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DATE: 20 – 22 August 2025

Leveraging Soil Reflectance Models with Sentinel-2 for Scalable Soil Moisture Mapping to Enhance Agricultural Resilience in South Africa.

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SHORT BIO

- Yonwaba Atyosi is a candidate researcher at the CSIR’s Precision Agriculture Research Group.
- Research focus: Remote sensing of soils; developing innovative techniques for precision agriculture.
- Academic background: Geology, Applied Remote Sensing and GIS
- PhD studies: Geoinformatics, University of Pretoria
- Current project: Enhancing hyperspectral & multispectral soil moisture retrieval by accounting for clay content

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Brief background

- Sensitivity analysis of subtle changes in soil moisture
- Conducted a canonical analysis –A multivariate statistical measure that helps identify the **most influential soil variables** affecting SMC retrieval.

Developed a hyperspectral based soil reflectance model that consider the interaction between soil moisture and soil clay content through Monte Carlo simulation.

$$Rsoil = aSMC + bSCC + c(SMC * SCC) + d \quad (1)$$

Where coefficients a,b,c were drawn from a Gaussian distribution , and SMC and SCC , uniform distribution.

- ✓ Tested on independent hyperspectral dataset from the EC.
- ✓ We resampled the hyperspectral soil library to Sentinel 2-configuration
- ✓ Tested on resampled hyperspectral independent dataset
- ✓ Tested on actual Sentinel-2 independent datasets from EC and Limpopo (Different growing seasons)

- Assessed this multivariate soil hyperspectral reflectance model for mapping SMC using Sentinel 2

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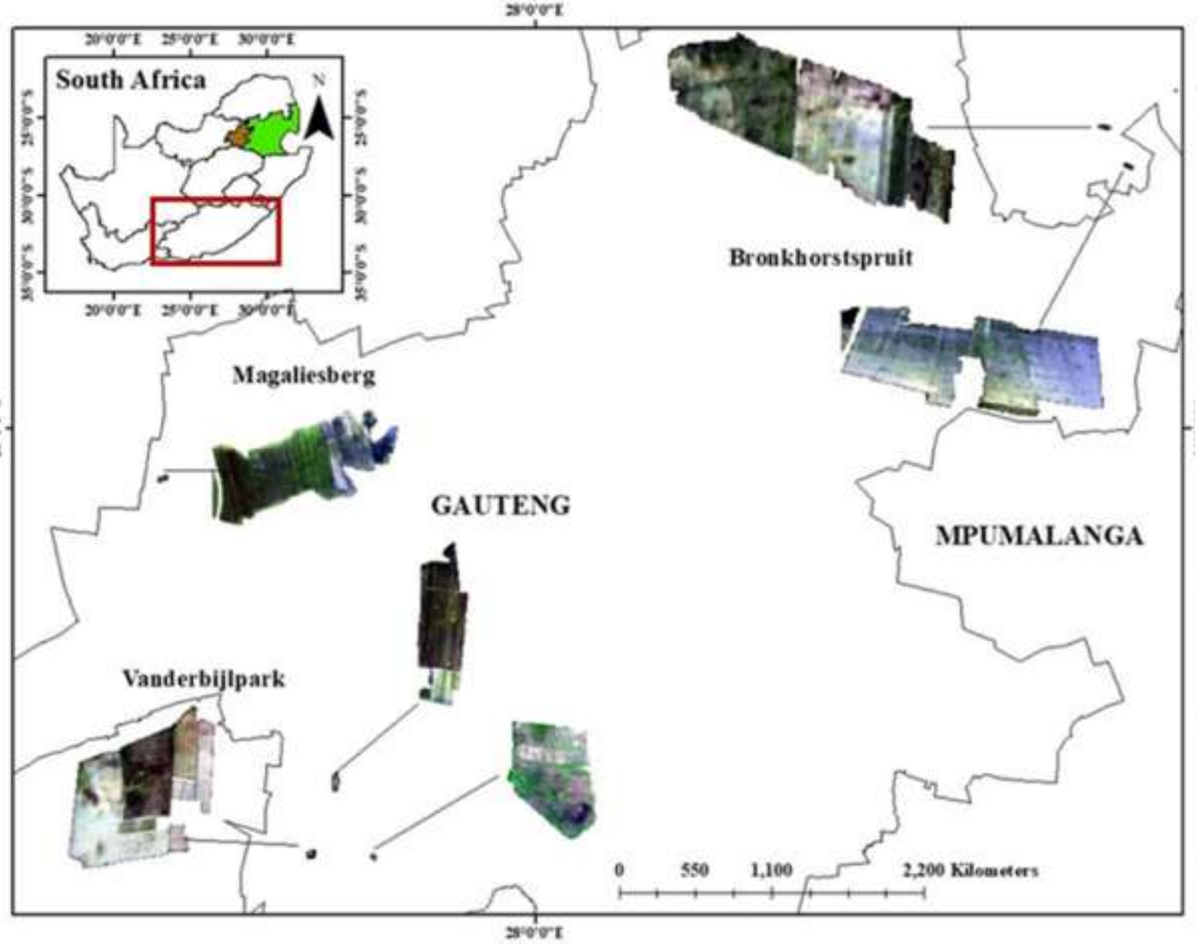
Study sites



Sample ID	Sample picture	Latitude (S)	Longitude (E)	Clay content (%)
1		26° 16' 2.64" S	27°40'7.572" E	9.5% (minimum percentile)
2		25° 36' 59.04" S	28° 51' 24.084" E	15% (20th percentile)
3		25° 37' 28.76" S	28° 52' 4.152" E	18% (40th percentile)
4		26° 4' 16.32" S	27° 23' 13.272" E	28% (60th percentile)
5		26° 4' 31.44" S	27° 27' 9.144" E	34% (80th percentile)
6		26° 4' 33.96" S	27° 27' 3.744" E	43% (maximum percentile)

The problem

- Accurate, timely and transferable SMC retrieval remains a challenge for precision agriculture, drought monitoring, and hydrological modeling.

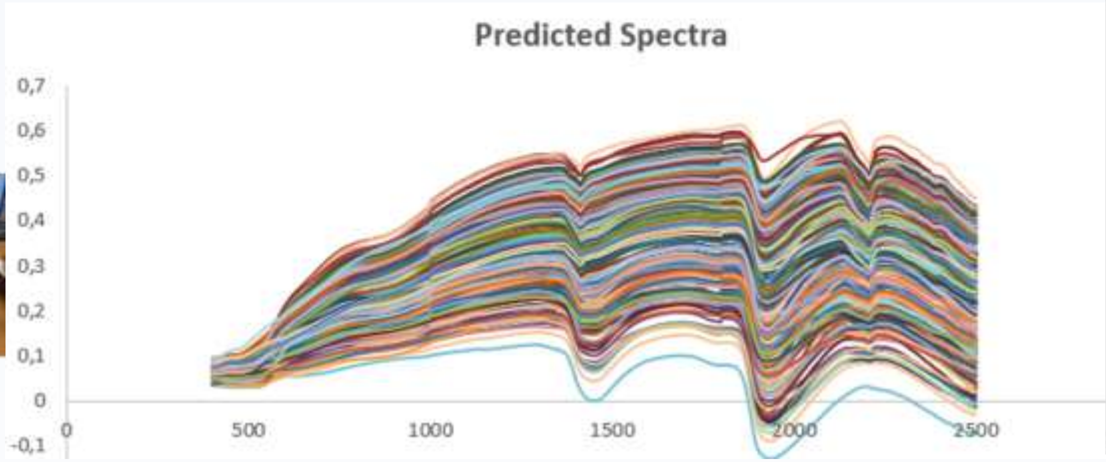
- Traditional methods (gravimetric sampling, in-situ sensors) provide reliable **point-based soil moisture data.** **However, they are labor intensive, spatial constrained and impractical for large scale monitoring.**

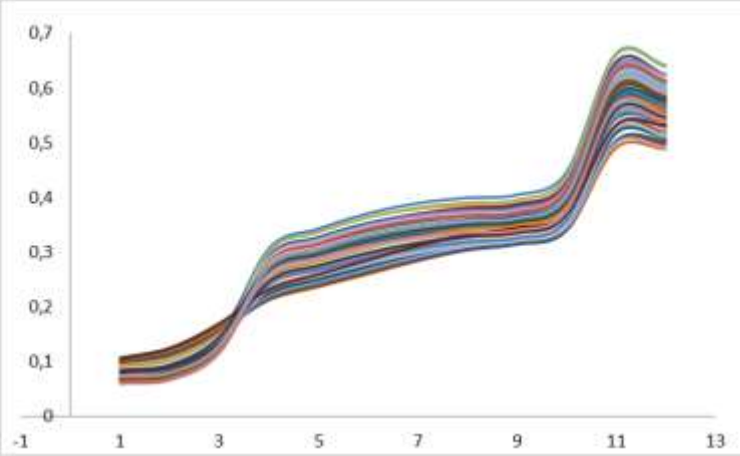
- Remote sensing offers scalable alternatives, yet **retrieving soil moisture from satellite data remains challenging**

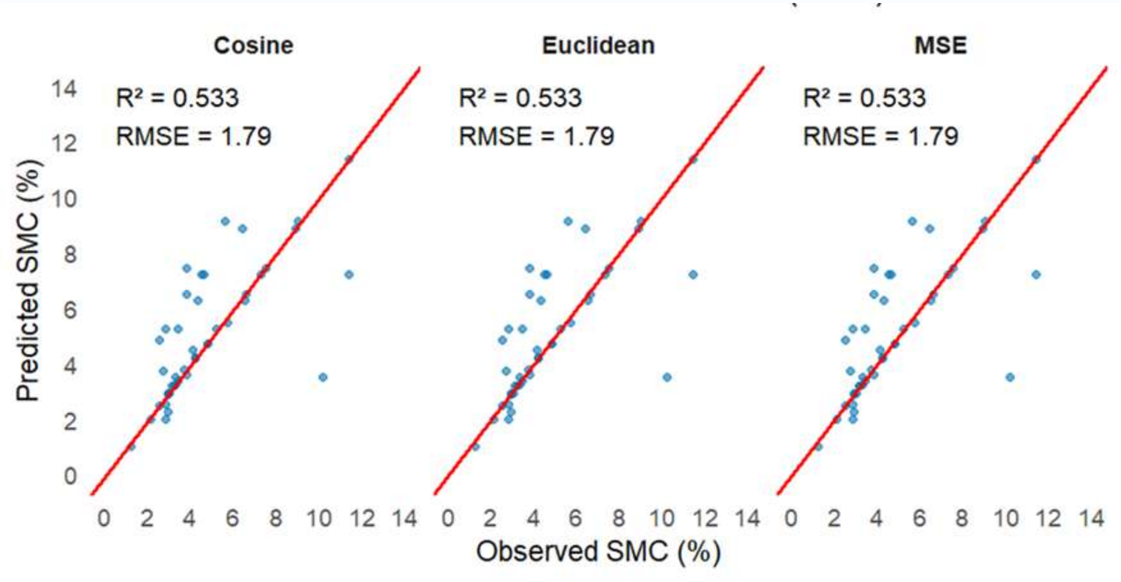
❖ **Hyperspectral RS-** capture subtle soil reflectance changes linked to moisture
  Limited operational use due to scarce, high-resolution, open-access data
❖ **Multispectral RS-** freely accessible, global coverage, high temporal resolution
  Broader bands reduce precision in capturing soil moisture dynamics

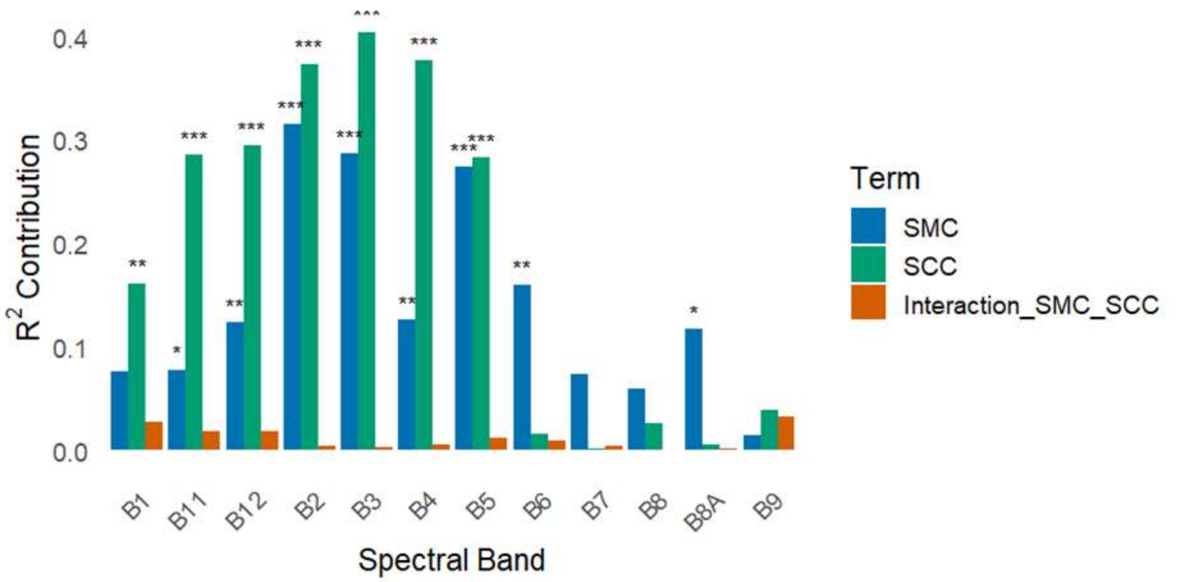
- **Existing empirical and machine learning approaches often neglect soil property interactions and lack spatiotemporal generalizability.**

Resampling from hyperspectral to multispectral via S2 SRF









The Solution

Ratio	R^2	$RMSE_p$	$RMSE_p$%
B3/B1	0,85646844	1,31309586	6,56510241
B12/B1	0,76110919	1,39941324	6,99686626
B12/B4	0,71623186	1,69385579	8,46918447
B12/B5	0,70896814	1,84626596	9,23092127
B12/B6	0,70643867	1,86979347	9,34857727
B12/B7	0,69779381	1,87776208	9,38854749
B12/B9	0,69677481	1,90507473	9,52528708
B12/B8	0,68422686	1,9084999	9,54219589
B12/B2	0,6774428	1,94740708	9,73691695
B12/B8A	0,67670377	1,96829332	9,84127391
B8A/B1	0,67430007	1,97047242	9,8522378
B3/B2	0,67335584	1,97778853	9,8888699
B12/B3	0,66781178	1,98080505	9,90379584
B11/B1	0,66377546	1,99737937	9,98675792
B9/B1	0,66094162	2,00951773	10,0473717
B8/B1	0,6576905	2,01863144	10,0921031
B2/B1	0,65069057	2,02757385	10,1376975
B12/B11	0,64609479	2,04823691	10,2410074
B7/B1	0,64515605	2,0615914	10,3079304
B11/B4	0,601554	2,06446983	10,3220059

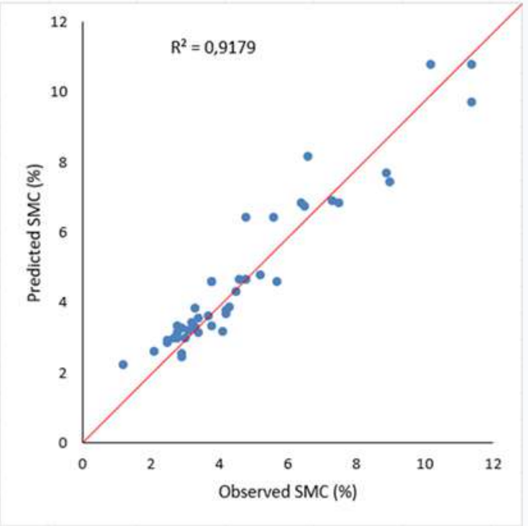
$$Rsoil = aSMC + bSCC + c(SMC * SCC) + d$$

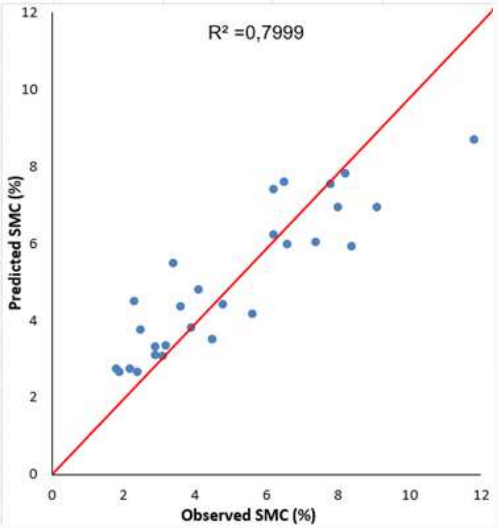
We developed a hyperspectral synthetic soil database

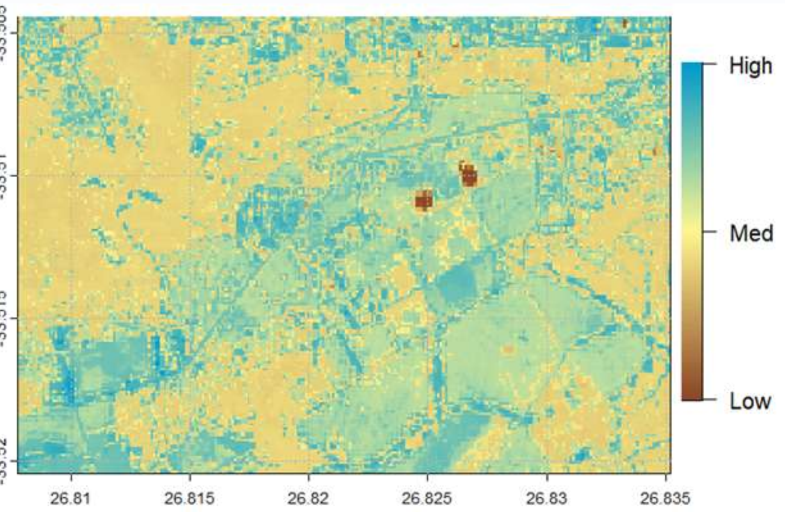
- Contains hundreds of thousands of spectra with corresponding SMC and SCC
- Representative of a wide range of different possible soil types in South Africa
- Explicitly incorporates SMC–SCC interactions into a multivariate modeling framework
- Enables a transferable, interpretable, and operational pathway for soil moisture retrieval
- Sentinel 2 spectral transformation and feature engineering (band ratios, developed 5 new SMIs)
- **Trained five machine learning models (SLR,MLR, RF, SVM, PLSR) with optimal band ratios and SMIs derived from our robust synthetic hyperspectral soil database to predict SMC**
- Applied the best model to Sentinel-2 imagery to spatio-temporally map SMC , ensuring scalability **across space and time.**

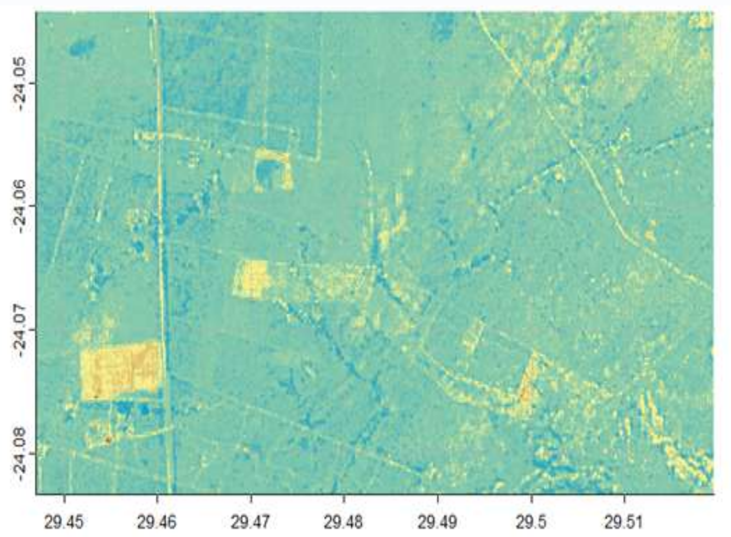
ENHANCED SMC PREDICTION ACCURACY

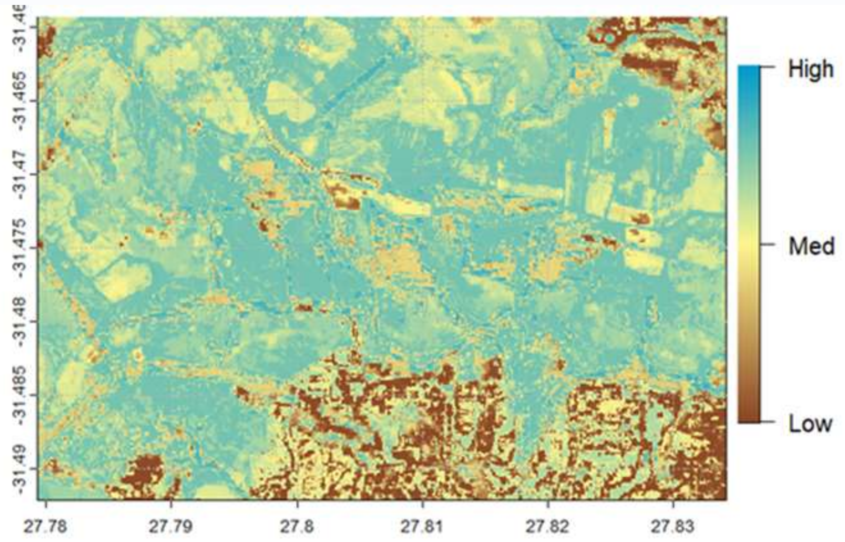
Model	RMSE	MAE	RMSE$_p$%	MAPE	R^2
Linear	1,48256224	1,19268966	29,0991078	33,7612852	0,67448176
SVM	1,46523953	1,13530982	28,7591051	34,819678	0,68204422
PLSR	1,48256224	1,19268966	29,0991078	33,7612852	0,67448176
RF	0,8761717	0,67424038	17,1971294	19,8572694	0,88630852
Linear	1,69341492	1,36518149	33,2376357	37,7790576	0,57530589
SVM	1,67229466	1,31038639	32,8230961	38,4542239	0,5858334
PLSR	1,69341492	1,36518149	33,2376357	37,7790576	0,57530589
RF	1,04154791	0,81629979	20,4430641	23,3875595	0,83933992
Linear	1,04995598	0,75829887	20,6080943	24,4697224	0,83673554
SVM	1,03098337	0,70140427	20,2357078	26,1918797	0,84258258
PLSR	1,04995598	0,75829887	20,6080943	24,4697224	0,83673554
RF	0,58048438	0,43356709	11,3935033	13,7086997	0,95009655
Linear	1,45187678	1,15372972	28,4968266	33,7971762	0,68781719
SVM	1,4674773	1,14348617	28,803027	35,218368	0,68107229
PLSR	1,45187678	1,15372972	28,4968266	33,7971762	0,68781719
RF	0,86071564	0,66777073	16,8937645	20,1808763	0,89028428
Linear	1,59995769	1,27733152	31,4032963	40,9362876	0,62088893
SVM	1,15526559	0,87747005	22,675067	29,0701767	0,80234257
PLSR	1,59995769	1,27733152	31,4032963	40,9362876	0,62088893
RF	0,70856367	0,53121581	13,9073896	15,3228448	0,9256455











CONCLUSSIONS

- Accounting for clay content and its interaction with soil moisture content in soil reflectance modelling, improves SMC prediction accuracy.

- Our multivariate hyperspectral model can accurately predict and map SMC with Sentinel 2 across space and time.

The framework bridges hyperspectral richness and multispectral practicality, offering scalable solutions for precision agriculture, water resource management, and environmental monitoring, with

❖ Current work is focussed on incorporating vegetation parameters for a fully integrated soil–canopy moisture mapping.

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