Remote Sensing and Machine Learning Accurately Predict Soil Moisture Dynamics within an In-Service Evapotranspiration Disposal Cell Cover

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Mission

LM's mission is to fulfill the Department of Energy's postclosure responsibilities and ensure the future protection of human health and the environment.

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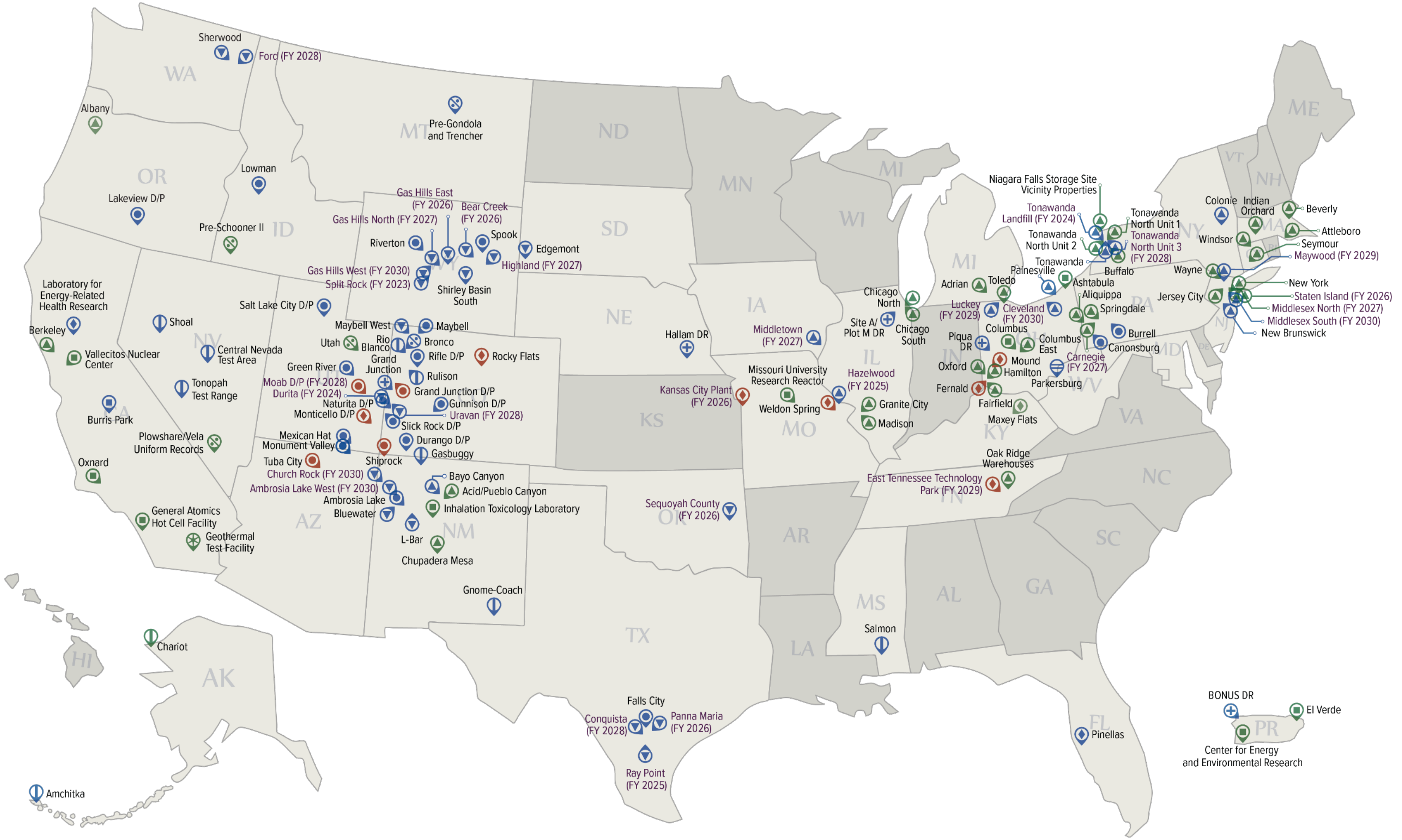
Site Map



Anticipated Sites in LM Through FY 2030 Requiring LTS&M

CERCLA/RCRA · D&D · FUSRAP · MED/AEC Legacy Site · Nevada Offsites · NWPA · Plowshare/Vela Uniform Program · State Water Quality Standards · UMTRCA Title I · UMTRCA Title II

Site Category

Category 1 activities typically include records-related activities and stakeholder support.

Category 2 activities typically include routine inspections (site visits are conducted to verify the integrity of engineered or institutional barriers) and monitoring/maintenance, records-related activities, and stakeholder support.

Category 3 activities typically include operation and maintenance of active remedial action systems, routine inspections (site visits are conducted to verify the integrity of engineered or institutional barriers) and monitoring/maintenance, records-related activities, and stakeholder support.

D/P = Disposal/Processing DR = Decommissioned Reactor 04/2023

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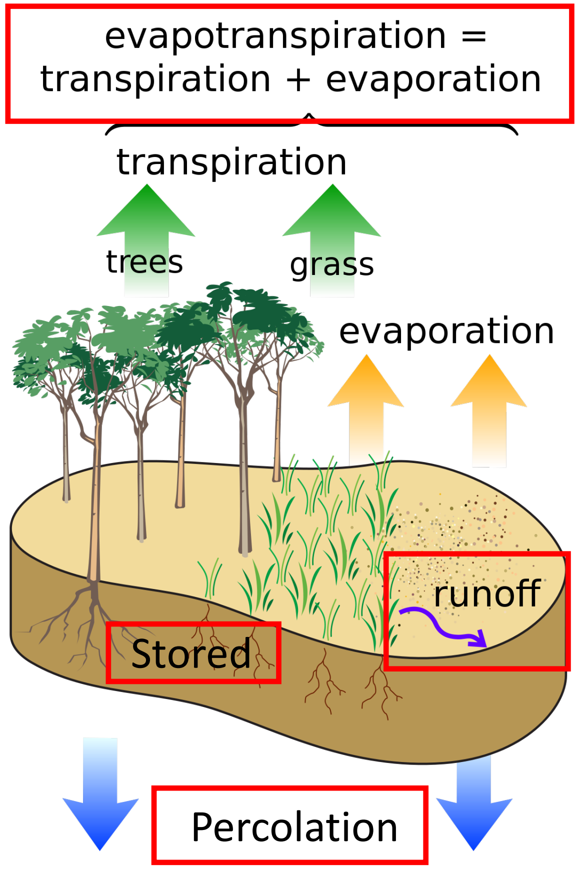
Background

- Conventional Uranium Mill Tailings Radiation Control Act covers include a “low-permeability radon barrier” to:
  - Limit surface flux of radon (NRC 1989).
  - Protect groundwater by controlling percolation (DOE 1989).
- Natural ecological and soil-forming processes have changed as-built engineering properties of conventional covers.
  - No longer have low-permeability, and radon diffusion and flux have increased (NRC 2011; NRC 2022)
- Investigating options for future management of selected conventional (unvegetated) covers as evapotranspiration (ET) covers
  - ET limits percolation
  - However, soil structure and drying by plants can increase radon diffusion and flux (NRC 2022)
  - Soil water content is a key performance parameter

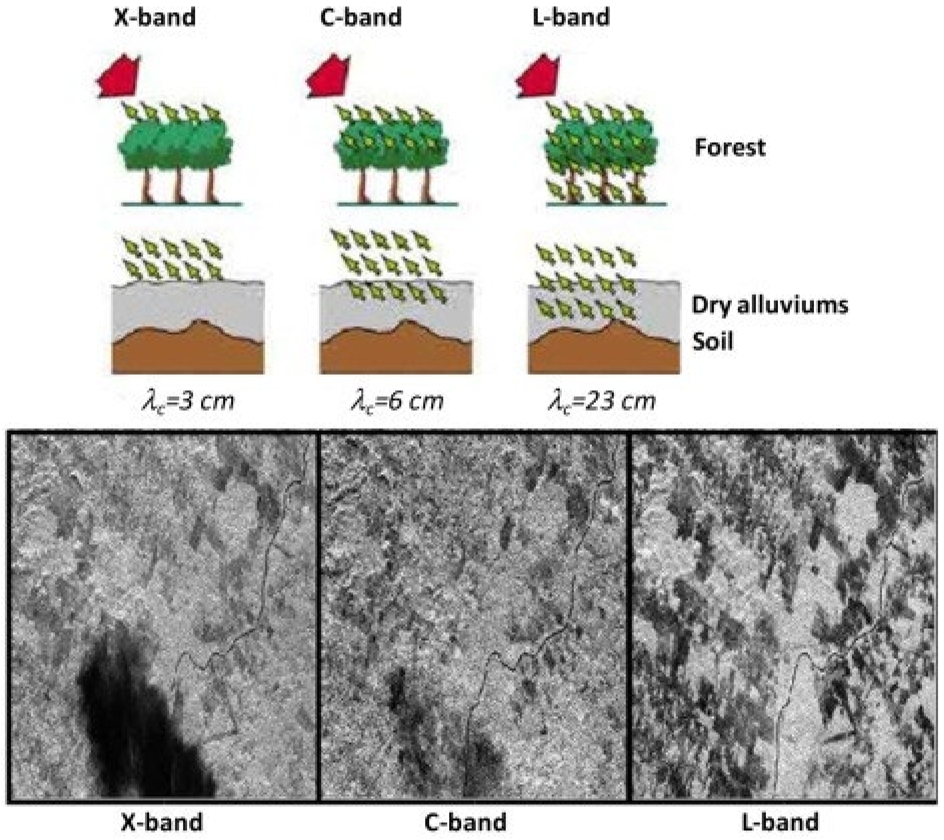


Objectives

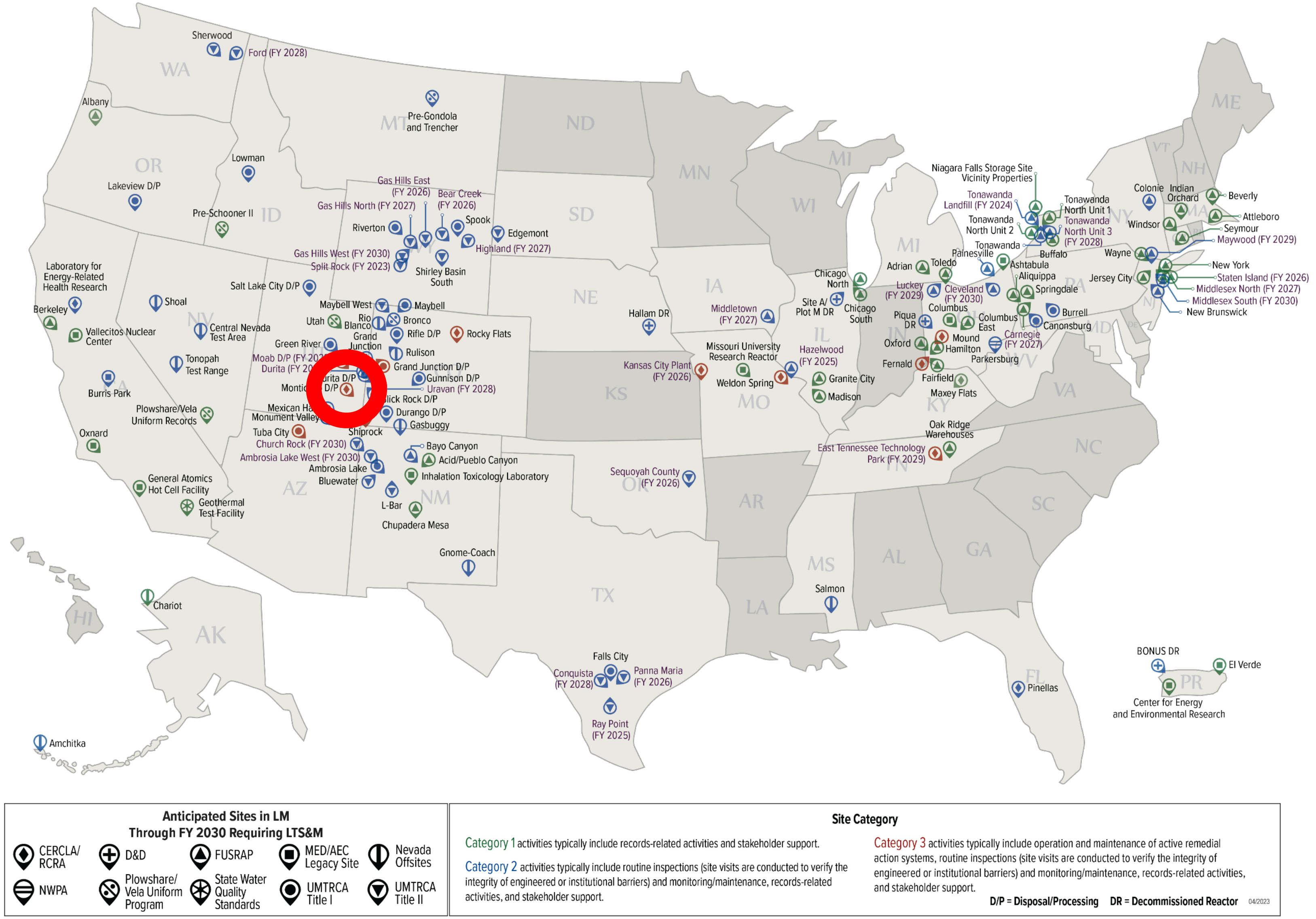
- Assess potential for direct soil moisture (SM) mapping using multifrequency synthetic aperture radar (SAR)
  - SAR sensitivity quantified through physical modeling of radar backscatter
  - P-, L-, C-, and X-bands
- Soil moisture profile mapping using multisource remote sensing
  - Test machine learning models using a field-scale lysimeter embedded within an in-service disposal cell for model training and validation
  - Freely available satellite SAR and optical remote sensing used as predictors for 3D SM mapping
- Potential tool for maintaining regulatory compliance at ET cover disposal cells

SAR

- Active imaging sensor
  - Emits pulses (bands) of microwave energy
  - Backscatter is used to identify/map features/materials on or below the earth's surface
  - ↑ frequency, ↓penetration
- Common bands
  - L and P (lower frequency)
  - C and X (higher frequency)
- Synthetic – uses motion to achieve a finer spatial resolution
  - Mounted on moving platform (aircraft, satellite)
    - Sentinel-1A/B in this study



Study Site



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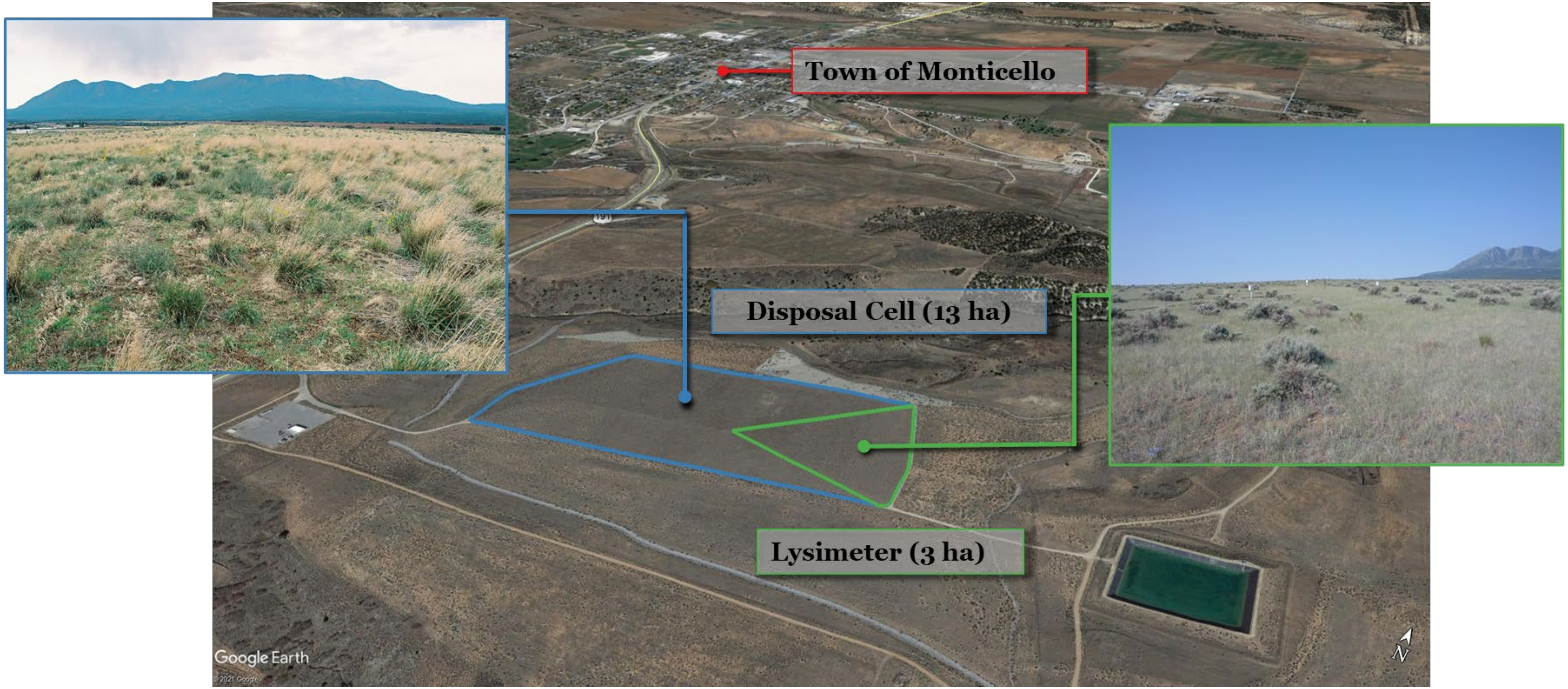
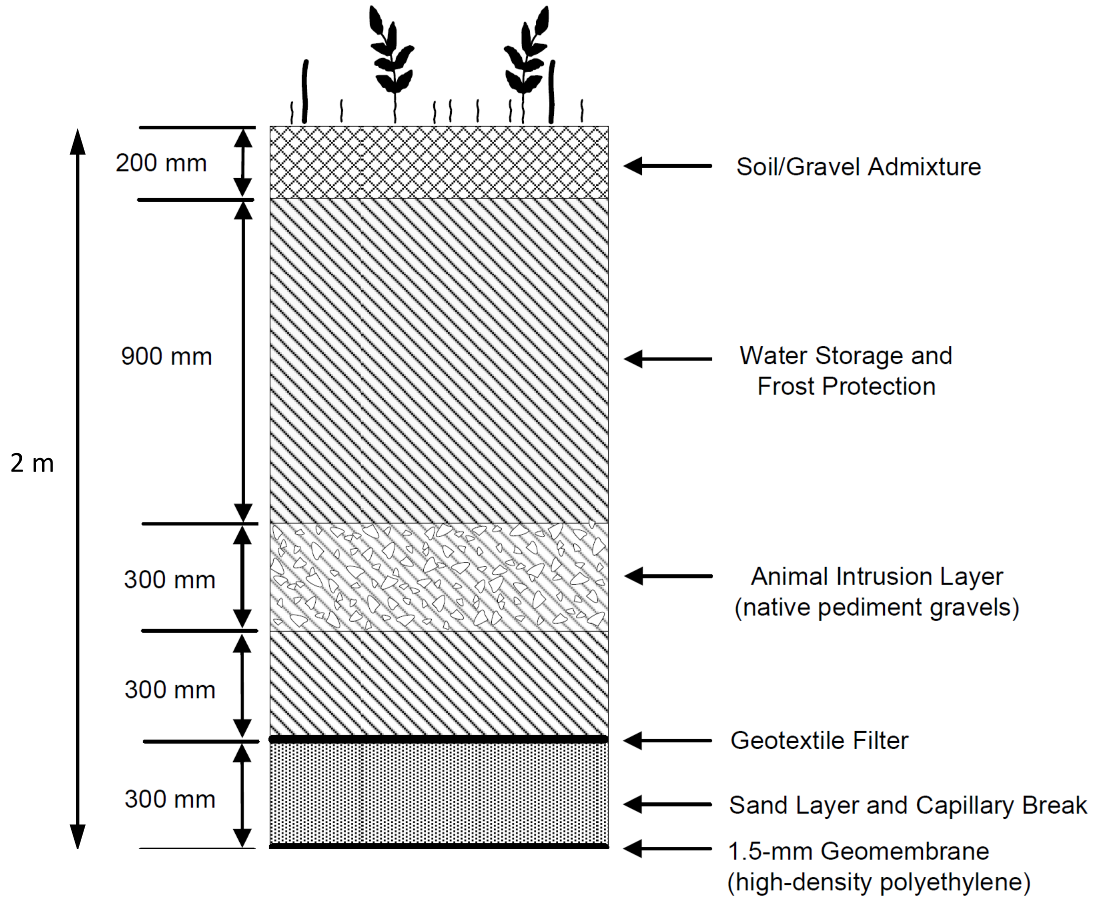
Monticello, Utah, Disposal Site



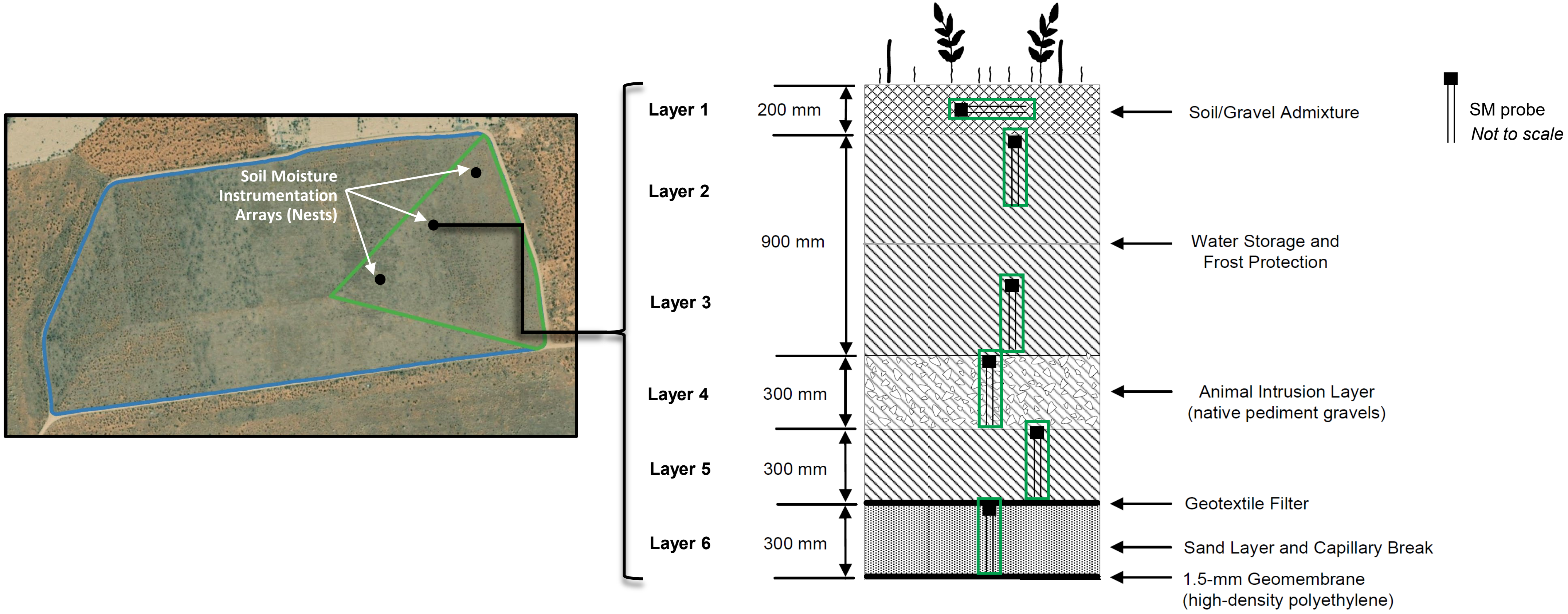
Monticello, Utah, Disposal Site Lysimeter

- Lysimetry
  - Allows us to quantify the components of the local water balance, where:
    - ET = precipitation − percolation − runoff − Δ water storage.
- Unique opportunity:
  - World's largest drainage lysimeter (observable by space satellite)
  - 20+ years of data

Vertical Profile of Cover/Lysimeter

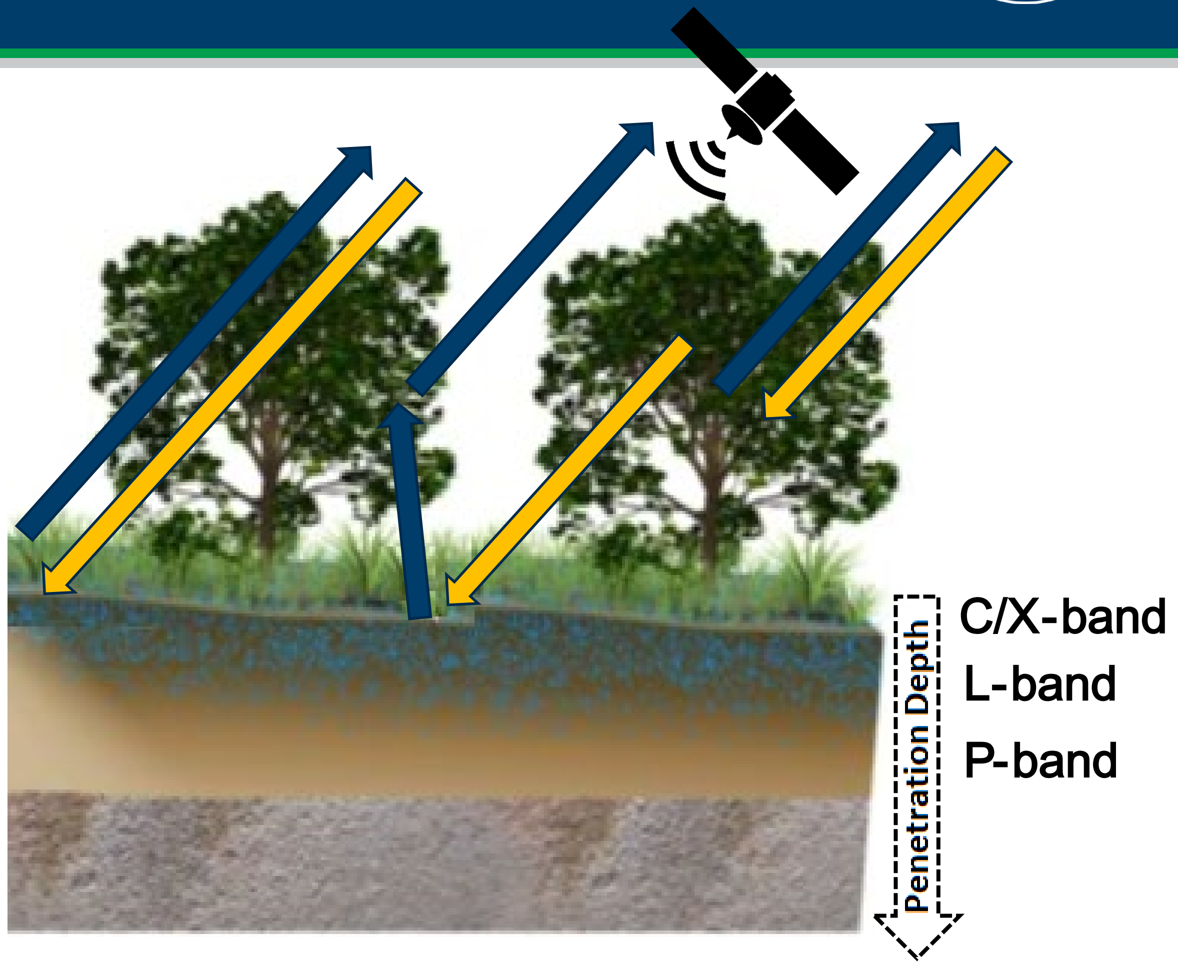


Soil Moisture Probes



Methods – Radar Backscatter Modeling

- **SAR backscatter modeling:**
  - Radiative transfer model used for simulating multifrequency (P-, L-, C-, X-band) microwave scattering and soil moisture sensitivity (Du et al. 2015)
  - Vegetation modeled as a collection of dielectric scatterers (e.g., discs for leaves, cylinders for stems)
  - Soil scattering modelled using Advanced Integral Equation Method (AIEM)
  - Multiple soil layers used to represent soil profile
  - Model parameterized using site vegetation and soil data



Radar backscatter consists of contributions from soil and vegetation and interactions between soil and canopy.

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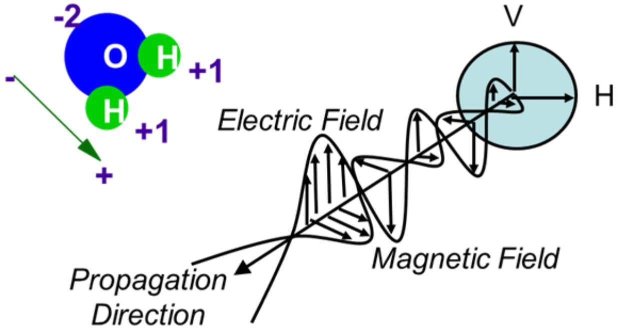
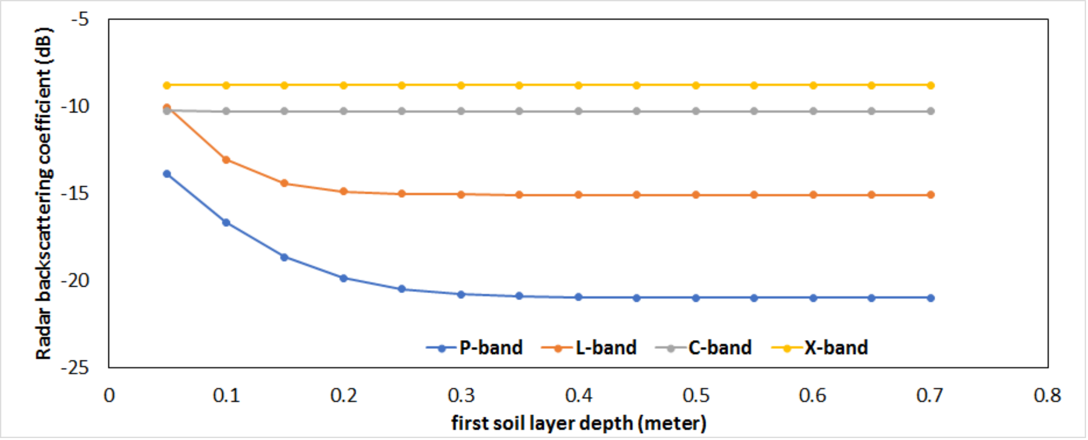
Results – Radar Backscatter Modeling

- Estimated multifrequency SAR sensitivity: P-band (0.43 GHz), L-band (1.27 GHz), C-band (5.404 GHz), X-band (9.6 GHz); incidence angle: 35 degrees; moderate shrubland vegetation cover
- Results confirm strong microwave sensitivity to soil moisture variability

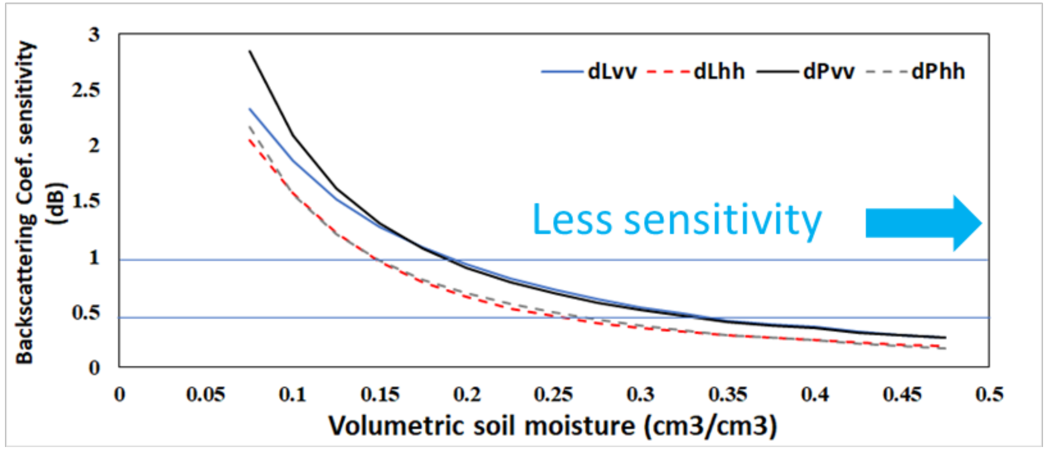


Radar backscatter change with topsoil depth*



*Two-layer soil: first layer depth from 5 cm to 70 cm, SM = 0.15 cm^3/cm^3; second layer: SM = 0.5 cm^3/cm^3

Radar backscatter sensitivity to Soil Moisture increase

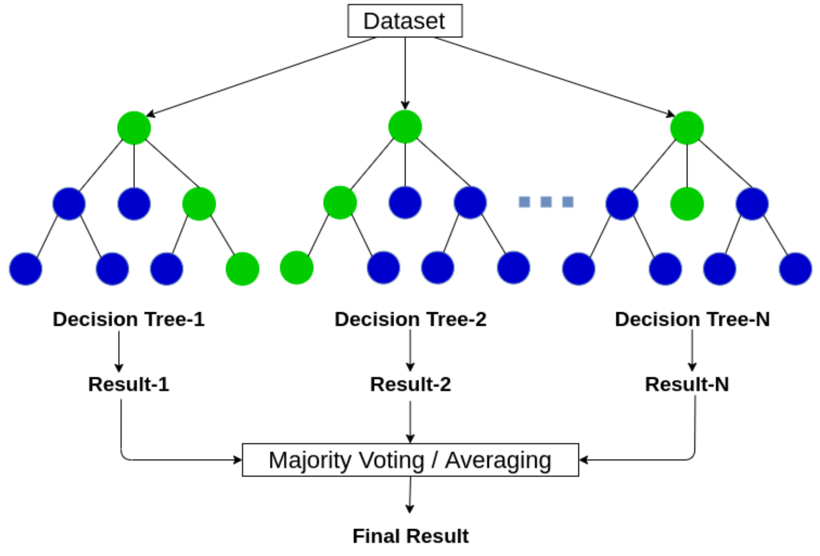


Results – Radar Backscatter Modeling

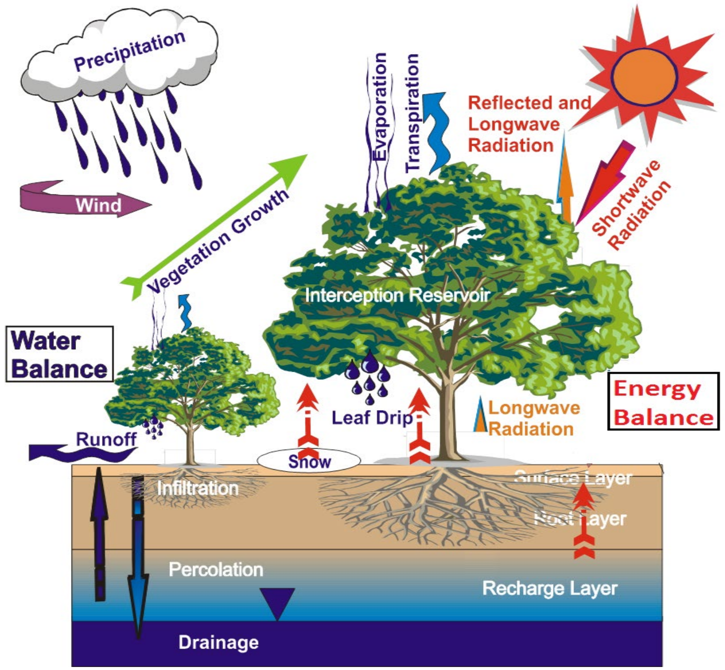
- Radar backscatter physical model established for simulating multifrequency radar sensitivity to soil moisture profile over semiarid shrubland
- Confirmed favorable SAR sensitivity over dry to moderate soil moisture levels
- All frequencies (C-, X-, L-, P-band) sensitive to similar SM dynamic range, but lower frequencies (L-, P-band) sensitive to deeper soil conditions
- Higher frequencies (C-, X-band) most useful for direct sensing of surface (0–1 cm) soil moisture and roughness
- Demonstrated capability of utilizing multiple SAR frequencies for mapping soil moisture profile

Methods – ML Models

- **Random forest (RF)**
- A forest of randomly created decision trees. Each node in the decision tree works on a random subset of features to calculate the output. The random forest then combines the output of individual decision trees to generate the final output.



Methods – ML Models

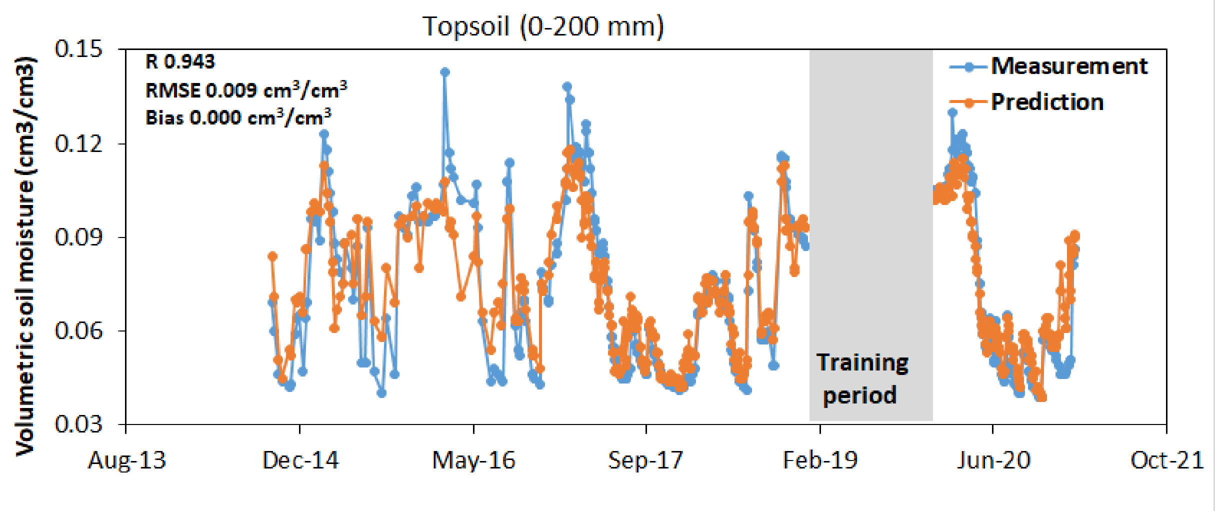


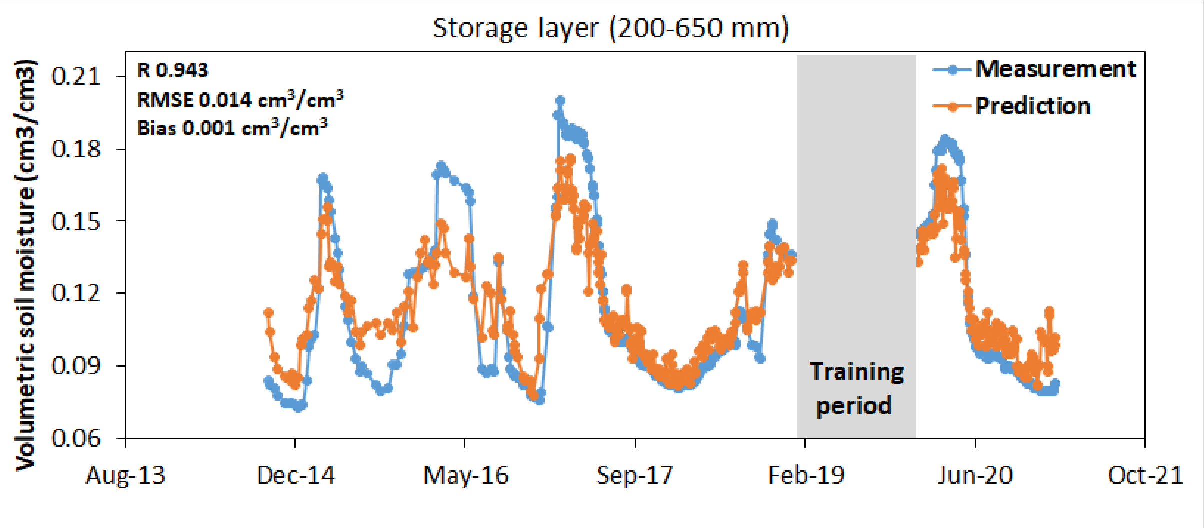
Soil moisture dynamics at different depths are governed by water and energy balance and are related to precipitation, ET, runoff, and soil properties and reflected by vegetation health.

- **ML models developed and tested for mapping soil moisture profile dynamics**
- **Predictors:**
- Sentinel-1 SAR C-band backscatter (30 m; 6- to 12-day repeat)
- Landsat normalized difference vegetation index (NDVI) (30 m; 16-day repeat)
- MODIS day/night (1:30 a.m./p.m.) land surface temperature (LST) difference (8-day)
- Accumulated precipitation (24-hour, 1-day; 1-, 2-, 3-, 4-, 5-week) measured by Daymet (Daily Surface Weather Data on a 1 km Grid for North America)
- **Target variable used for model training and validation:** measured soil moisture
- **Platform:** GEE

Results – ML Models

- In situ measurements from 2019 were used for training an RF model
- The RF model was applied to the other years for a more comprehensive accuracy assessment
- The RF model was applied to the whole study area and all the years of data production





High correlations (R ~0.94) and low uncertainties (RMSE ~0.01 cm3/cm3; bias ~0.00 cm3/cm3) between measured and predicted soil moisture in the first two layers (0–650 mm).

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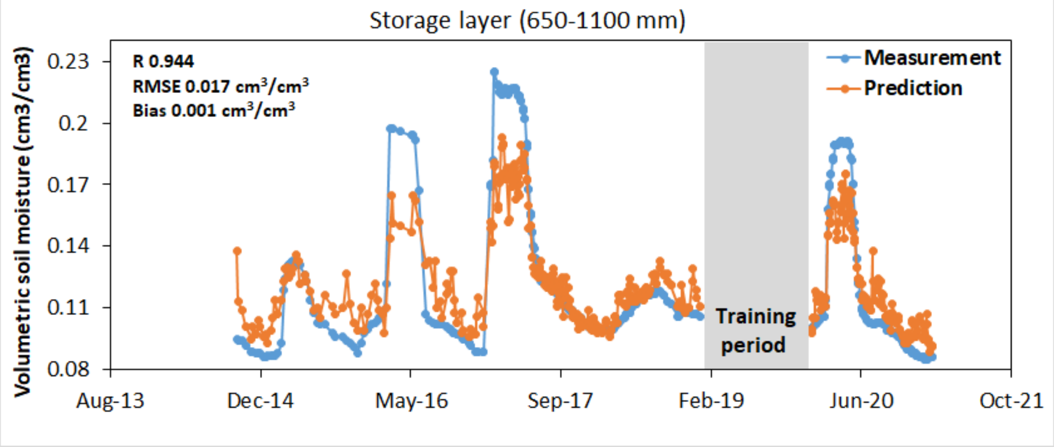
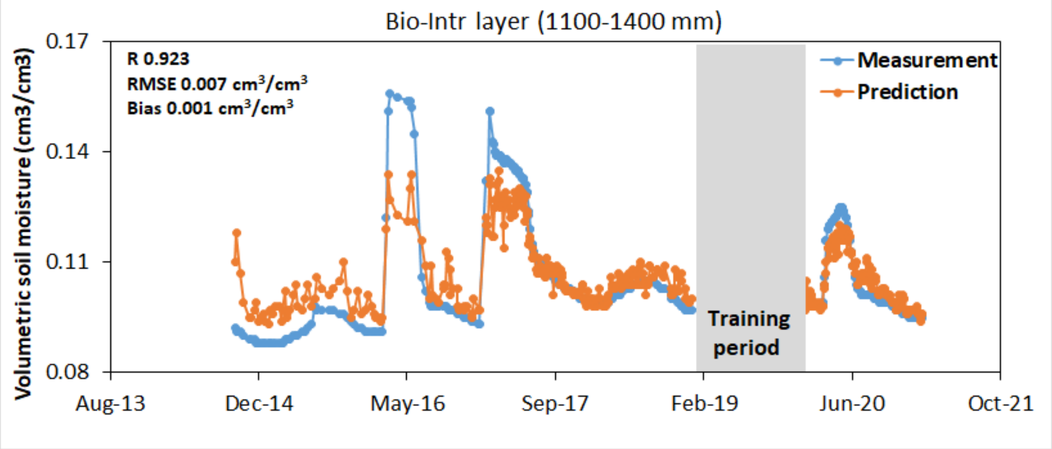
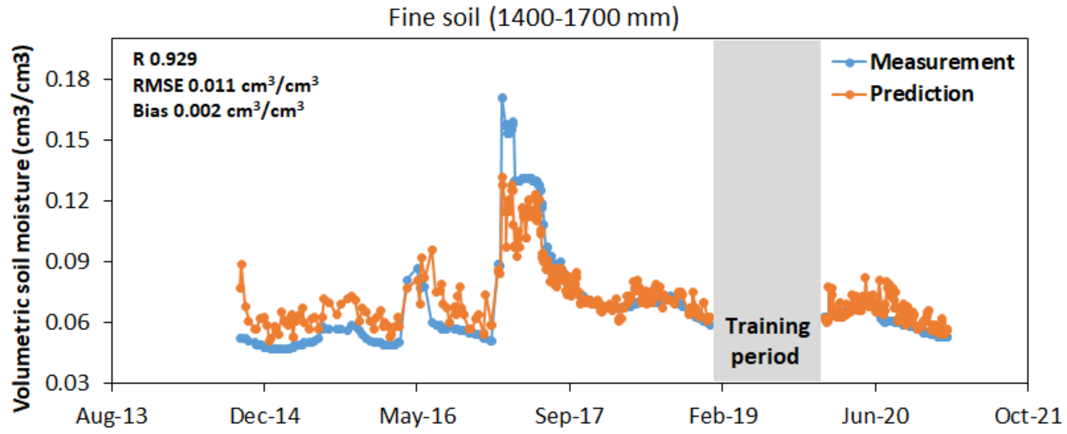
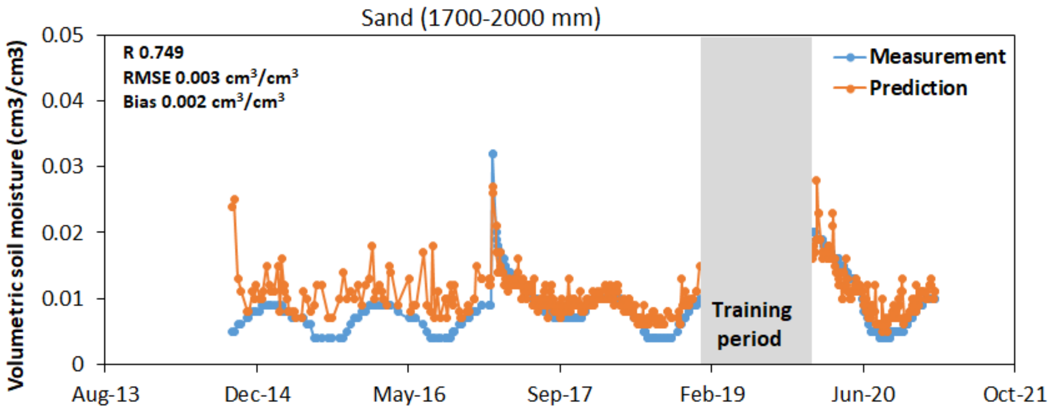
Results – ML Models



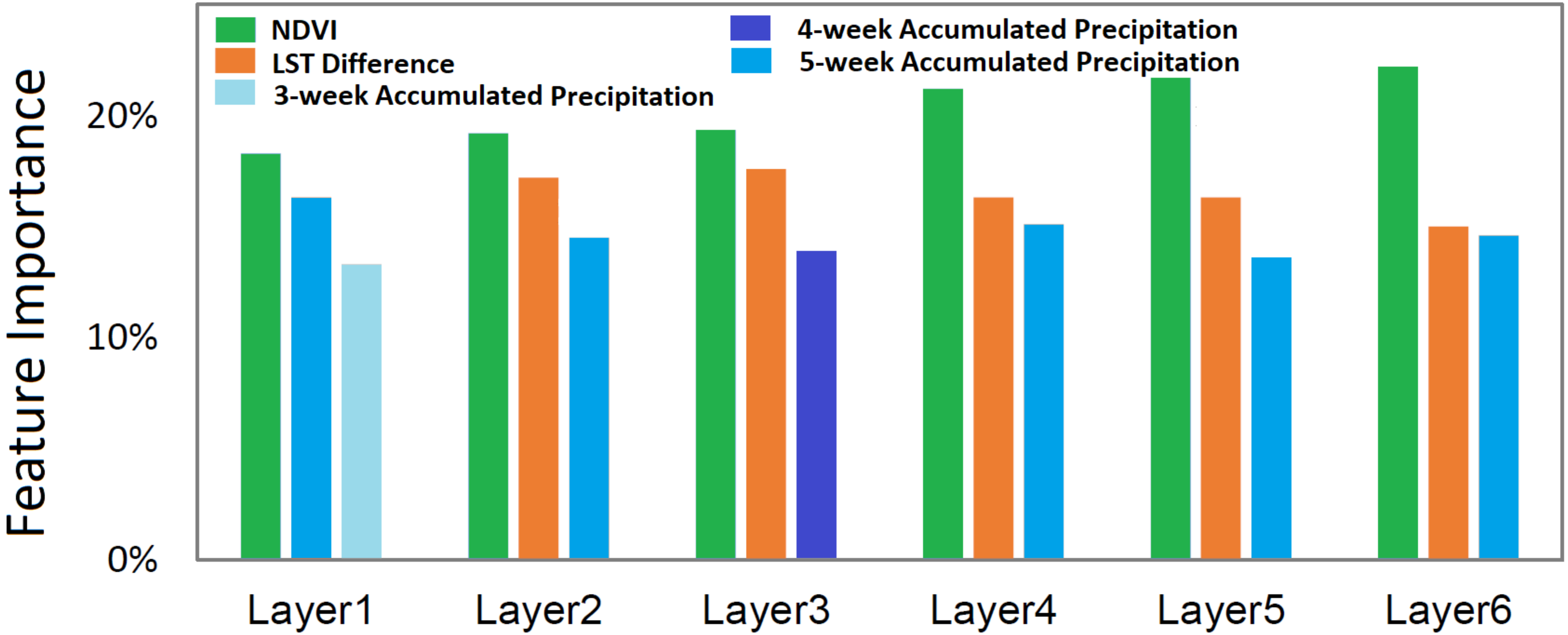






High correlations (R >0.92) and low uncertainties (RMSE <0.02 cm3/cm3; bias ~0.00 cm3/cm3) between measured and predicted soil moisture for deeper layers, except for the deepest (sand) layer. (R 0.749) where soil moisture variation/magnitude is low.

Results – ML Models



- NDVI is the most important predictor for all layers
- Accumulated precipitation and LST day-night difference are among the second and third most important factors

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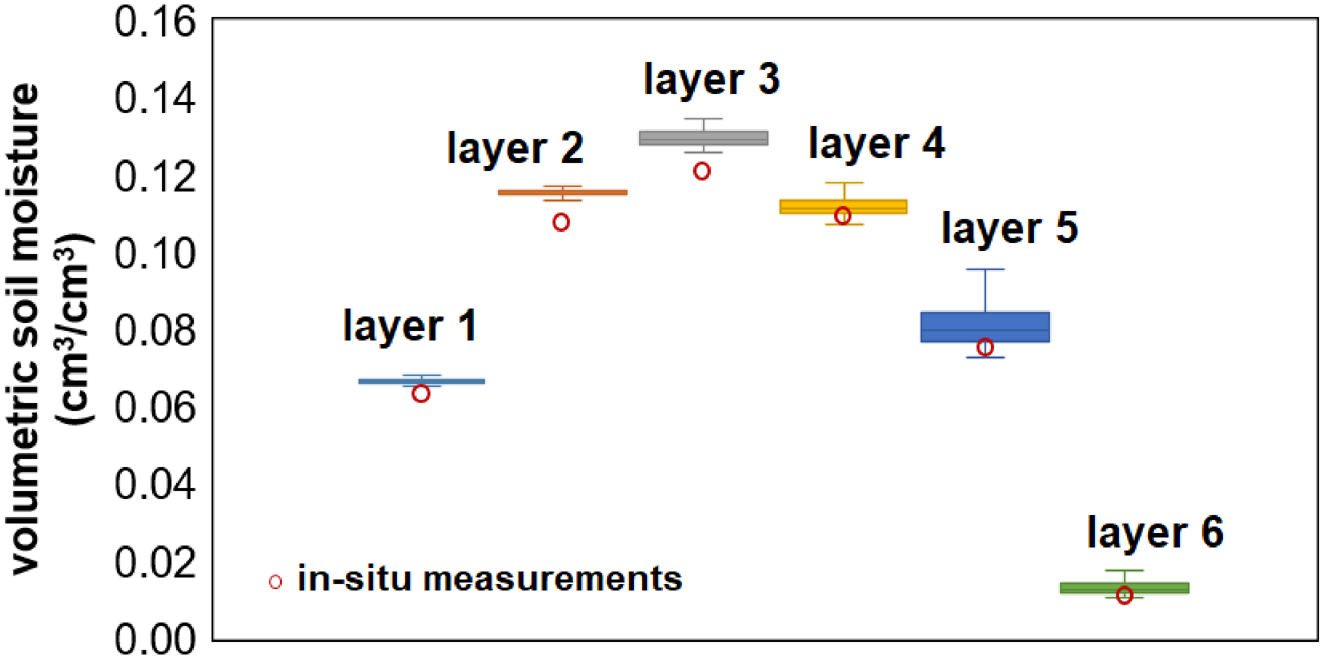
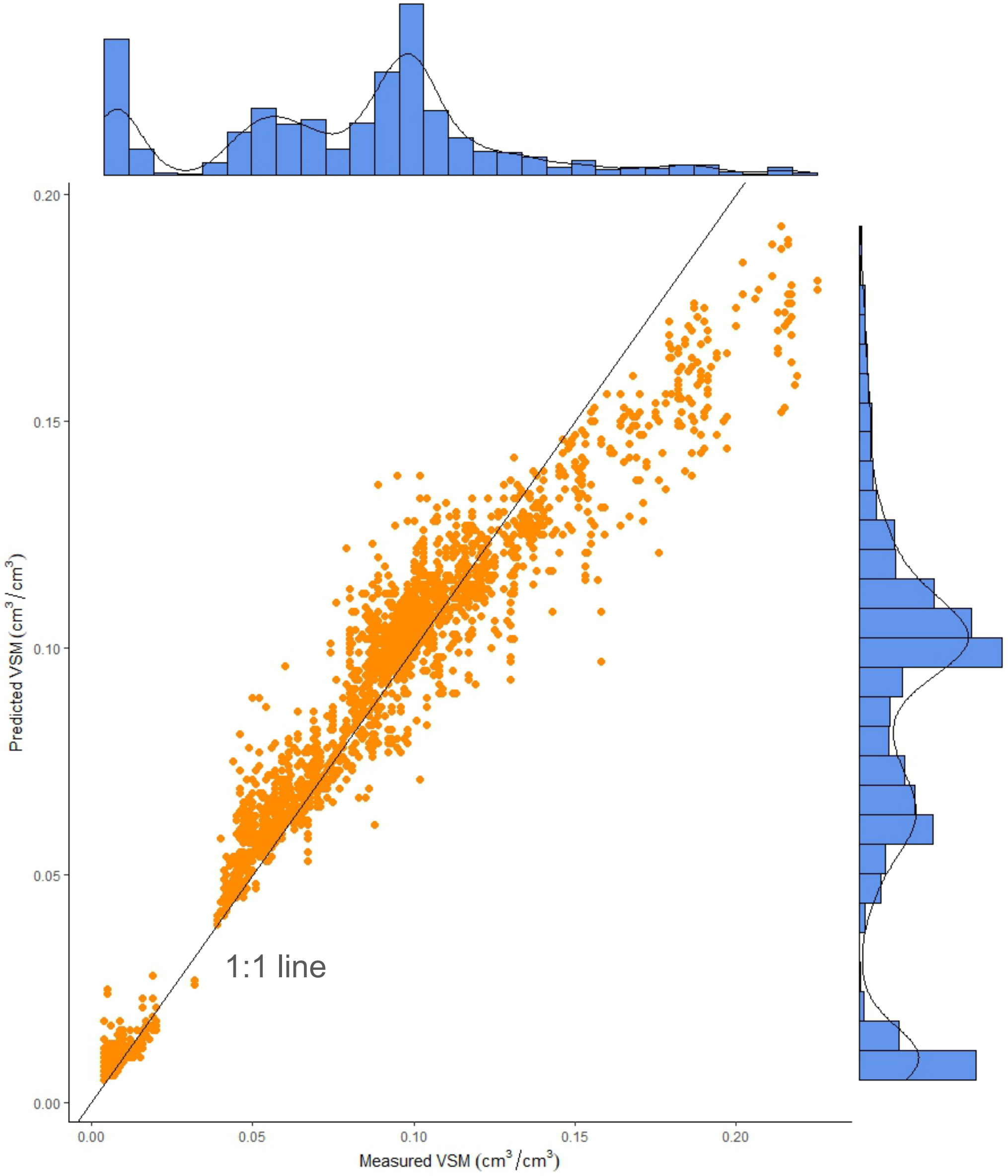
Results – ML Models



Soil moisture variability over the lysimeter for the growing season (May to September) from 2014 to 2021



Predicted versus measured soil moisture for all soil layers and months/years (R = 0.97)

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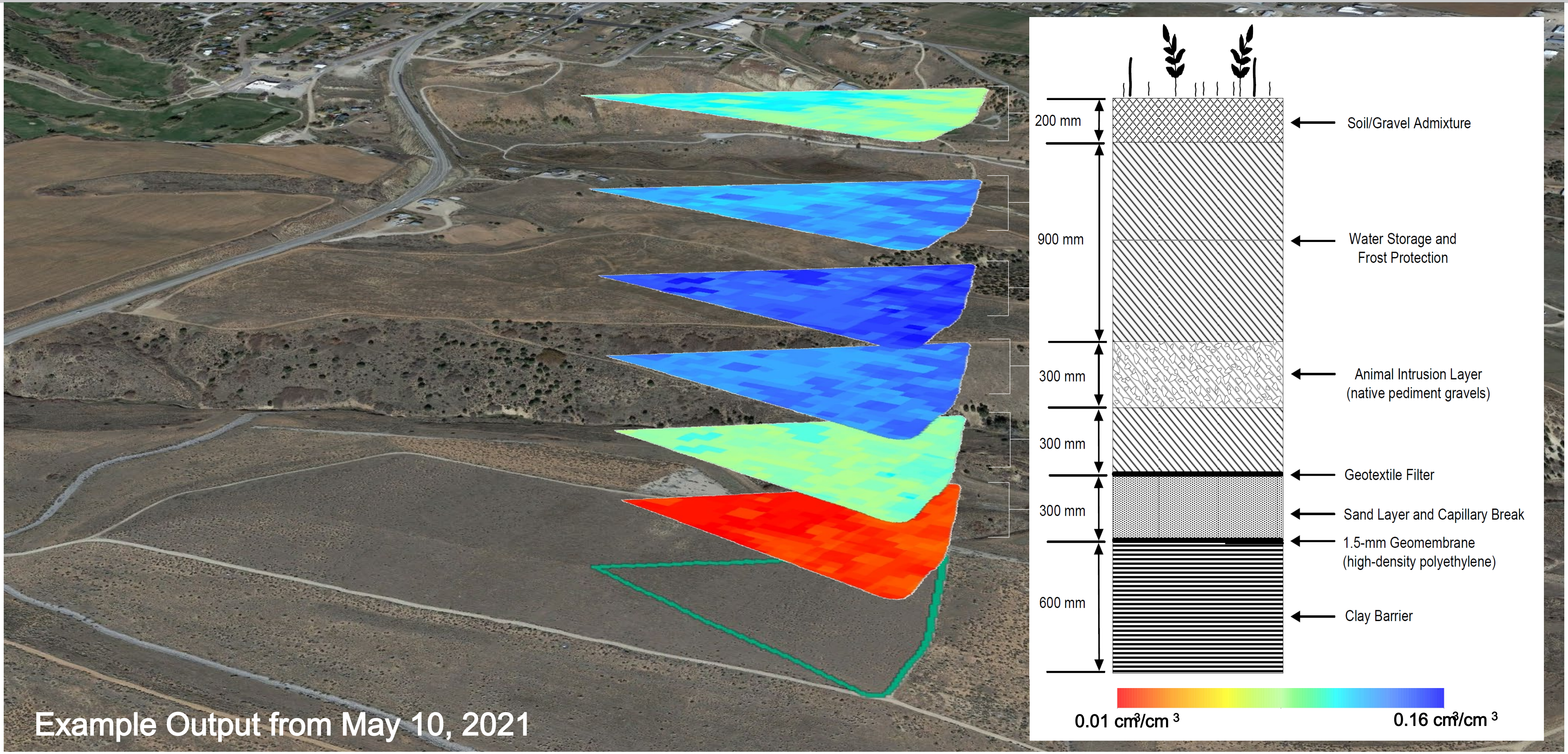
Results – ML Models



Example Output from May 10, 2021

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Summary

- Conventional ML (RF) models, driven by free satellite and other geospatial data, accurately predict 3D soil moisture profile (0–2 m) distribution and seasonal dynamics
  - Very low error/bias
  - Only 1 year of training data provided accurate multiyear (2014–2021) results
- Could be effective tool for addressing regulator recommendations on ET cover performance monitoring
- NDVI was the most important predictor among all soil layers
  - Illustrates role of plants/rooting characteristics in moderating dryland SM dynamics
  - May expand utility of ML approach to vegetated, rock armored covers where SAR cannot penetrate
- ML results suggest conventional probe measurements may not adequately account for SM heterogeneity across horizontal space (layers 1–3) – additional SM arrays will help verify
- Effect of direct low frequency (L-band) GNSS radar measurements TBD

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