SOIL MOISTURE PROFILE MONITORING AND FORECASTING USING IN-SITU SENSORS, SATELLITE REMOTE SENSING AND MACHINE LEARNING

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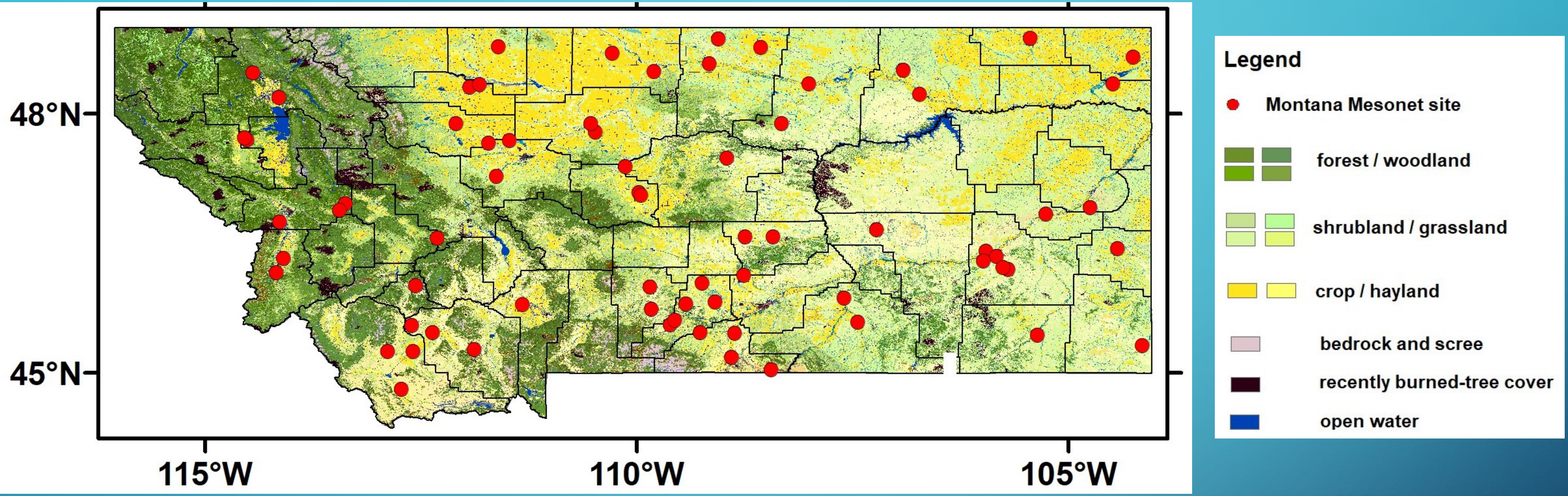
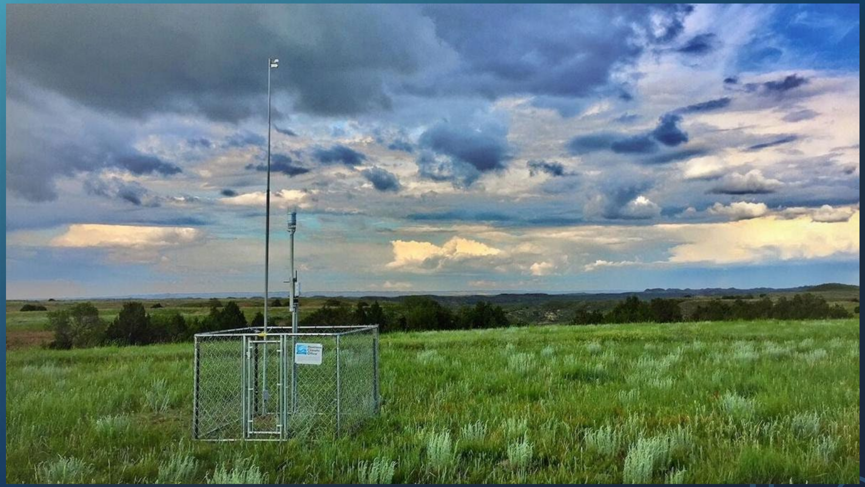
THE NEED FOR EFFECTIVE SOIL MOISTURE PREDICTIONS

- Soil moisture (SM) is a critical component of the terrestrial water cycle and a key variable for monitoring and predicting drought events;
- Operational satellite SM products have limitations including coarse spatial resolution (e.g., 10-40km), shallow sensing depth (e.g., 0-5 cm), and no direct forecast capability;
- Multi-layer SM monitoring and forecasts at local scales (e.g., 30-m) are needed for many applications, including precision agriculture, environmental monitoring, and drought risk mitigation.

MT STUDY AREA (~380,000 KM^2)

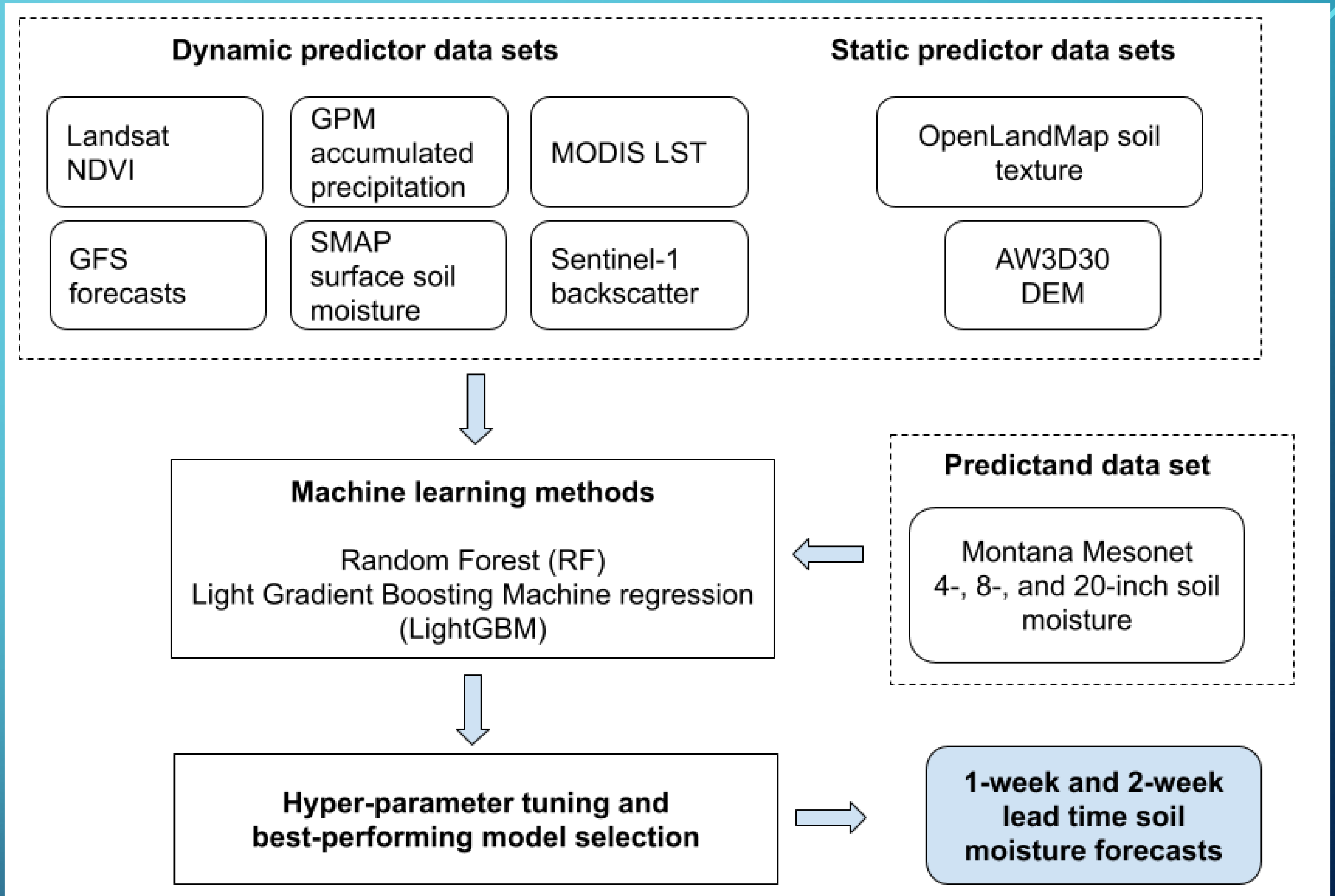


- Interior continental climate with montane forests (west) to semi-arid grasslands, croplands, and rangelands (central-eastern).
- MT Mesonet: A regionally dense monitoring network with daily surface to root zone (10-90cm depth) SM measurements.



METHOD AND WORKFLOW

- Objective: Multi-layer SM forecasts at 30-m scale with 1-2 wk lead times
- Method: Data-driven machine-learning (ML) approach; Model training and validation using in-situ SM measurements from 3 soil layers (4", 8", 20")
- Two ML models tested; best performing model used for SM predictions
- Assessments for regional drought and local SM monitoring



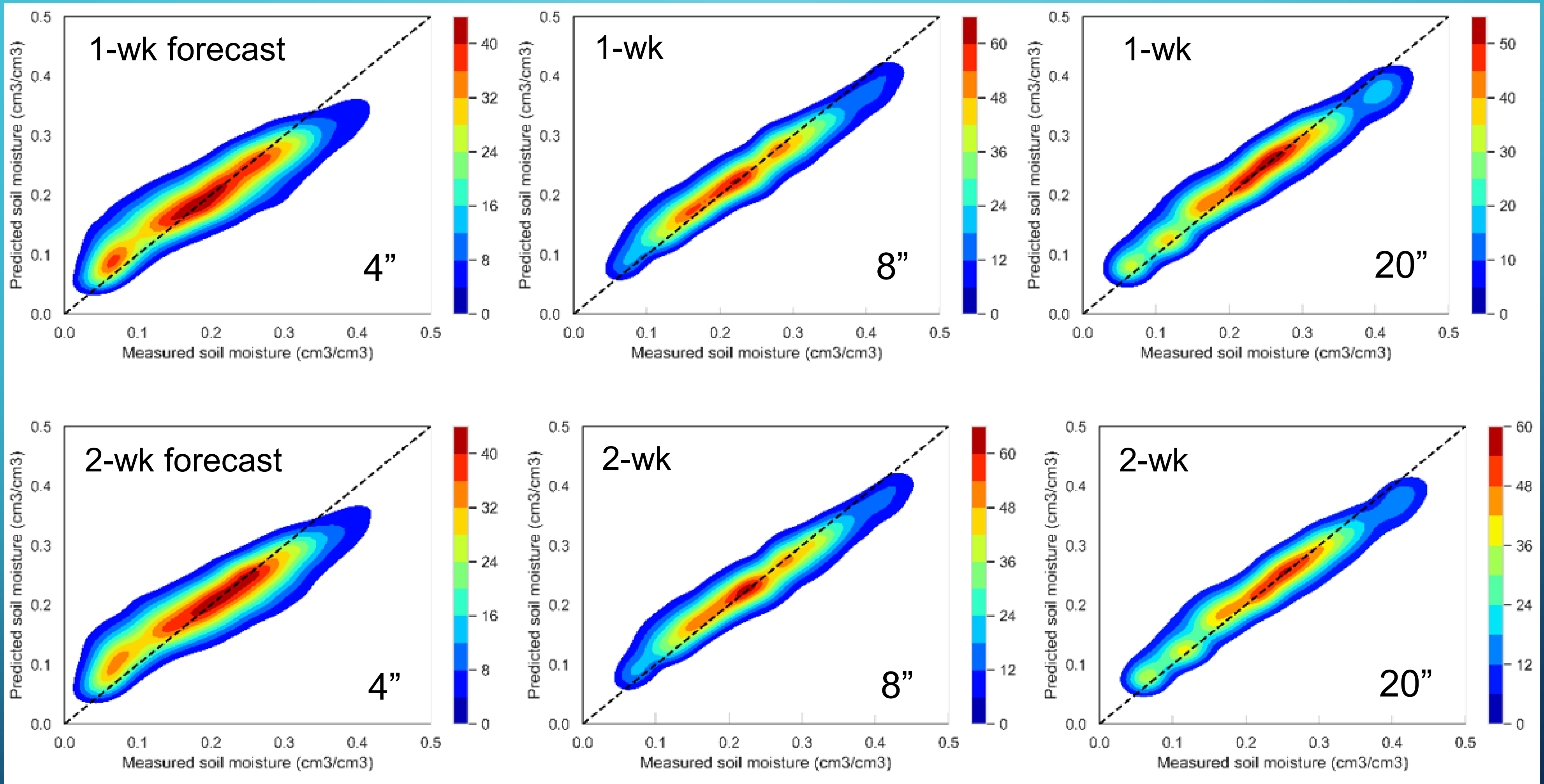
RESULTS: MODEL ASSESSMENT AND SELECTION

Summary of the model performance assessed by five-fold cross validations for SM in three soil layers (4", 8", 20" depths)

Model comparisons	Layer 1 (4-inch)		Layer 2 (8-inch)		Layer 3 (20-inch)	
	RMSE (cm^3/cm^3)	R	RMSE (cm^3/cm^3)	R	RMSE (cm^3/cm^3)	R
1-week lead time						
Random forest	0.047	0.919	0.032	0.956	0.033	0.964
LightGBM	0.048	0.903	0.035	0.940	0.034	0.956
2-week lead time						
Random forest	0.047	0.920	0.033	0.954	0.032	0.964
LightGBM	0.051	0.893	0.037	0.932	0.033	0.956

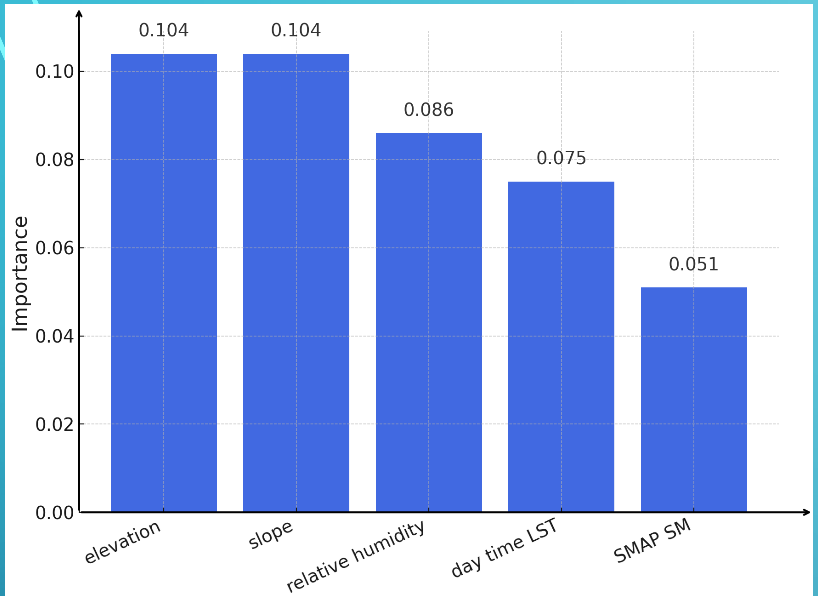
- Random Forest method selected due to lower RMSE and higher R values than LightGBM

RESULTS: SM FORECAST PERFORMANCE

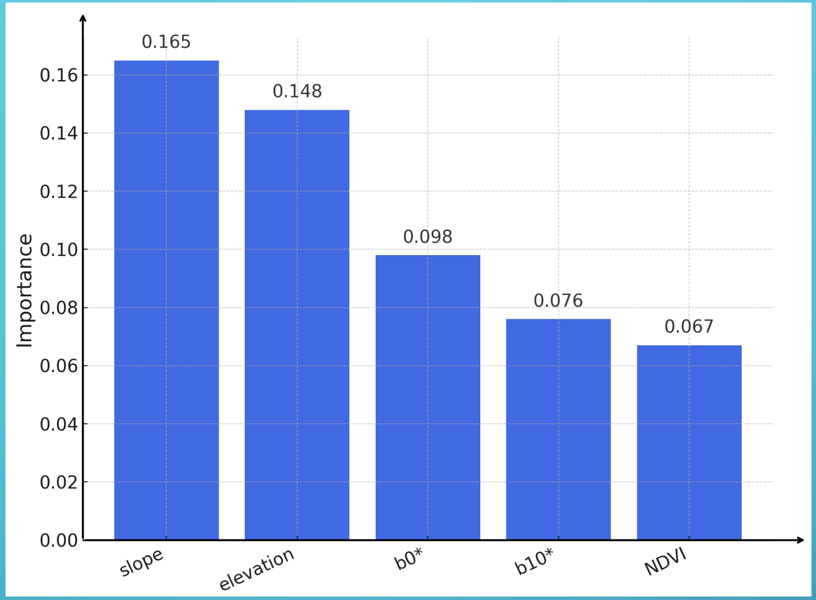


- Favorable model SM performance at all soil depths, but slightly lower correspondence in surface layer.
- Consistent performance between 1-wk and 2-wk leading forecasts

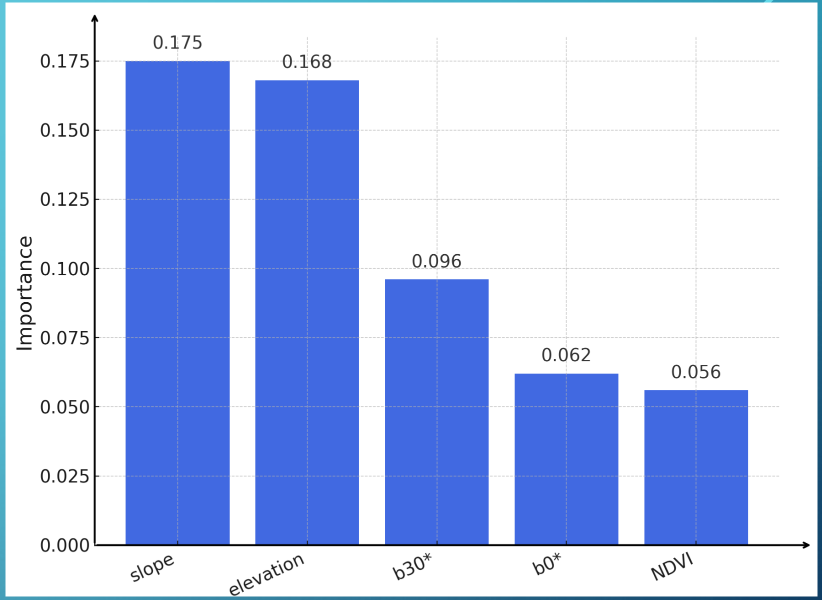
RESULTS: KEY SM PREDICTORS



Layer 1 (4”)



Layer 2 (8”)

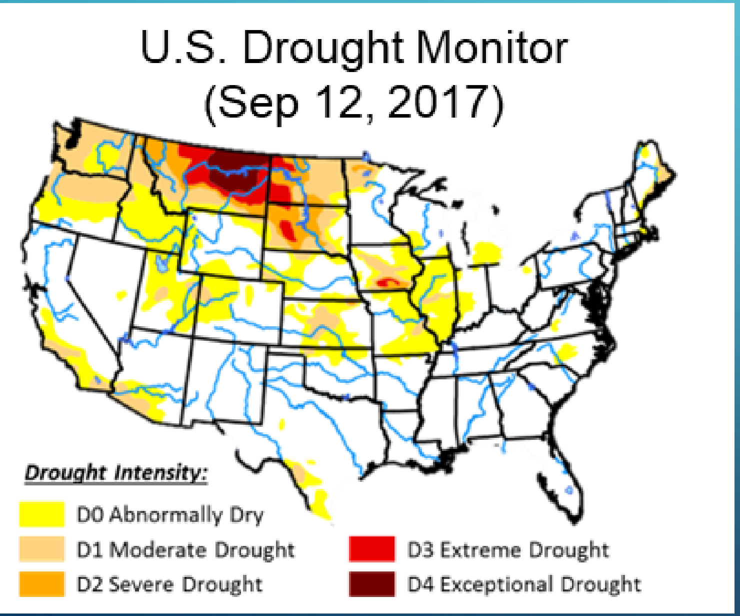


Layer 3 (20”)

- Local (30-m) terrain (slope, elevation) most important for SM prediction across all soil layers
- Surface T and moisture conditions (MODIS LST, SMAP SM) have greater importance for surface (4”) SM predictions; whereas, soil texture and NDVI (Landsat) have greater importance in deeper soil layers.

REGIONAL CASE STUDY: THE 2017 NORTHERN PLAINS SUMMER DROUGHT

- [1]Worst drought to impact U.S. Northern Plains in decades
- Early spring onset, followed by rapid (SM) dry down and hot, dry summer. Widespread collapse in Veg. growth during exceptional (D4) summer "Flash" drought
- MT was regional epicenter, with impacts Incl.: >70 % of pasture and rangeland rated poor or very poor; Crop production well below normal; >400,000 acres burned by wildfires.

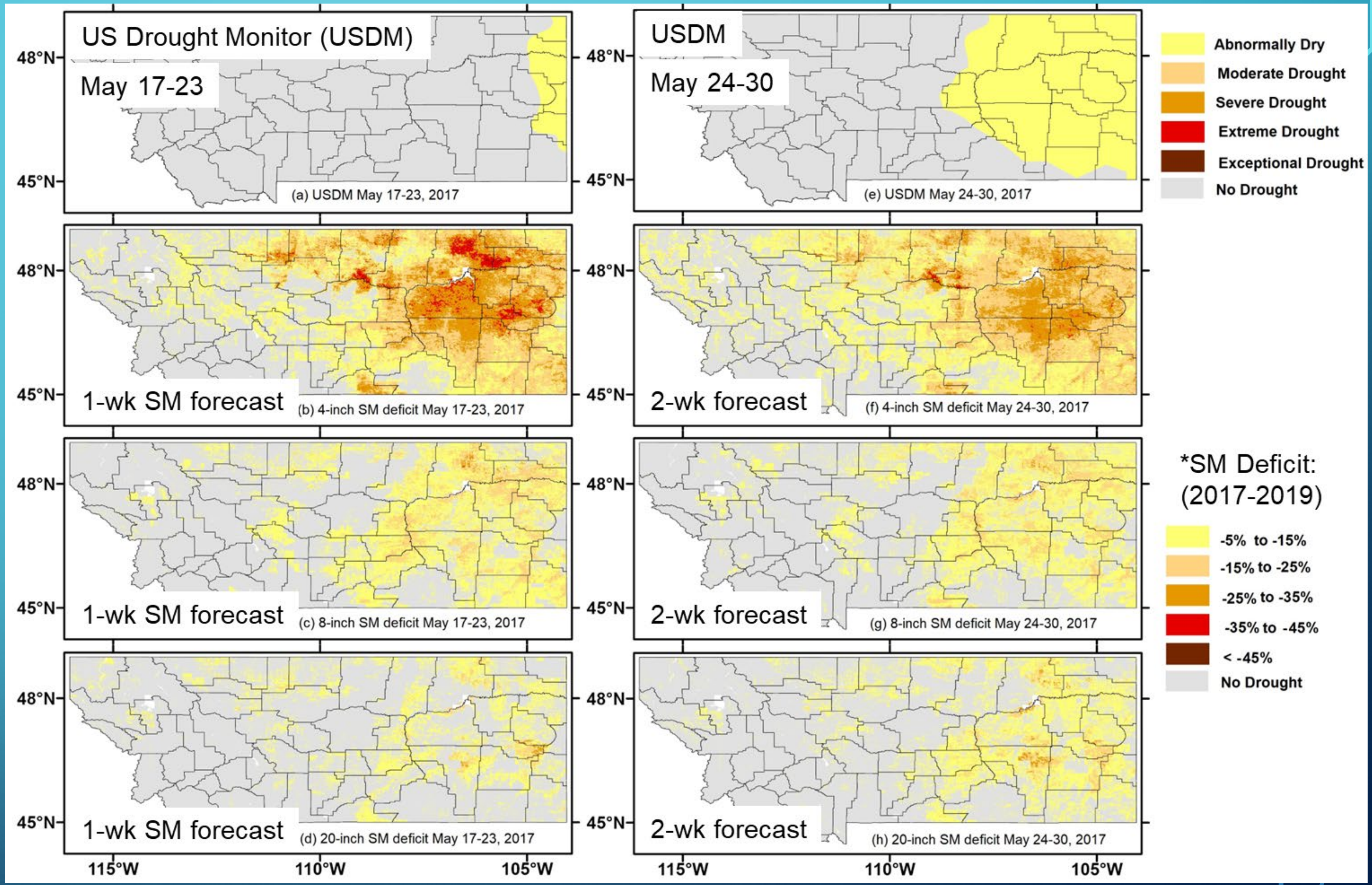


Billings Gazette (Aug 19, 2017)

[1]Jencso, et al. 2019: noaa_23004_DS1.pdf

2017 MT DROUGHT ONSET (MAY 17-23; 24-30)

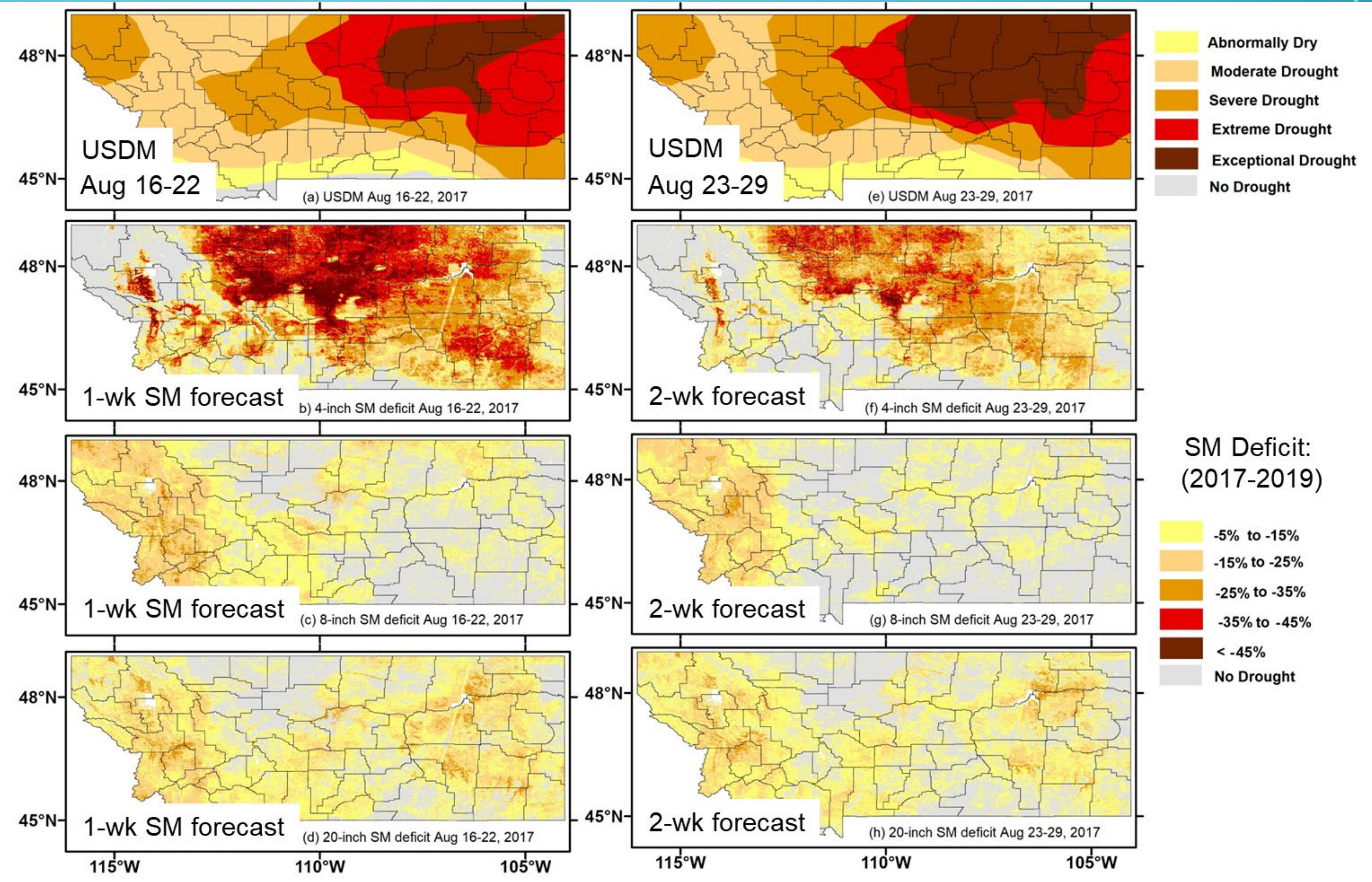
- Widespread spring SM deficit in east-central MT generally preceding USDM.
- General consistency in 1-2 wk SM forecasts
- Larger surface than root zone SM deficit



$$^{*}SM_{deficit} = (SM_{target} - SM_{reference})/SM_{reference}$$

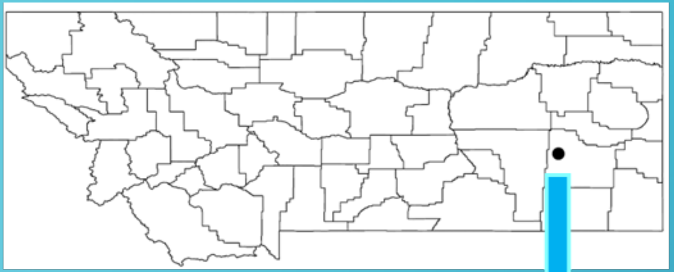
2017 MT DROUGHT PEAK (AUG 16-22; 23-29)

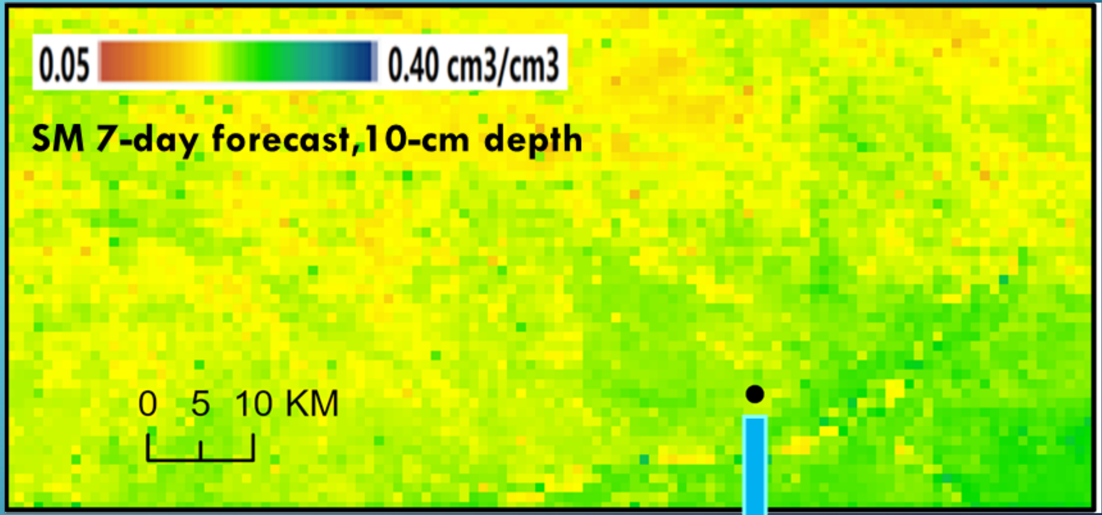
- General overlap in USDM and SM drought zones spanning nearly all of MT.
- Finer (30-m) delineation of (SM) drought than USDM
- Ongoing consistency in 1-2 wk forecast SM deficits
- Persistent larger surface than root zone SM deficit

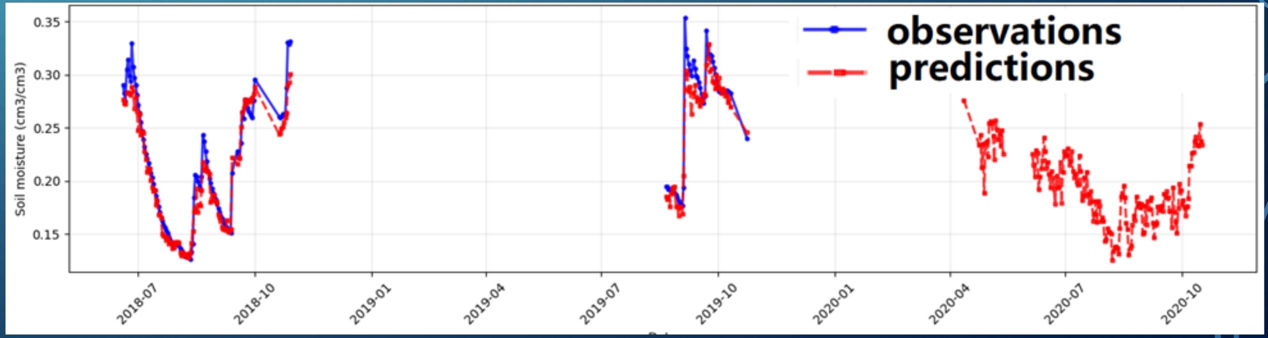


EXTENDED APPLICATIONS

- 30-m pixel resolution allows localized applications, Incl. remediation and waste storage sites
  - Similar to models applied to Monticello UT Disposal Site (Jarchow et al. 2024), but with enhanced forecast ability
- Accessible: global coverage and open-source predictor datasets, but can be tuned to local conditions
- Forecasting can be used to:
  - Prepare for infiltration/percolation and runoff events (pre-saturation awareness)
  - Target optimal revegetation timing on evapotranspiration (ET) covers
  - Predict/assess wildfire risk







SUMMARY

- Strong ML performance against in situ SM data (R>0.91, RMSE≤4.7%).
- Capture surface-to-root zone (0-20cm) daily SM dynamics at field scale (30-m) with up to 2-wk effective forecasts.
- Key role of (surface) SM as a leading indicator of the 2017 MT flash drought
- Successful methods extension to an in-service disposal cell cover, indicating potential to predict SM dynamics over other remediation sites.
- Opportunities for further ML enhancements, but performance depends on availability and representativeness of in situ SM measurements for training/validation.

THANK YOU!

- References:

  - Du, J., J.S. Kimball, K. Jencso, et al., 2024. Machine-learning based multi-layer soil moisture forecasts – An application case study of the Montana 2017 flash drought. *Water Resources Research*, 60, 10, e2023WR036973.
  - Jarchow, C.J., J. Du, J.S. Kimball, D. Steckley, and A. Kuhlman, 2024. Multi-source machine learning and spaceborne remote sensing data accurately predict three-dimensional soil moisture in an in-service uranium disposal cell. *Journal of Environmental Management,* 369.