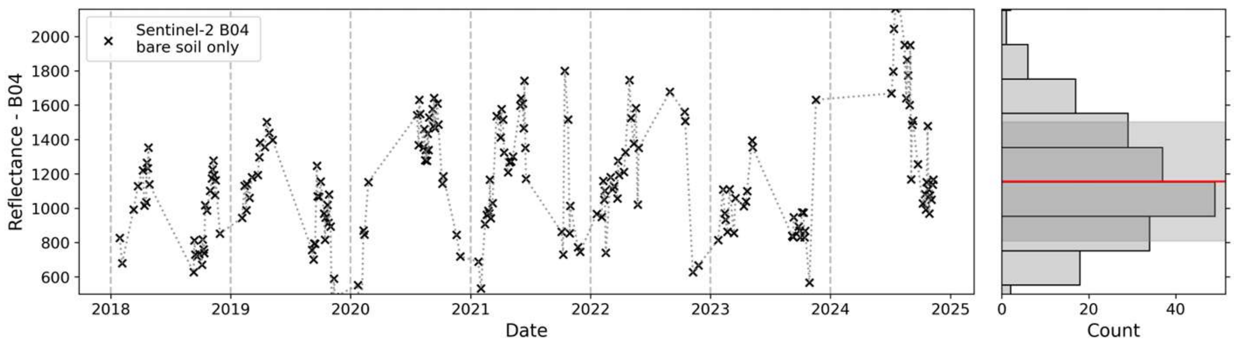
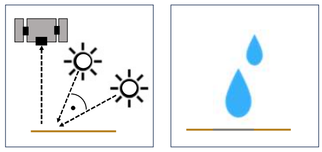
Drivers of spectro-temporal variability in multi-spectral soil reflectance



Variability in the bare soil reflectance of a pixels in the Band B04 in Sentinel-2 over 7 years (here LUCAS site 49382698). On the right, the distribution of soil pixels, its mean (red line at 1155 units) and the +- standard deviation (gray area, 347 units) is visualized.



Observation: In multi-year timeseries of bare-soil pixels of Landsat 8 / Sentinel-2, we see substantial and temporally structured variations in the surface reflectance throughout the spectral domain.
Research Question: How much of this variability is driven by changes in **Surface Soil Moisture** or **Sun Incidence Angle?**

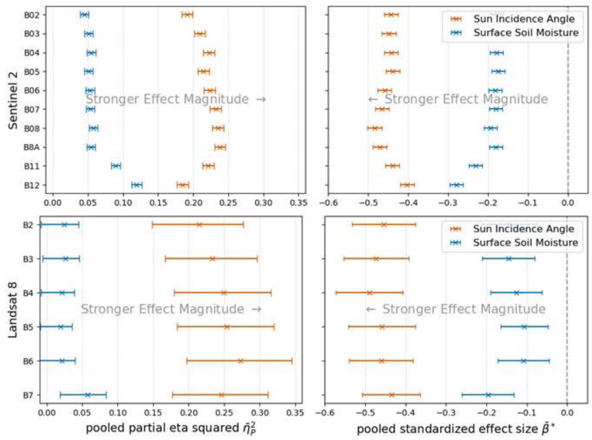
METHODOLOGY

We quantify how much of the temporal variance in soil reflectance can be attributed to surface soil moisture and effects due to illumination geometry. The analysis is conducted at 27,819 sites across Europe using seven-year (2018-2024) time series of bare-soil reflectance derived from Sentinel-2 and Landsat-8 observations.
Surface soil moisture is represented by the Copernicus Surface Soil Moisture product, while illumination conditions are characterized by the sun incidence angle.

Study area. 27,819 7-year long timeseries of LS 8 / S2

At each site, multivariant ordinary least squares regression is used to estimate standardized effect strengths β^*, and decomposition of variance partitions the proportion of reflectance variance uniquely explained by each independent variable, expressed as η_P^2. Finally, a random-effects meta-analysis accounts for between-site heterogeneity and pools site-level effect sizes to derive global estimates of both regression coefficients $\overline{\beta^*}$ and explained partial variance $\overline{\eta_P^2}$.

RESULTS



Pooled values and their respective prediction internals as estimated via meta-analysis for the explained variance $\overline{\eta_P^2}$ and $\overline{\beta^*}$ for Sentinel-2 (top row) and Landsat 8 (bottom row)

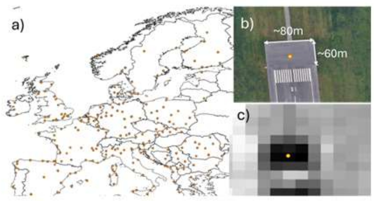
1st Result: Variations in illumination introduce greater variability into reflectance than changes in surface soil moisture.

Two components linked to **sun geometry:**

1. The illumination-atmosphere effect
2. The surface shadowing effect

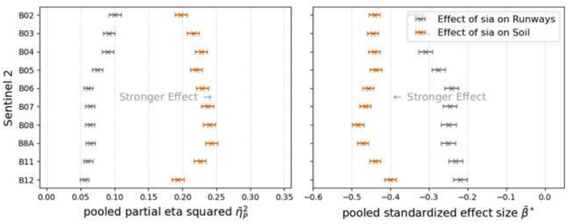
To separate them, soil data was compared to a control set: **airport runaways**:

- 727 locations
  227 large airports across Europe
- Hand-picked, stable locations



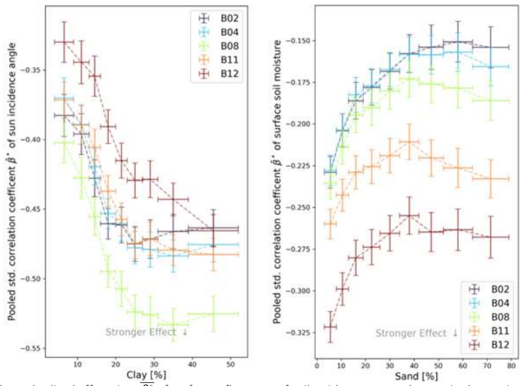
a) Spatial distribution of control set
b) Example of a frequently selected location: the buffer area preceding the actual runway.
c) Illustration of the spatial relationship between a Sentinel-2 20m resolution and the runway surface, demonstrating that pixels located near the runway center are spectrally pure.

Below: Effect magnitude of the sun incidence angle in terms of $\overline{\eta_P^2}$ (left) and the standardized $\overline{\beta^*}$ (right) with prediction intervals in bare soil and paved surfaces.



2nd Result: The systematic decline in reflectance with increasing solar incidence angle over rough natural soils is largely attributed to surface shadowing caused by micro-topography and anisotropic scattering resulting from soil roughness.

The large number of sample sites and the presence of soil texture information from the LUCAS survey allowed us to investigate how the standardized effect sizes vary across percentile stratified subclasses based on the soil texture:



Left: Pooled standardized effect sizes $\overline{\beta^*}$ of surface reflectance of soils with respect to changes in the sun incidence angle. Percentile-Stratified by the clay content of the soil at the sample site. Right: Similar the effect size $\overline{\beta^*}$ of surface reflectance of soils with respect to changes in surface soil moisture. Percentile-Stratified by the fraction of sand content at the sites soil. Width of a step represent the interval size of clay / sand content and the error bars are prediction intervals as estimated by the meta analysis that pools only sites with the respective interval

3rd Result:

- Sandy soils exhibit lower reflectance sensitivity to changes in soil surface moisture.
- Clay-rich (tendency to form larger soil clumps, thus being rougher) soils are more sensitive to changes in solar incidence angle.

Related Publication: Karlshoefer P., Alewell C., d'Angelo P., Heiden U., 2026, Drivers of spectro-temporal variability in multi-spectral soil reflectance measured from space: A continental-scale analysis. *Remote Sensing of Environment*, https://doi.org/10.1016/j.rse.2026.115599

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