LINKING REFLECTANCE SIGNATURES TO NUTRIENT DEFICIENCY IN DRAGON FRUIT USING SPECTRAL ANALYSIS

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Abstract

Rapid and non-destructive assessment of plant nutritional status is critical for precision agriculture, yet most hyperspectral studies focus narrowly on nitrogen (N) detection and limited wavelength ranges. This study presents a Nutrient Deficiency Scoring (NDS) framework that integrates eleven macro- and micronutrient concentrations. Nitrogen (N), calcium (Ca), potassium (K), magnesium (Mg), phosphorus (P), sulfur (S), boron (B), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) into a single composite index and evaluates its correlation with full-range hyperspectral reflectance (350–2500 nm) across three growing seasons. Macronutrients were standardized to parts per million (ppm) via a ×10,000 conversion factor, enabling comparison across all nutrients on a unified scale. A weighted, proximity-to-optimum NDS (range 0–100) was constructed with sign-inversion transformations to align correlation directionality with spectral reflectance. The composite NDS achieved a maximum Pearson correlation of $r = 0.794$ ($p < 0.001$) at 816 nm within the near-infrared (NIR) plateau, with 1,905 wavelengths exhibiting $r > 0.60$. Individual deficiency indices revealed strong spectral sensitivity for N ($r = -0.738$, 811 nm), P ($r = -0.712$, 1,997 nm), S ($r = -0.653$, 817 nm), K ($r = -0.607$, 2,002 nm), Fe ($r = -0.484$, 769 nm), Mg ($r = -0.461$, 715 nm), and Zn ($r = -0.423$, 996 nm). Boron, Mn, and Cu exhibited weaker spectral associations ($|r| < 0.35$). NDS increased significantly across seasons (2022: 28.3 ± 19.9; 2024: 68.7 ± 9.1; 2025: 83.6 ± 8.5; ANOVA: $F = 91.03$, $p < 0.001$), reflecting progressive intensification of nutrient stress. These findings demonstrate that NIR (700–1300 nm) and SWIR (1300–2500 nm) spectral regions provide complementary windows for estimating a broad panel of plant nutrient deficiencies non-destructively, establishing a spectral basis for field-deployable multi-nutrient monitoring tools.

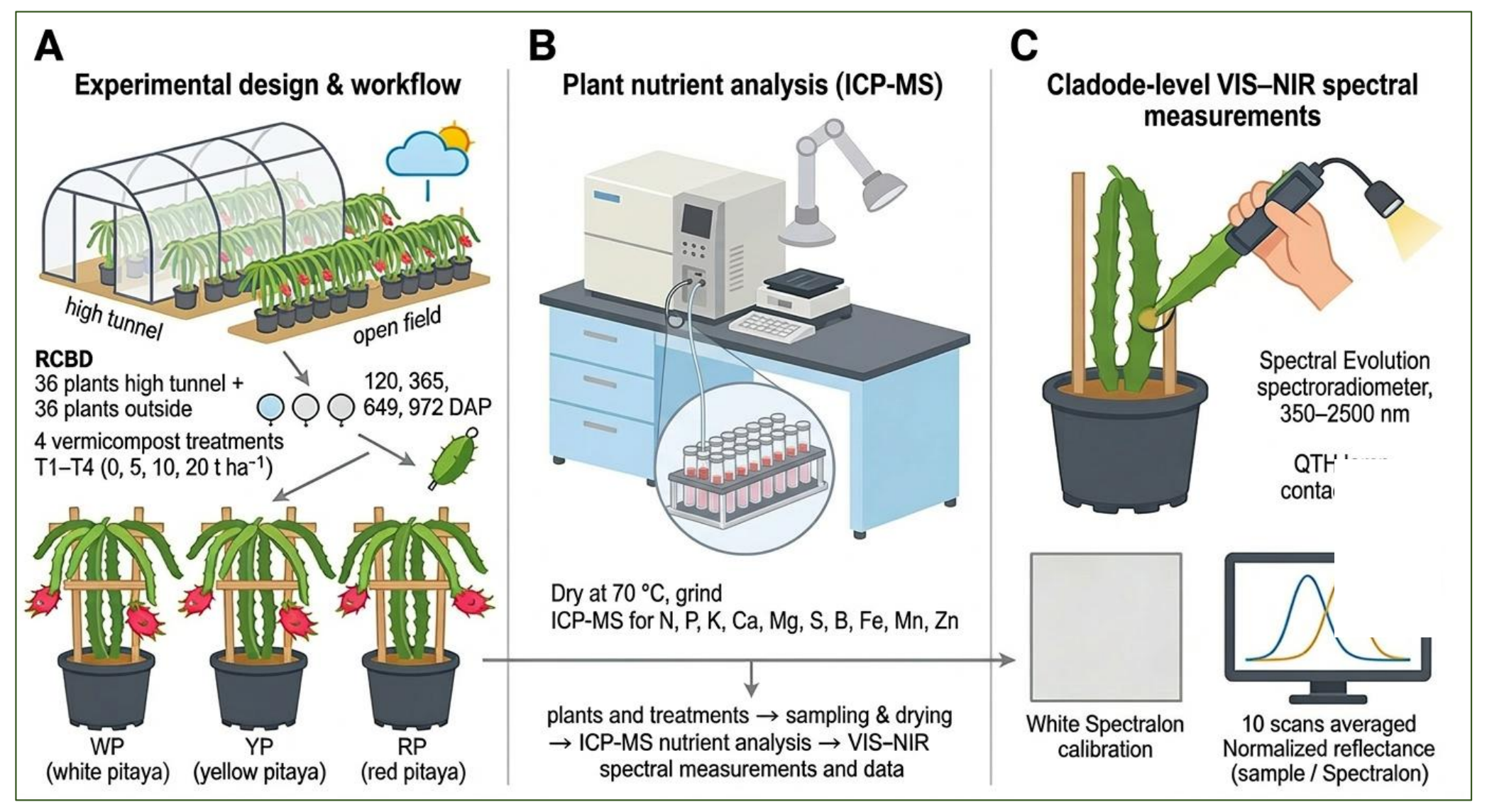
Introduction

Why spectral sensing?
Traditional nutrient analysis: slow, costly, destructive, VIS–NIR reflectance: rapid, non-destructive, field-deployable

Key spectral mechanisms:
Chlorophyll absorbs at 430–450 nm & 640–680 nm → N & M. Red-edge (680–760 nm) → chlorophyll & cell structure change. NIR plateau → governed by mesophyll architecture → Ca, K, Zn

Gap addressed:
Multi-nutrient deficiency indices across multiple seasons are rarely correlated with full-range hyperspectral data. Most studies target N alone and use narrow wavelength windows.

Experimental Design



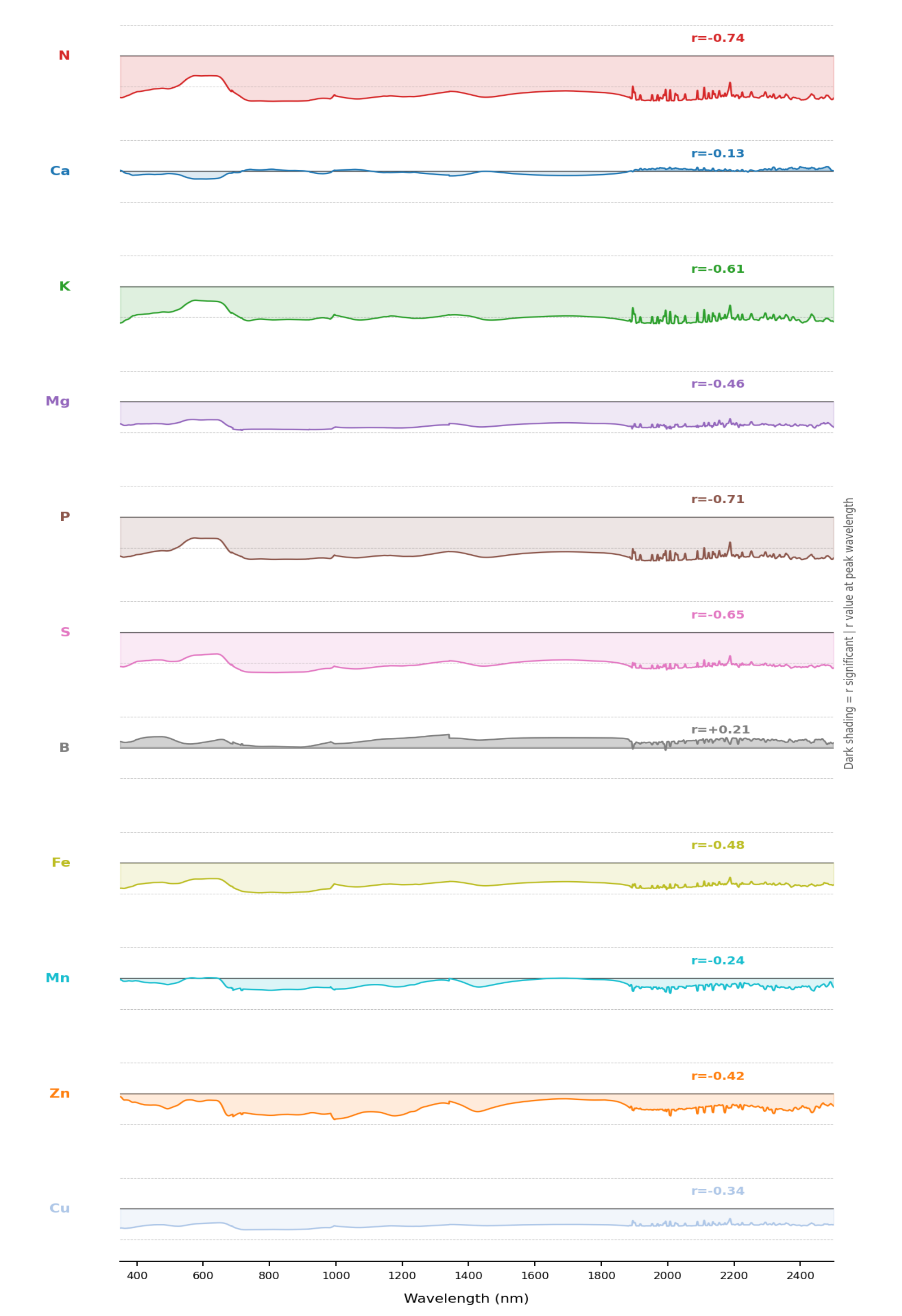
Nutrient Deficiency–Spectral Reflectance Workflow

Step 1 – Unit Standardization
↓
Step 2 – Treatment Averaging
↓
Step 3 – NDS Construction (0–100)
↓
Step 4 – Sign Inversion (Deficiency)
↓
Step 5 – Spectral Correlation Analysis

Figure 1: Experimental design and workflow showing high tunnel/open field setup, ICP-MS nutrient analysis, and VIS–NIR spectral measurements, and Statistical Analysis

Results

Spectral Correlation (350-2500nm)



Dark shading = p < 0.05 | Light = p < 0.10 | r values at peak wavelength shown

Figure 2: Partial spectral correlation profiles showing relationships between reflectance (350-2500 nm) and nutrient concentrations.

NDS vs. Spectral Reflectance — Correlation Spectrum

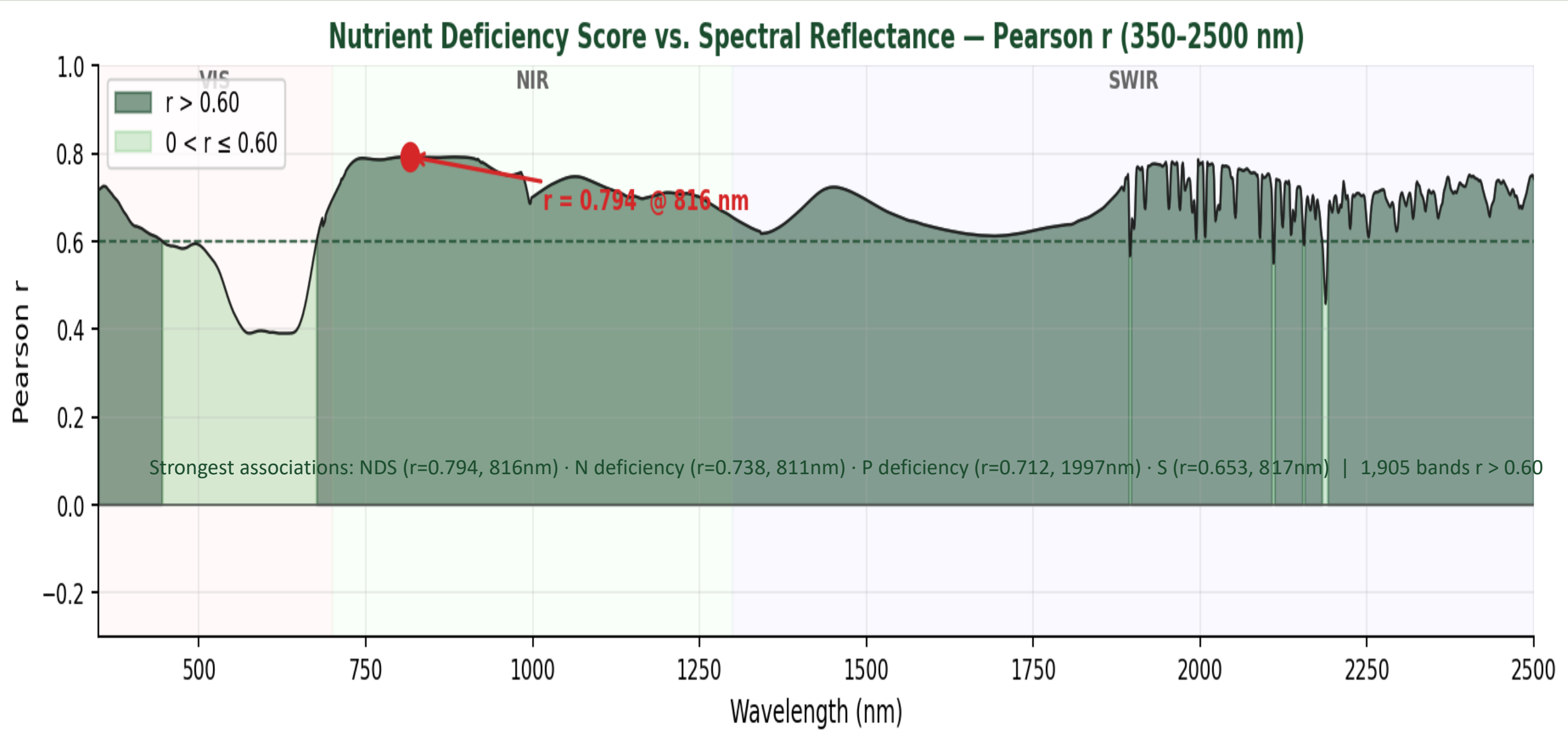


Figure 3: Pearson r between Nutrient Deficiency Score and reflectance. Peak $r = 0.794$ @ 816 nm. 1,905 wavelengths with $r > 0.60$ (dark green shading).

Mean Leaf Reflectance Spectra by Year

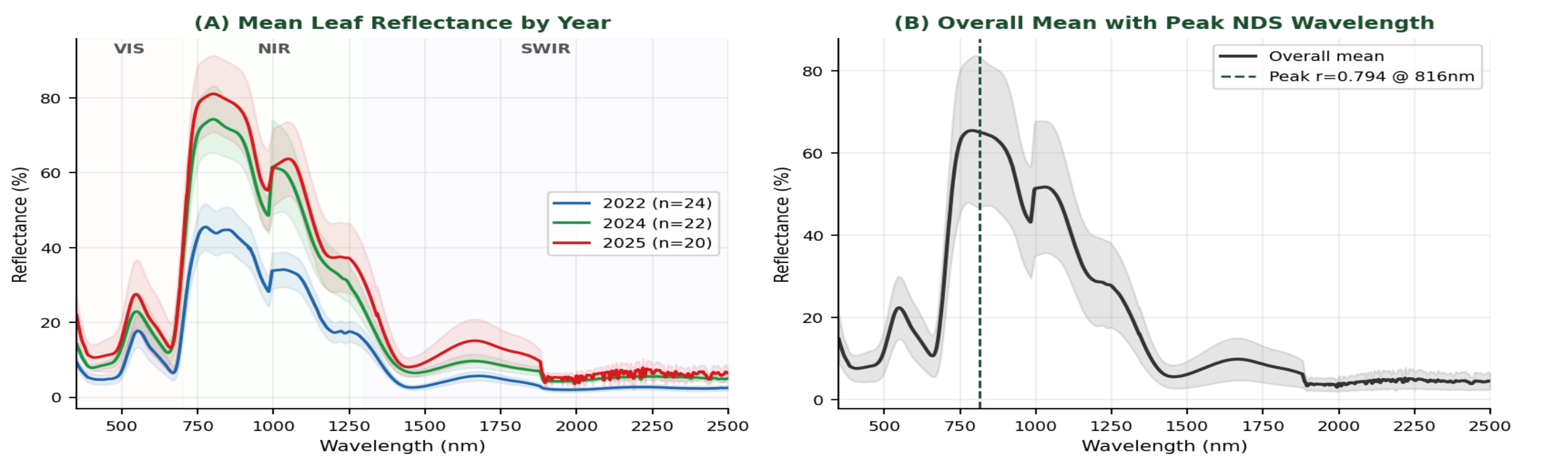


Figure 4: Annual mean spectral reflectance (±1 SD). Peak NDS correlation wavelength (816 nm) marked.

Scatter Plots — NDS vs Reflectance at Key Wavelengths

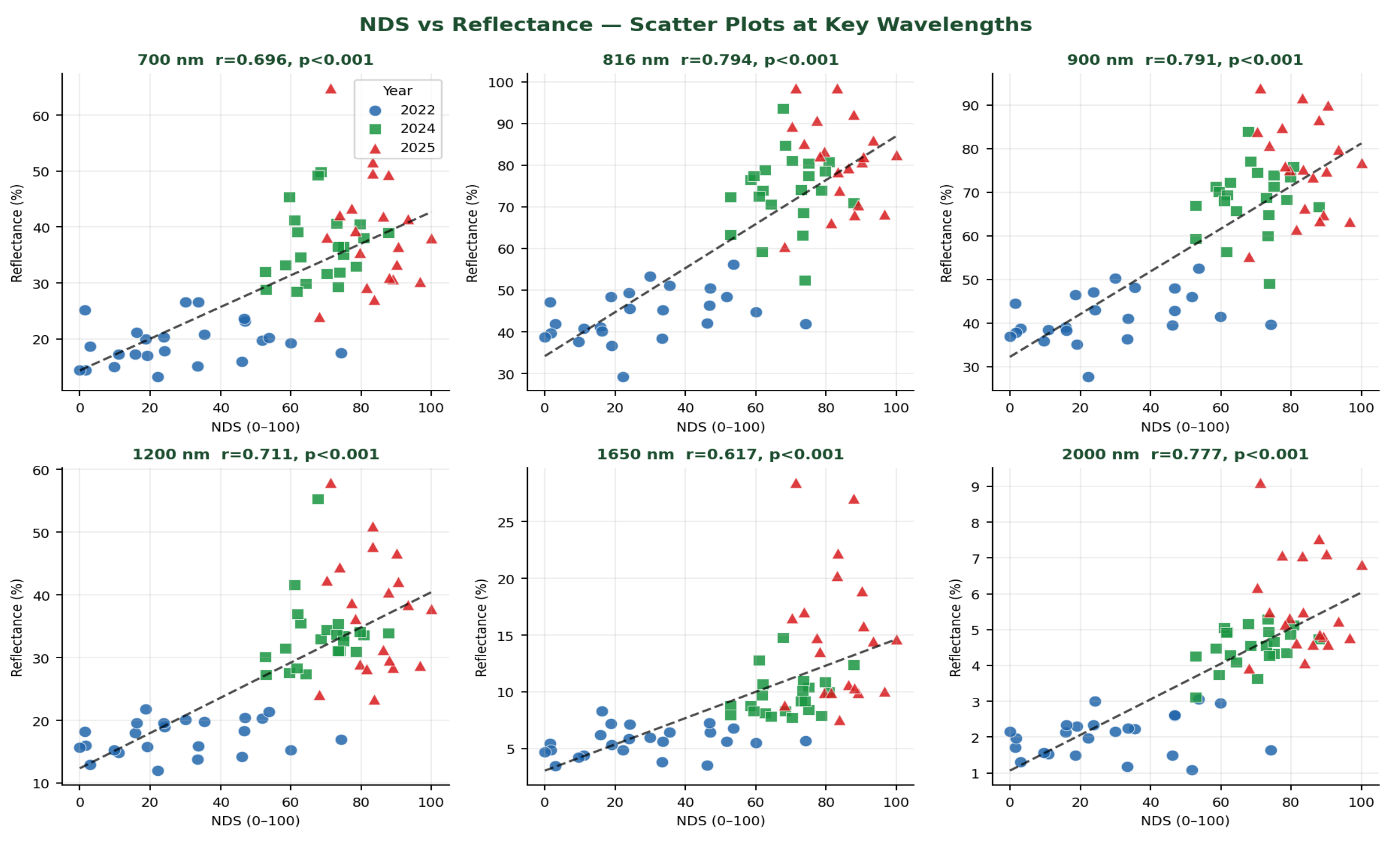


Figure 5: NDS vs spectral reflectance scatter plots at six key wavelengths. Dashed line = OLS regression.

Vegetation Index × NDS Correlations

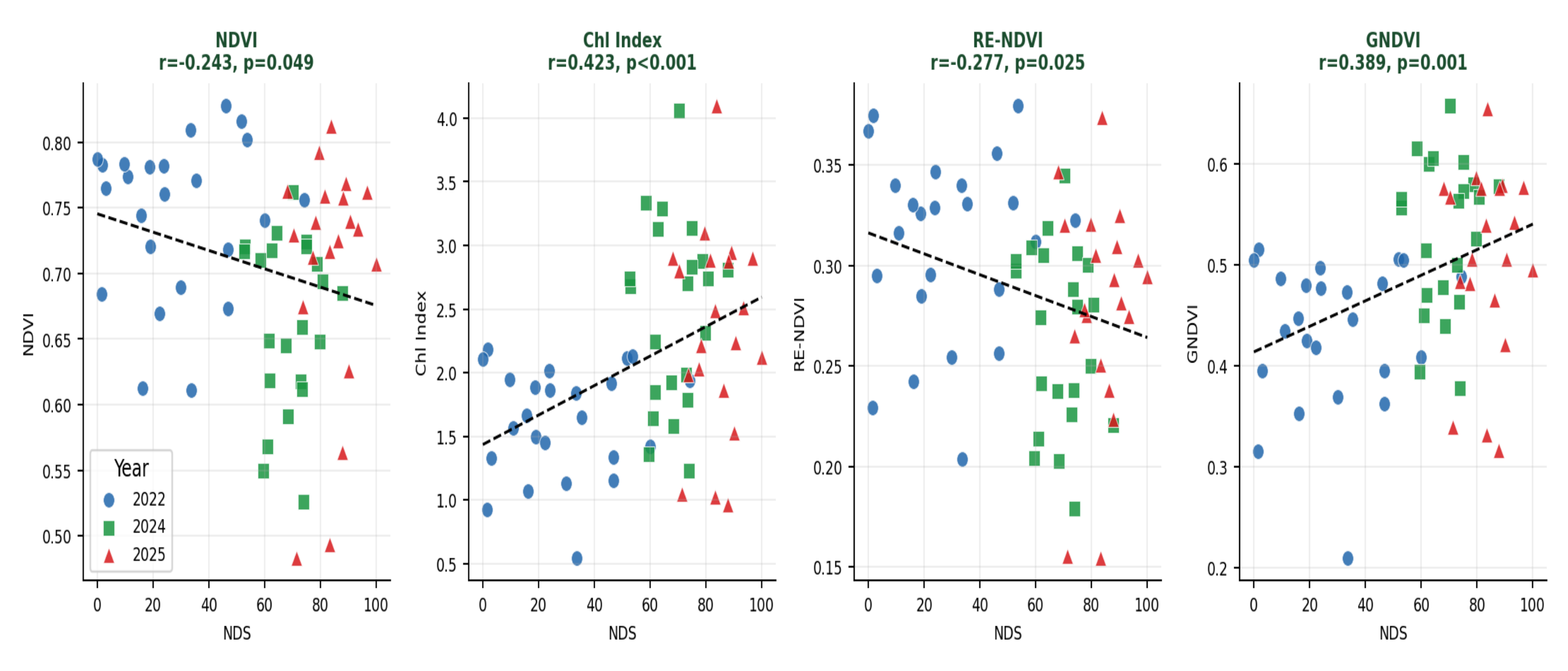


Figure 6: Vegetation index correlations with NDS. Negative r reflects inverse health/deficiency relationship

Key Results Summary

NDS :	816nm	+0.794**	NIR
N deficiency:	811nm	+0.738**	NIR
P deficiency :	1997nm	+0.712**	SWIR
S deficiency:	817nm	+0.653**	NIR
K deficiency :	2002nm	+0.607**	SWIR

*** p<0.01*

Conclusion

✓ NDS achieved $r = 0.794$ @ 816 nm — strong positive correlation with NIR reflectance.

✓ 1,905 wavelengths with $r > 0.60$ identified as prediction-capable spectral bands.

✓ Sign-inversion transformation resolves negative correlation directionality problem

✓ N (811 nm, NIR) and P (1997 nm, SWIR) are most spectrally detectable individual nutrients.

✗ Conventional VIs (NDVI, GNDVI) show only weak association with NDS ($r \approx -0.24$ to -0.31)

Practical implication: *Full-spectrum hyperspectral data at 700–1300 nm (NIR) and ~2000 nm (SWIR) can non-destructively screen for multi-nutrient deficiency. NDS framework provides foundation for PLSR or ML prediction models.*

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