In [2]:
```
!pip install rasterio
```

```
Collecting rasterio
  Downloading rasterio-1.4.3-cp313-cp313-win_amd64.whl.metadata (9.4 kB)
Collecting affine (from rasterio)
  Downloading affine-2.4.0-py3-none-any.whl.metadata (4.0 kB)
Requirement already satisfied: attrs in c:\users\admin\appdata\local\programs\python
\python313\lib\site-packages (from rasterio) (25.3.0)
Requirement already satisfied: certifi in c:\users\admin\appdata\local\programs\pyth
on\python313\lib\site-packages (from rasterio) (2025.6.15)
Requirement already satisfied: click>=4.0 in c:\users\admin\appdata\local\programs\p
ython\python313\lib\site-packages (from rasterio) (8.1.8)
Collecting cligj>=0.5 (from rasterio)
  Downloading cligj-0.7.2-py3-none-any.whl.metadata (5.0 kB)
Requirement already satisfied: numpy>=1.24 in c:\users\admin\appdata\local\programs
\python\python313\lib\site-packages (from rasterio) (2.2.5)
Collecting click-plugins (from rasterio)
  Downloading click_plugins-1.1.1.2-py2.py3-none-any.whl.metadata (6.5 kB)
Requirement already satisfied: pyparsing in c:\users\admin\appdata\local\programs\py
thon\python313\lib\site-packages (from rasterio) (3.2.3)
Requirement already satisfied: colorama in c:\users\admin\appdata\local\programs\pyt
hon\python313\lib\site-packages (from click>=4.0->rasterio) (0.4.6)
Downloading rasterio-1.4.3-cp313-cp313-win_amd64.whl (25.4 MB)
   ---------------------------------------- 0.0/25.4 MB ? eta -:--:--
   --- ------------------------------------ 2.4/25.4 MB 18.9 MB/s eta 0:00:02
   --------- ------------------------------ 5.8/25.4 MB 18.6 MB/s eta 0:00:02
   --------------- ------------------------ 10.0/25.4 MB 19.1 MB/s eta 0:00:01
   ---------------------- ----------------- 14.2/25.4 MB 19.3 MB/s eta 0:00:01
   ---------------------------- ----------- 18.1/25.4 MB 19.2 MB/s eta 0:00:01
   ---------------------------------- ----- 21.8/25.4 MB 19.1 MB/s eta 0:00:01
   ---------------------------------------  25.2/25.4 MB 18.6 MB/s eta 0:00:01
   ---------------------------------------- 25.4/25.4 MB 17.6 MB/s eta 0:00:00
Downloading cligj-0.7.2-py3-none-any.whl (7.1 kB)
Downloading affine-2.4.0-py3-none-any.whl (15 kB)
Downloading click_plugins-1.1.1.2-py2.py3-none-any.whl (11 kB)
Installing collected packages: affine, cligj, click-plugins, rasterio
Successfully installed affine-2.4.0 click-plugins-1.1.1.2 cligj-0.7.2 rasterio-1.4.3
```

```
[notice] A new release of pip is available: 24.3.1 -> 25.2
[notice] To update, run: python.exe -m pip install --upgrade pip
```

In [5]:
```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from scipy.interpolate import interp1d
from scipy.spatial.distance import cosine
import rasterio
from sklearn.metrics.pairwise import cosine_similarity


SENTINEL2_ALL_BANDS = {
    'B1': 443,   # Coastal aerosol (EXCLUDED)
    'B2': 490,   # Blue
    'B3': 560,   # Green
    'B4': 665,   # Red
```

```
    'B5': 705,   # Red Edge 1
    'B6': 740,   # Red Edge 2
    'B7': 783,   # Red Edge 3
    'B8': 842,   # NIR
    'B8A': 865,  # Narrow NIR
    'B9': 940,   # Water vapor (EXCLUDED)
    'B11': 1610, # SWIR 1
    'B12': 2190  # SWIR 2
}


SENTINEL2_BANDS = {
    'B2': 490,   # Blue
    'B3': 560,   # Green
    'B4': 665,   # Red
    'B5': 705,   # Red Edge 1
    'B6': 740,   # Red Edge 2
    'B7': 783,   # Red Edge 3
    'B8': 842,   # NIR
    'B8A': 865,  # Narrow NIR
    'B11': 1610, # SWIR 1
    'B12': 2190  # SWIR 2
}

def load_ecostress_data(file_path):
    """Load ECOSTRESS spectral data from text file"""
    data = []
    with open(file_path, 'r') as f:
        lines = f.readlines()


    data_start = 0
    for i, line in enumerate(lines):
        if line.strip() and not line.startswith('Name:') and not line.startswith('T
            try:

                parts = line.strip().split()
                if len(parts) == 2:
                    float(parts[0])
                    float(parts[1])
                    data_start = i
                    break
            except ValueError:
                continue


    wavelengths = []
    reflectances = []

    for line in lines[data_start:]:
        line = line.strip()
        if line and not line.startswith('#'):
            try:
                parts = line.split()
                if len(parts) >= 2:
                    wl = float(parts[0]) * 1000  # Convert to nm
```

```
                    refl = float(parts[1]) / 100.0  # Convert to 0-1 range
                    wavelengths.append(wl)
                    reflectances.append(refl)
            except ValueError:
                continue

    return np.array(wavelengths), np.array(reflectances)

def resample_to_sentinel2(wavelengths, reflectances, s2_bands):

    # Create interpolation function
    interp_func = interp1d(wavelengths, reflectances, kind='linear',
                          bounds_error=False, fill_value='extrapolate')

    # Sample at Sentinel-2 band centers
    s2_wavelengths = list(s2_bands.values())
    s2_reflectances = interp_func(s2_wavelengths)

    return np.array(s2_wavelengths), s2_reflectances

def spectral_angle_mapper(spectrum1, spectrum2):


    spectrum1 = np.array(spectrum1).flatten()
    spectrum2 = np.array(spectrum2).flatten()

    # Remove any NaN or infinite values
    mask = np.isfinite(spectrum1) & np.isfinite(spectrum2)
    spectrum1 = spectrum1[mask]
    spectrum2 = spectrum2[mask]

    if len(spectrum1) == 0 or len(spectrum2) == 0:
        return np.pi/2


    cos_sim = np.dot(spectrum1, spectrum2) / (np.linalg.norm(spectrum1) * np.linalg


    cos_sim = np.clip(cos_sim, -1, 1)


    angle = np.arccos(cos_sim)

    return angle

def find_closest_matches(sentinel2_data, reference_spectrum, n_matches=100):

    height, width, bands = sentinel2_data.shape


    if len(reference_spectrum) != bands:
        print(f"Warning: Reference spectrum has {len(reference_spectrum)} bands, "
              f"but Sentinel-2 data has {bands} bands")
        if len(reference_spectrum) > bands:
            reference_spectrum = reference_spectrum[:bands]
        else:
```

```
            print("Cannot proceed: Reference spectrum has fewer bands than Sentinel
            return []

    # Reshape Sentinel-2 data to 2D (pixels x bands)
    s2_reshaped = sentinel2_data.reshape(-1, bands)

    # Calculate spectral angles for all pixels
    angles = []
    valid_indices = []

    for i, pixel_spectrum in enumerate(s2_reshaped):
        # Skip pixels with invalid data (zeros, NaNs)
        if np.any(np.isnan(pixel_spectrum)) or np.all(pixel_spectrum == 0):
            continue

        angle = spectral_angle_mapper(pixel_spectrum, reference_spectrum)
        angles.append(angle)
        valid_indices.append(i)

    # Sort by spectral angle and get closest matches
    angles = np.array(angles)
    sorted_indices = np.argsort(angles)

    closest_matches = []
    for i in range(min(n_matches, len(sorted_indices))):
        idx = valid_indices[sorted_indices[i]]
        row = idx // width
        col = idx % width
        angle = angles[sorted_indices[i]]
        spectrum = s2_reshaped[idx]

        closest_matches.append({
            'row': row,
            'col': col,
            'angle': angle,
            'spectrum': spectrum,
            'rank': i + 1
        })

    return closest_matches

def plot_spectral_comparison(ecostress_wl, ecostress_refl, s2_wavelengths,
                           matches, reference_name, ranks_to_plot=[1, 50, 100]):

    plt.figure(figsize=(12, 8))

    # Plot ECOSTRESS reference spectrum
    plt.plot(ecostress_wl, ecostress_refl, 'k-', linewidth=2,
             label=f'ECOSTRESS {reference_name}', alpha=0.8)

    # Plot resampled ECOSTRESS at Sentinel-2 bands
    ecostress_s2 = resample_to_sentinel2(ecostress_wl, ecostress_refl, SENTINEL2_BA
    plt.plot(s2_wavelengths, ecostress_s2, 'ko', markersize=8,
             label=f'ECOSTRESS resampled to S2 bands')

    # Plot selected Sentinel-2 matches
```

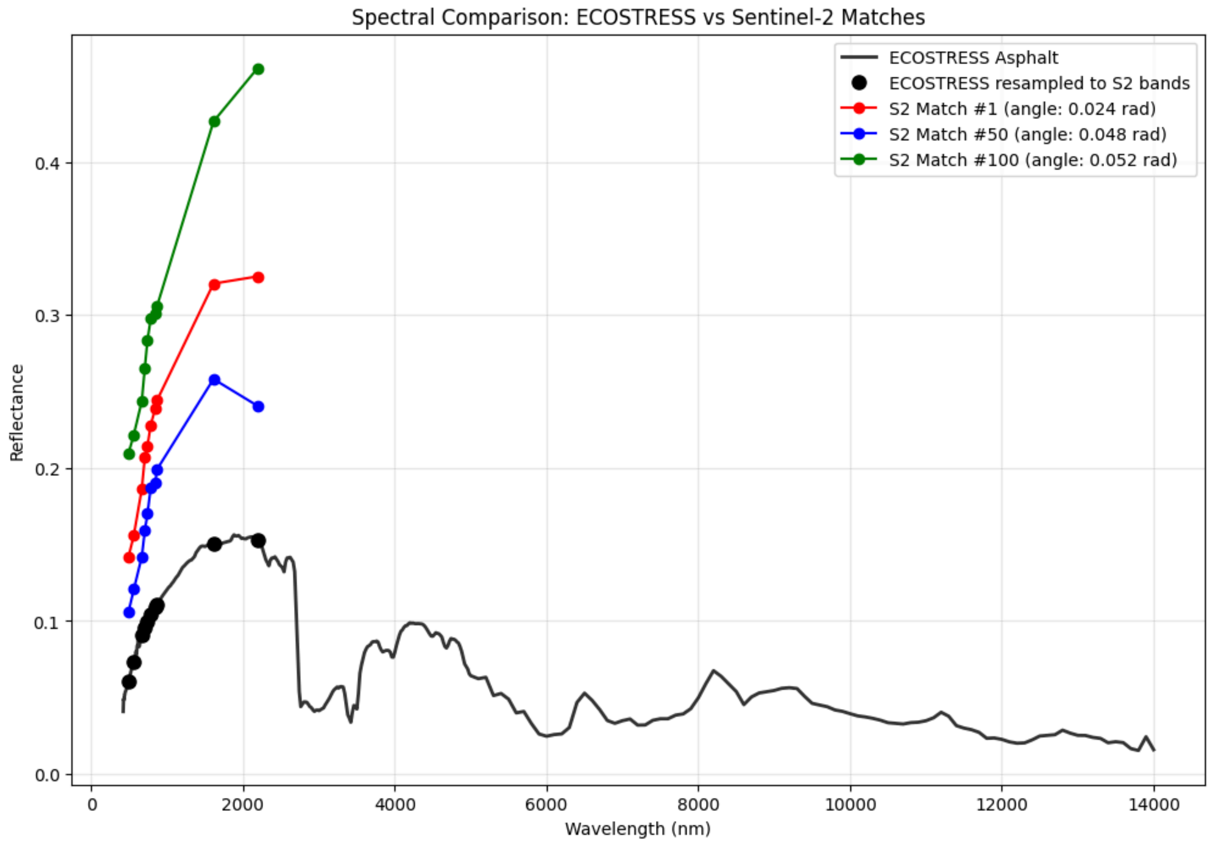
```python
    colors = ['red', 'blue', 'green']
    for i, rank in enumerate(ranks_to_plot):
        if rank <= len(matches):
            match = matches[rank - 1]
            plt.plot(s2_wavelengths, match['spectrum'], 'o-',
                    color=colors[i % len(colors)], markersize=6,
                    label=f'S2 Match #{rank} (angle: {match["angle"]:.3f} rad)')

    plt.xlabel('Wavelength (nm)')
    plt.ylabel('Reflectance')
    plt.title(f'Spectral Comparison: ECOSTRESS vs Sentinel-2 Matches')
    plt.legend()
    plt.grid(True, alpha=0.3)
    plt.show()

def create_classification_map(sentinel2_data, reference_spectra, threshold_angle,
                             material_names):

    height, width, bands = sentinel2_data.shape
    classification_map = np.zeros((height, width), dtype=int)

    for i in range(height):
        for j in range(width):
            pixel_spectrum = sentinel2_data[i, j, :]

            # Skip invalid pixels
            if np.any(np.isnan(pixel_spectrum)) or np.all(pixel_spectrum == 0):
                continue

            # Find best match among reference spectra
            best_angle = float('inf')
            best_class = 0

            for class_idx, ref_spectrum in enumerate(reference_spectra):
                angle = spectral_angle_mapper(pixel_spectrum, ref_spectrum)
                if angle < best_angle and angle < threshold_angle:
                    best_angle = angle
                    best_class = class_idx + 1  # 1-indexed classes

            classification_map[i, j] = best_class

    return classification_map

def visualize_classification(classification_map, material_names):

    plt.figure(figsize=(10, 8))

    # Create custom colormap
    colors = ['black', 'green', 'gray']  # background, vegetation, road
    from matplotlib.colors import ListedColormap
    cmap = ListedColormap(colors[:len(material_names) + 1])

    plt.imshow(classification_map, cmap=cmap, vmin=0, vmax=len(material_names))

    # Add colorbar with labels
    cbar = plt.colorbar(ticks=range(len(material_names) + 1))
```

```
    labels = ['Unclassified'] + material_names
    cbar.set_ticklabels(labels)

    plt.title('Spectral Classification Map')
    plt.xlabel('Column')
    plt.ylabel('Row')
    plt.show()


def main_analysis(asphalt_file, vegetation_file, sentinel2_file):


    print("Loading ECOSTRESS data...")
    # Load ECOSTRESS data
    asphalt_wl, asphalt_refl = load_ecostress_data(asphalt_file)
    vegetation_wl, vegetation_refl = load_ecostress_data(vegetation_file)

    print("Loading Sentinel-2 data...")

    sentinel2_data = np.load(sentinel2_file)

    print(f"Sentinel-2 data shape: {sentinel2_data.shape}")


    height, width, actual_bands = sentinel2_data.shape

    # Create a mapping based on the number of bands in your data
    if actual_bands == 12:

        print("Detected 12-band Sentinel-2 data. Selecting bands excluding B1, B9,

        band_indices = [1, 2, 3, 4, 5, 6, 7, 8, 10, 11]  # Skip B1(idx 0) and B9(id
        sentinel2_data = sentinel2_data[:, :, band_indices]
        selected_bands = SENTINEL2_BANDS
    elif actual_bands == 10:
        # Already filtered data
        print("Detected 10-band Sentinel-2 data (pre-filtered).")
        selected_bands = SENTINEL2_BANDS
    elif actual_bands == 13:

        print("Detected 12-band Sentinel-2 data. Selecting bands excluding B1, B9,

        band_indices = [1, 2, 3, 4, 5, 6, 7, 8, 10, 12]  # Skip B1(0), B9(9), B10(1
        sentinel2_data = sentinel2_data[:, :, band_indices]
        selected_bands = SENTINEL2_BANDS
    else:
        print(f"Unexpected number of bands: {actual_bands}. Using first {min(actual
        selected_bands = dict(list(SENTINEL2_BANDS.items())[:min(actual_bands, 10)]
        if actual_bands < 10:
            sentinel2_data = sentinel2_data[:, :, :actual_bands]

    print(f"Using {sentinel2_data.shape[2]} bands for analysis")
    print(f"Final Sentinel-2 data shape: {sentinel2_data.shape}")

    print("Resampling ECOSTRESS to Sentinel-2 bands...")
    # Resample to Sentinel-2 bands
```

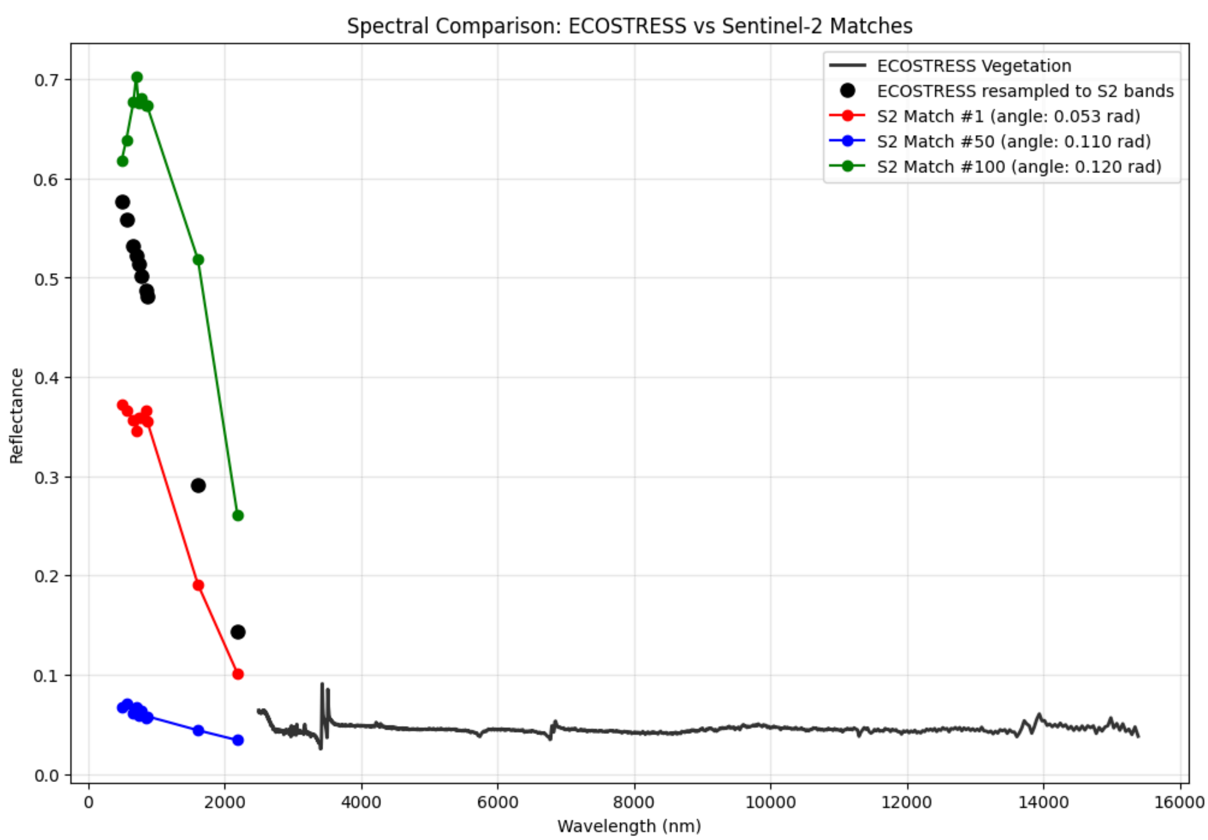
```
    s2_wl, asphalt_s2 = resample_to_sentinel2(asphalt_wl, asphalt_refl, selected_ba
    _, vegetation_s2 = resample_to_sentinel2(vegetation_wl, vegetation_refl, select

    # Ensure the resampled spectra match the number of bands in the Sentinel-2 data
    if len(asphalt_s2) != sentinel2_data.shape[2]:
        print(f"Adjusting reference spectra to match {sentinel2_data.shape[2]} band
        asphalt_s2 = asphalt_s2[:sentinel2_data.shape[2]]
        vegetation_s2 = vegetation_s2[:sentinel2_data.shape[2]]
        s2_wl = s2_wl[:sentinel2_data.shape[2]]

    print("Finding closest matches for asphalt...")
    # Find closest matches for asphalt
    asphalt_matches = find_closest_matches(sentinel2_data, asphalt_s2, 100)

    print("Finding closest matches for vegetation...")
    # Find closest matches for vegetation
    vegetation_matches = find_closest_matches(sentinel2_data, vegetation_s2, 100)

    print("Plotting spectral comparisons...")
    # Plot comparisons
    plot_spectral_comparison(asphalt_wl, asphalt_refl, s2_wl,
                             asphalt_matches, "Asphalt")

    plot_spectral_comparison(vegetation_wl, vegetation_refl, s2_wl,
                             vegetation_matches, "Vegetation")

    # Print analysis of matches
    print("\nAsphalt Match Analysis:")
    for rank in [1, 50, 100]:
        if rank <= len(asphalt_matches):
            match = asphalt_matches[rank - 1]
            print(f"  Rank {rank}: Spectral angle = {match['angle']:.4f} radians ({

    print("\nVegetation Match Analysis:")
    for rank in [1, 50, 100]:
        if rank <= len(vegetation_matches):
            match = vegetation_matches[rank - 1]
            print(f"  Rank {rank}: Spectral angle = {match['angle']:.4f} radians ({

    # Set threshold angle (you can adjust this based on your analysis)
    threshold_angle = 0.2  # radians (~11.5 degrees)
    print(f"\nUsing threshold angle: {threshold_angle:.3f} radians ({np.degrees(thr

    print("Creating classification map...")
    # Create classification map
    reference_spectra = [vegetation_s2, asphalt_s2]
    material_names = ['Vegetation', 'Road/Asphalt']

    classification_map = create_classification_map(sentinel2_data, reference_spectr
                                                    threshold_angle, material_names)

    # Visualize results
    visualize_classification(classification_map, material_names)

    # Print classification statistics
    total_pixels = classification_map.size
```

```python
    for i, material in enumerate(material_names):
        count = np.sum(classification_map == i + 1)
        percentage = (count / total_pixels) * 100
        print(f"{material}: {count} pixels ({percentage:.1f}%)")

    unclassified = np.sum(classification_map == 0)
    print(f"Unclassified: {unclassified} pixels ({(unclassified/total_pixels)*100:.

    return asphalt_matches, vegetation_matches, classification_map


if __name__ == "__main__":

    asphalt_file = "manmade.road.pavingasphalt.solid.all.0095uuuasp.jhu.becknic.spe
    vegetation_file = "vegetation.tree.quercus.agrifolia.tir.vh080.ucsb.nicolet.spe
    sentinel2_file = "sentinel2_rochester.npy"


    asphalt_matches, vegetation_matches, classification_map = main_analysis(
        asphalt_file, vegetation_file, sentinel2_file
    )
```

```
Loading ECOSTRESS data...
Loading Sentinel-2 data...
Sentinel-2 data shape: (954, 716, 12)
Detected 12-band Sentinel-2 data. Selecting bands excluding B1, B9, B10...
Using 10 bands for analysis
Final Sentinel-2 data shape: (954, 716, 10)
Resampling ECOSTRESS to Sentinel-2 bands...
Finding closest matches for asphalt...
Finding closest matches for vegetation...
Plotting spectral comparisons...
```

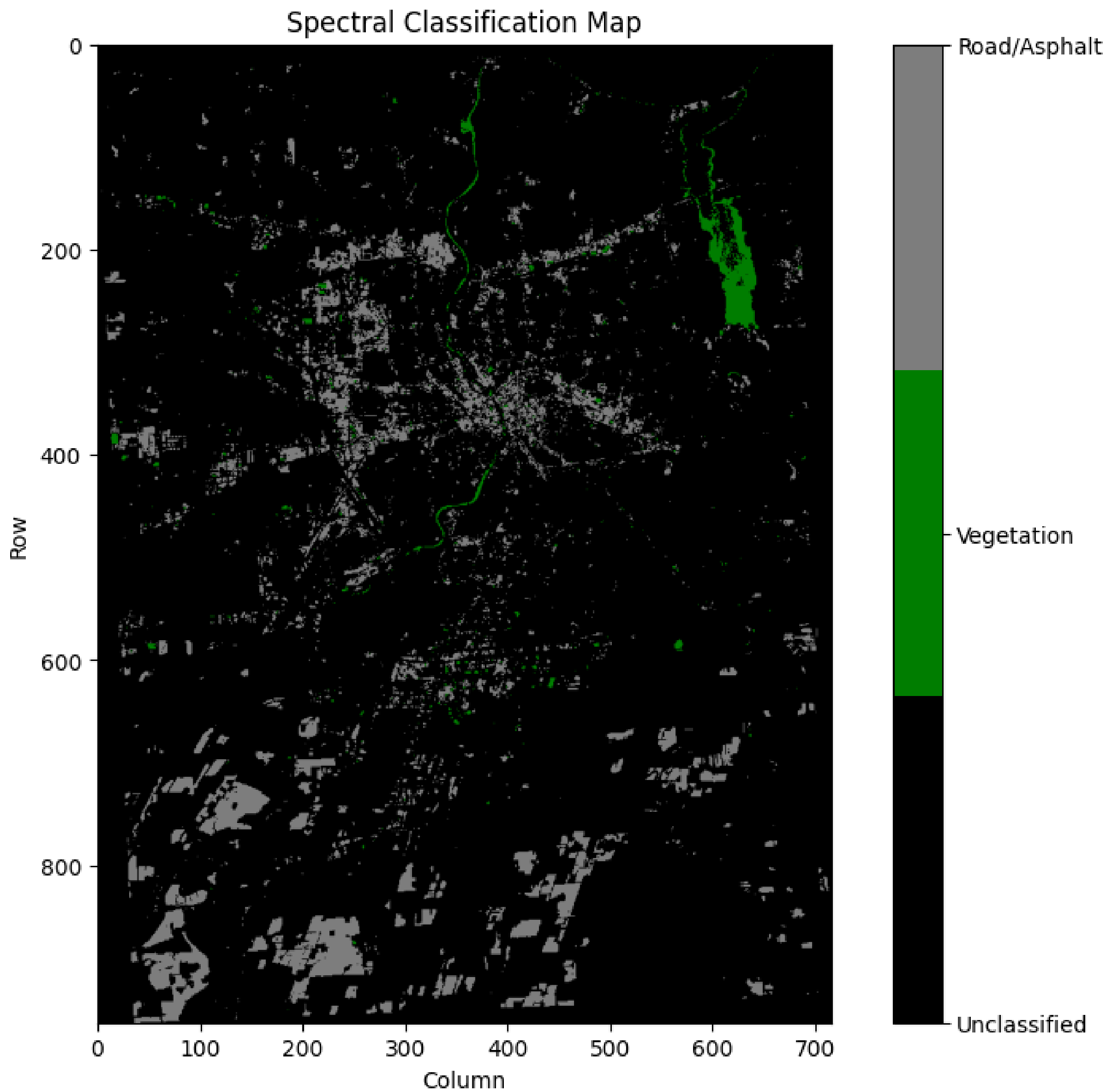


Spectral Comparison: ECOSTRESS vs Sentinel-2 Matches
ECOSTRESS Asphalt
ECOSTRESS resampled to S2 bands
S2 Match #1 (angle: 0.024 rad)
S2 Match #50 (angle: 0.048 rad)
S2 Match #100 (angle: 0.052 rad)
Reflectance
Wavelength (nm)



Spectral Comparison: ECOSTRESS vs Sentinel-2 Matches
ECOSTRESS Vegetation
ECOSTRESS resampled to S2 bands
S2 Match #1 (angle: 0.053 rad)
S2 Match #50 (angle: 0.110 rad)
S2 Match #100 (angle: 0.120 rad)
Reflectance
Wavelength (nm)

```
Asphalt Match Analysis:
  Rank 1: Spectral angle = 0.0239 radians (1.37°)
  Rank 50: Spectral angle = 0.0480 radians (2.75°)
  Rank 100: Spectral angle = 0.0521 radians (2.99°)

Vegetation Match Analysis:
  Rank 1: Spectral angle = 0.0532 radians (3.05°)
  Rank 50: Spectral angle = 0.1101 radians (6.31°)
  Rank 100: Spectral angle = 0.1198 radians (6.86°)

Using threshold angle: 0.200 radians (11.5°)
Creating classification map...
```




```
Vegetation: 5915 pixels (0.9%)
Road/Asphalt: 47888 pixels (7.0%)
Unclassified: 629261 pixels (92.1%)
```

In [ ]:

EXPLANATION Sentinel-2 satellite imagery is compared to reference spectral signatures from the ECOSTRESS spectral library in order to perform spectral classification. No-data is handled by eliminating pixels with values of 0 or NaN from the analysis. In order to determine the closest spectral matches, the code loads reference spectra for materials such as asphalt and vegetation from ECOSTRESS text files, resamples these high-resolution laboratory spectra to match the band centers of Sentinel-2, and then uses the Spectral Angle Mapper (SAM) algorithm to determine the angular distances between each satellite pixel and the reference spectra. By allocating pixels to material classes (roads, vegetation, etc.) when their spectral angle falls below a certain threshold, it generates classification maps and displays the outcomes using color-coded maps.