

Remote Sensing of Soil: Key Spectral Indices and Their Applications

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INTRODUCTION

Soils are essential natural resources that support agriculture, ecosystems, water regulation, and carbon storage. Traditional field-based soil assessment methods, while accurate, are often labour-intensive, time-consuming, and insufficient for large-scale monitoring. Remote sensing (RS) has completely revolutionised, the capacity to track the dynamic processes of the soil system, from anthropogenic effects to natural environmental changes. Remote sensing technologies, ranging from multispectral satellite sensors to hyperspectral imaging, offer an efficient and scalable means to evaluate soil conditions over broad areas. Within this approach, spectral indices play a central role by transforming reflectance data from various wavelength bands into meaningful indicators of specific soil properties. Since the outset of the first earth-observing satellite for civilian use, Landsat-1, in 1972, remote sensing monitoring has started. By utilizing their spectrum behaviour, spectral indices can characterize and even quantify specific qualities of various objects, acting as a link between unprocessed spectral data and significant environmental interpretations.

The family of spectral indices keeps growing due to the emergence of new sensors and the expansion of data sources. The most representative set of spectral indices gathers vegetation indices (VIs), which includes the Normalized Difference Vegetation Index (NDVI). Several additional indices were produced and changed based on this index, partly because of the addition of new and even hyperspectral bands. The number of spectral indices has surpassed hundreds till date and continues to increase with the ongoing developments and advances in publications.

Principles of Soil Spectral Indices

Spectral indices are mathematical combinations of reflectance values from different wavelengths designed to enhance specific soil characteristics like organic matter, moisture, and mineral content, while minimizing the influence of illumination, vegetation cover, and sensor noise. The principles involve using specific wavelength bands that are sensitive to certain soil components, creating a relationship (like a ratio or difference) that enhances the signal for the property of interest while reducing interference from other factors. These indices act as proxies for properties that are expensive or time-consuming to measure directly, often used in remote sensing to provide cost-effective and large-scale soil analysis. In general, spectral indices combine these bands to highlight specific soil characteristics:

- Visible wavelengths (400–700 nm) relate to soil colour, iron oxides, and organic matter.
- Near-infrared (NIR, 700–1300 nm) respond to soil moisture and internal soil structure.
- Shortwave infrared (SWIR, 1300–2500 nm) provide insights into clay minerals, carbonates, and salinity.

Key soil attributes that influence spectral response include:

Remote sensing of soil relies on how different soil properties interact with electromagnetic radiation across the visible, near-infrared (NIR), shortwave infrared (SWIR), and thermal infrared (TIR) regions. Each soil attribute alters the absorption, reflection, or scattering of energy in distinct ways, creating diagnostic spectral signatures. The following attributes are the most influential.

1. Soil Moisture Content

Water strongly absorbs electromagnetic radiation, especially in the NIR (700–1300 nm) and SWIR (1300–2500 nm) ranges. Key effects include:

- Wet soils decrease in overall reflectance and appear darker than dry soils
- Moisture masks mineral absorption features and flattens spectral curve
- Dominant absorption peaks at ~1450 nm and ~1950 nm due to water.

This makes soil moisture one of the most critical factors influencing soil reflectance, and therefore many indices (e.g., Moisture Stress Index, NDWI) rely on this property.

2. Soil Organic Matter (SOM)

Organic matter significantly affects soil colour and reflectance in the following way:

- SOM darkens soil, reducing reflectance across visible and NIR wavelengths.
- High SOM content results in smooth spectral curves with reduced contrast.
- Absorption is stronger in the visible range due to humic substances.

Thus, SOM-rich soils appear darker in imagery, while low-SOM soils are brighter.

3. Soil Texture (Sand, Silt, Clay Proportions)

Texture affects both shape and depth of spectral absorption features, making it central for soil mineral mapping. The characteristics are:

- Sandy soils: High reflectance, especially in visible and NIR, due to larger particle size and high brightness.
- Clayey soils: Distinct absorption features at 1400, 1900, 2200, and 2330 nm, associated

with clay minerals (kaolinite, montmorillonite, illite).

- Silty soils: Intermediate reflectance and smoother spectral curves compared to sand.

4. Mineralogical Composition

Mineral composition therefore serves as the basis for hyperspectral soil classification. Different minerals have unique spectral signatures. For example, iron oxides (hematite, goethite) cause strong absorption in blue and green bands and increase reflectance in red and NIR; carbonates (calcite, dolomite) absorption around 2330 nm; gypsum shows diagnostic features around 1750 nm and 2200 nm; silicates and quartz have high reflectance in visible and NIR and becomes transparent until SWIR.

5. Soil Colour

Colour is one of the easiest soil attributes to detect using satellite imagery. Soil colour integrates effects of minerals, organic matter, and moisture. For instance; dark soils (low visible reflectance) mean higher organic matter or moisture; red soils have high iron oxides, which is a characteristic absorption signature; pale or white soils (high reflectance) contain carbonates, salts, or sand.

6. Soil Salinity and Sodicity

Salinity alters soil brightness, cracking patterns, and moisture retention, all of which affect spectral response. Salt-affected soils show distinct optical characteristics. High reflectance is seen across visible and NIR due to salt crusts. Diagnostic absorption features are visible at 1450 nm, 1750 nm, and 1950 nm. Saline soils often display a “white patch” appearance in imagery.

7. Surface Roughness and Microrelief

Surface roughness influences how incoming radiation is scattered. Smooth, compacted surfaces (e.g., crusted soils) have higher reflectance, while rough or aggregated soils show increased shadowing and lower reflectance. Ploughed, eroded, or crusted soils therefore show different brightness levels even if composition is similar.

8. Soil Structure and Aggregation

Soils with strong aggregation exhibit increased multiple scattering, especially in NIR; reflectance variation due to differential shadowing; enhanced absorption when aggregates trap light internally. Structure interacts with moisture and texture, making its impact wavelength-dependent.

9. Soil Temperature (TIR Region)

In the thermal infrared (8–14 μm) soils emit radiation according to their temperature and emissivity. Texture, moisture, and mineralogy influence emissivity in this range. Dry sandy

soils heat up faster, while moist clayey soils have lower thermal emission. Thermal data help distinguish soils that appear similar in visible/NIR imagery.

Table 1: Common Soil Spectral Indices, formulas, and explained Soil Parameters

Spectral Index	Formula	Explained Soil Parameter
1. Soil Adjusted Vegetation Index (SAVI)	$(\text{NIR} - \text{Red}) (1 + L) / (\text{NIR} + \text{Red} + L)$	Reduces vegetation influence; soil brightness
2. Normalized Difference Soil Index (NDSI)	$(\text{SWIR} - \text{NIR}) / (\text{SWIR} + \text{NIR})$	Soil moisture, mineral absorption
3. Soil Moisture Index (SMI)	$(\text{Red} - \text{SWIR}) / (\text{Red} + \text{SWIR})$	Soil moisture content
4. Normalized Difference Water Index (NDWI)	$(\text{NIR} - \text{SWIR}) / (\text{NIR} + \text{SWIR})$	Soil water content
5. Clay Mineral Ratio (CMR)	$\text{SWIR1} / \text{SWIR2}$	Clay mineral abundance
6. Ferrous Iron Index	NIR / SWIR	Ferrous iron oxides
7. Ferric Iron Index	Red / Blue	Ferric iron oxides
8. Redness Index (RI)	$\text{Red}^3 / (\text{Blue} * \text{Green}^2)$	Soil redness; iron oxides
9. Brightness Index (BI)	$\sqrt{(\text{Red}^2 + \text{NIR}^2)/2}$	Soil brightness; sand/salts
10. Salinity Index 1 (SI1)	$\text{Red} / \text{Green}$	General soil salinity
11. Salinity Index 2 (SI2)	$(\text{NIR} * \text{Red}) / \text{Green}$	Saline-sodic soil detection
12. Carbonate Index (CI)	SWIR / NIR	Carbonate-rich soils
13. Organic Matter Index (OMI)	Red / NIR	Soil organic matter content
14. Normalized Burn Ratio (NBR)	$(\text{NIR} - \text{SWIR2}) / (\text{NIR} + \text{SWIR2})$	Soil exposure, organic changes, bare land

NIR: Near Infra-red; SWIR: Short-Wave Infrared; L: soil brightness correction factor

Challenges

The use of spectral indices can lead to several issues that are still unsolved. First and foremost, the large number of spectral indices makes it difficult to choose suitable and useful ones for a particular goal. Additionally, meaning duplication may result in redundancy, and naming confusion may lead to misuse. Results can alter based on different sensors and correction techniques, even when the same index is used, making them less comparable and explicable between investigations.

CONCLUSION

Overall, spectral indices form the backbone of modern soil remote sensing, providing a powerful framework for translating spectral signatures into actionable insights. Their expanding applications will continue to strengthen soil resource management, enhance agricultural productivity, and support environmental monitoring in an increasingly data-driven world.

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