons learned

- The modelling outputs are sensitive to vegetation LAI values and the performance of the tested covers is affected by LAI increase.
  → Adjust cover design (e.g. change thickness, material properties)
  → Control vegetation evolution (e.g. decrease aboveground leaf area)

- **Limits**: numerical simulations are simplified, complex to calibrate, thus exploratory.
- **Recommendations**: validate the model ability to realistically predict vegetation effects on the cover performance by measuring on one side the evolution of vegetation parameters and on the other side the cover performance and checking concordance with modelling outputs.

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23

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Two options if it happens...
However, since ... it is recommended to...
Simplification: Does not take into account vegetation effects on run off, interception, infiltration, etc.
Complexity: Calibration implies adjusting simultaneously material properties and vegetation parameters: multiple possibilities.

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USING NATURAL ANALOGUES OF COVER SYSTEMS

What is an analogue?

- A physical system used to represent another system that is difficult to observe or analyze due to its size or to the distance at which it is located in space or time (Sterett 2017).

What is a natural analogue?

- An analogue that is submitted to natural ecological processes, including vegetation.

Relevance to use a natural analogue of a cover system

- A system that has common characteristics with a cover after construction but submitted to processes that cannot already be apprehended by field studies in the short term or by existing numerical models (Albright et al. 2010).

→ It allows oneself to project in time regarding potential vegetation effects

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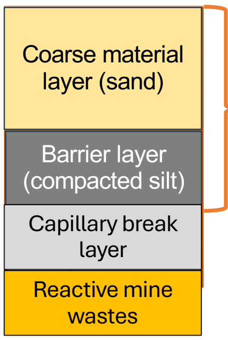
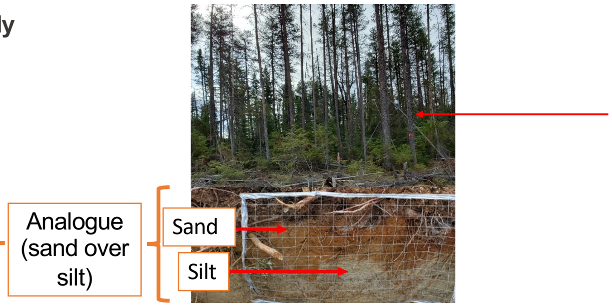
USING NATURAL ANALOGUES OF COVER SYSTEMS

CCBE case study



Aubertin et al. (1995)



Jack pine mature community: tree often colonizing sandy soils under boreal climates

Cissé et al. (2022, 2025)

General selection criteria

- Essential characteristics that are associated to the cover system and control its performance are present in the natural analogue.
- Soil and vegetation conditions are close to those anticipated or desired in the long-term on the cover system.

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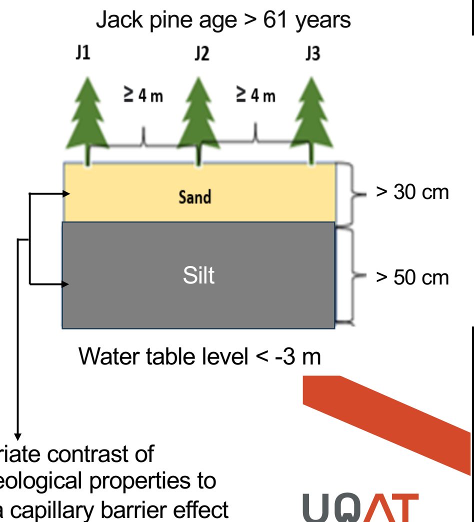
USING NATURAL ANALOGUES OF COVER SYSTEMS

Step by step analogue selection

- **Site selection**: Favorable stratigraphy with alternate coarse and fine layers of materials, no slope → one site
- **Plot preselection**: mature jack pines with adequate spacing → 12 plots (16 × 16 m)
- **Final plot selection**: 30 drills to measure the water table depth and the material layer thicknesses → 3 plots
- **Trench validation**: 54 trenches to measure grain size distribution and porosity of materials around 9 cut trees to measure their age → 44 selected trenches (81%)



Cissé et al. (2025)

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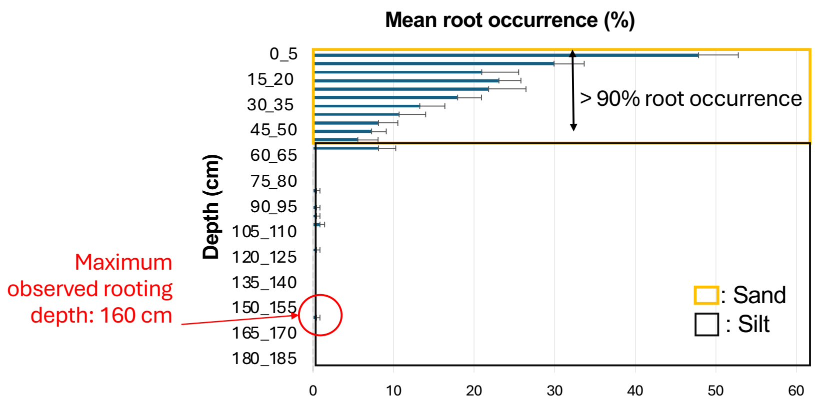
USING NATURAL ANALOGUES OF COVER SYSTEMS

Root profile characterization: maximum rooting depth



Cissé et al. (2025)

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USING NATURAL ANALOGUES OF COVER SYSTEMS

Some lessons learned

- Natural analogues can provide values of vegetation parameters close to the specific context associated to cover system
- Key vegetation parameters that influence cover system performance can be targeted, especially those used as input in modeling (LAI, Rt_{max})
- **Advantages**: valuable tool to practically demonstrate the compatibility between the long-term vegetation and the integrity of a cover system
- **Limits**: difficult to find some analogues that meet all analogy criteria, and limited to covers made of natural materials

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29

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CONCLUSION

Key messages

- **Vegetation** has a potential **important effect** on cover systems **performance** in the long-term and needs to be **integrated** in their **design** and **monitoring**.

- To evaluate **long-term performance** and maintain environment protection:
  → **Add vegetation** in physical and numerical models used for cover design
  → **Use analogues and sensitivity analyses** to anticipate the possible evolution of vegetation and cover material properties through time

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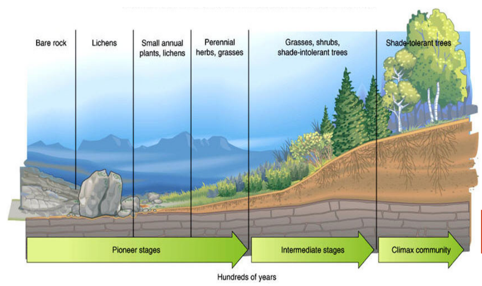
Investigating the evolution of cover systems after vegetation colonization

PERSPECTIVES

- To improve the consideration of cover systems as **evolving systems including vegetation** (DeJong et al. 2015; Piet et al. 2005):
  - → **Continued knowledge development** and **transfer** supported by **interdisciplinarity**.
  - → **Long-term monitoring** of vegetated cover systems to **validate anticipated evolution scenari** and their **effects.**

- In forest environments, longer-term **follow-ups of hydrogeological properties evolution** in parallel to **woody root diameter increase and possible coarse root decay** is recommended.



Credit: http://loretocollegebiology.weebly.com/primary-succession.html

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32

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Especially in cover systems whose performance relies on fine grained materials with initial maximum pore sizes smaller than root diameters.

Root biomass indeed increases during 100 years in forest stands then stabilizes or decreases (Yuan et Chen, 2010). (Lazorko and Van Rees 2012, Yuan and Chen, 2010)

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THANK YOU TO OUR INSTITUTIONS AND PARTNERS !

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Institut de recherche en mines et environnement

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33

Industrial and governmental partners, as well as funding organizations!

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