Handling spectral indices

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This study analyzes the seasonal dynamics of vegetation, with a specific focus on the cultivation of tomatoes (pomodorini) typical of the coastal area between Sperlonga, Terracina, and Fondi, during the summer months (June to September) of 2022 and 2023. Using data from Sentinel-2 and Landsat-8 processed within the Google Earth Engine platform, the Normalized Difference Vegetation Index (NDVI) and the Modified Normalized Difference Water Index (MNDWI) were computed and compared to estimate the extent of healthy vegetation and surface water. Additionally, NDVI-based greenest pixel composites and temporal NDVI series were produced to detect the peak periods of vegetation activity. Results show a greater extent of healthy vegetation in 2023 compared to 2022, alongside a slight decrease in water-covered areas. These findings provide insights into irrigation efficiency and crop health monitoring, particularly concerning cherry tomato production.

Keywords: NDVI, MNDWI, Sentinel-2, Landsat-8, Earth Engine, Sperlonga, Terracina, Fondi, vegetation, water, greenest pixel, tomatoes

I. INTRODUCTION

The coastal agricultural area between Sperlonga, Terracina, and Fondi is one of the most productive horticultural zones in southern Lazio, particularly known for the cultivation of tomatoes during the summer season. In this period, local agriculture relies heavily on the availability of water resources and effective monitoring of crop health. The objective of this study is to assess interannual variations in the extent of healthy vegetation and surface water using spectral indices derived from satellite imagery. The analysis focuses specifically on the months of June, July, August, and September in the years 2022 and 2023. The main tools employed are:

- NDVI (Normalized Difference Vegetation Index), used to monitor vegetation vitality;
- Greenest Pixel Composite, a temporal aggregation method that selects, for each pixel, the image with the highest NDVI value over the season, highlighting peak vegetation activity.
- MNDWI (Modified Normalized Difference Water Index), used to identify water-covered surfaces.

All data processing was conducted using Google Earth Engine, a cloud-based geospatial analysis platform that allows access to and processing of large volumes of satellite data in an efficient manner.

II. THEORY AND SPECTRAL INDICES

Remote sensing analysis is based on the processing of multispectral satellite imagery, from which it is possible to compute indices that quantitatively and objectively describe the state of the Earth's surface. The use of spectral indices is fundamental, as it allows for the enhancement of specific surface features-such as soil, vegetation, or water-through mathematical combinations of selected spectral bands. The data were sourced from two satellite missions:

- Sentinel-2: a constellation operated by the European Space Agency (ESA), providing spatial resolutions of 10, 20, and 60 meters and a revisit time of 5 days. Its wide range of spectral bands in the visible, near-infrared (NIR), and shortwave infrared (SWIR) makes it particularly suitable for vegetation monitoring.
- Landsat-8: a joint mission of NASA and the USGS, offering a spatial resolution of 30 meters with a 16-day revisit cycle. It is widely used for hydrological, environmental, and land-use studies due to its broad spectral coverage.

in particular:

- Sentinel-2 SR (Surface Reflectance): used to compute the NDVI and to generate the Greenest Pixel composite.
- Landsat-8 TOA (Top of Atmosphere Reflectance): used to compute the MNDWI.

A. NDVI Normalized Difference Vegetation Index

NDVI is a standardized index used to monitor vegetation health and activity. It is calculated (Ravanelli 2023, Tucker 1979):

$$\text{NDVI} = \frac{NIR - RED}{NIR + RED}$$

For Sentinel-2 imagery:

- NIR, Band B08: The near infrared band is good for mapping shorelines and biomass content, as well as at detecting and analyzing vegetation.
- RED, Band B04: It is strongly reflected by dead foliage and is useful for identifying vegetation types, soils and urban (city and town) areas. It has limited water penetration and doesnt reflect well from live foliage with chlorophyll.

NDVI values range from -1 to +1. The interpretation is as follows:

- Negative NDVI values (typically -1 to 0.1): : These often represent surfaces like water, snow, or clouds, which reflect very little near-infrared light.
- NDVI values near zero (approximately 0 to 0.2): These generally indicate barren areas like rock, sand, or soil.
- Low positive NDVI values (up to 0.2): These represent sparse vegetation (the higher the value the healthier/denser the vegetation)

B. Greenest Pixel Composite

The Greenest Pixel Composite is a temporal aggregation technique that selects, for each pixel, the observation with the highest NDVI value throughout the seasonal period (Ravanelli 2023). This method creates a synthetic image that reflects peak vegetation activity while mitigating the influence of cloud contamination and transient anomalies. It is particularly useful in agricultural monitoring to highlight areas with the most vigorous photosynthetic activity.

C. MNDWI Modified Normalized Difference Water Index

MNDWI was developed to improve the detection of open water surfaces, distinguishing them more effectively from built-up areas and vegetation. It is calculated (Ravanelli 2023, Xu 2006):

$$\text{MNDWI} = \frac{GREEN - SWIR}{GREEN + SWIR}$$

For Sentinel-2 imagery:

- GREEN, Band B03: It gives excellent contrast between clear and turbid (muddy) water, and penetrates clear water fairly well. It helps in highlighting oil on water surfaces, and vegetation. It reflects green light stronger than any other visible color. Man-made features are still visible.
- SWIR, Band B11: It is useful for measuring the moisture content of soil and vegetation, and it provides good contrast between different types of vegetation. It helps differentiate between snow and clouds. On the other hand, it has limited cloud penetration.

MNDWI values greater than zero (> 0) are typically associated with surface water or saturated soils.

III. METHODS

The study area focuses on the coastal agricultural landscape between the municipalities of Sperlonga, Terracina, and Fondi, located in the southern part of the Lazio region, Italy. It was delineated using a rectangular Region of Interest (ROI) in the Google Earth Engine platform, encompassing the main cultivated zones. Particular attention was given to open-field areas used for the summer production of tomatoes, a characteristic crop of this region. The analysis was conducted over the time interval from June to September in the years 2022 and 2023, which corresponds to the core growing season for this crop in the study area. All processing steps were carried out within the Google Earth Engine platform, following the workflows below.

A. NDVI and GDC-Based Processing

Sentinel-2 imagery was filtered to include only acquisitions between June 1st and September 30th, with cloud coverage below 50% and intersecting the defined study area. Cloud masking was performed using the QA60 band: pixels flagged as cloudy (bit 10) or cirrus (bit 11) were excluded to ensure data quality.Digital numbers were then converted to surface reflectance by multiplying each band by a scaling factor of 0.0001. The NDVI was computed using bands B8 (NIR) and B4 (RED) according to the standard formula. To isolate areas with active vegetation, a threshold of NDVI > 0.3 was applied. The number of pixels above this threshold was converted into surface area in square kilometers based on the spatial resolution of the NIR band. In addition to the standard calculation, a Greenest Pixel Composite was generated by selecting, for each spatial location, the image with the maximum NDVI value over the time range. This composite provided a synthetic map representing peak vegetation activity during the summer season. Finally, a time series chart of mean NDVI across the study area was produced to analyze the phenological evolution of crops throughout the summer months.

B. MNDWI-Based Processing

For the MNDWI analysis, Landsat-8 imagery was used. For each year, the first image with the lowest cloud coverage was selected. Radiometric scaling was applied to convert digital numbers into reflectance values.The MNDWI was calculated using the green band (B3) and the shortwave infrared band (B6 for Landsat-8, or B11 for Sentinel-2), with the aim of highlighting surface water presence. Pixels with MNDWI values greater than 0 were considered indicative of open water or saturated soil. The number of MNDWI-positive pixels was then converted to area in square kilometers. Unlike the NDVI workflow, no Greenest Pixel Composite was generated for MNDWI, as the goal was to identify the presence of water from a single, cloud-free seasonal image.

IV. RESULTS

The processing of satellite imagery for the months of June through September in 2022 and 2023 yielded significant quantitative and visual results for both vegetation (NDVI) and surface water (MNDWI).

- 2022: approximately 487.69 km^2 of healthy vegetation area (See Figure 3a) and 8447.28 km^2 of extension water area (See Figure 5a)
- 2023: approximately 534.77 km^2 of healthy vegetation area (See Figure 3b) and 8377.56 km^2 of extension water area (See Figure 5b)

The surface area classified as healthy vegetation was larger in 2023, with an increase of about 47 km^2 compared to 2022. This difference may reflect more favorable climatic conditions, improved agricultural practices, or greater irrigation efficiency during that season.

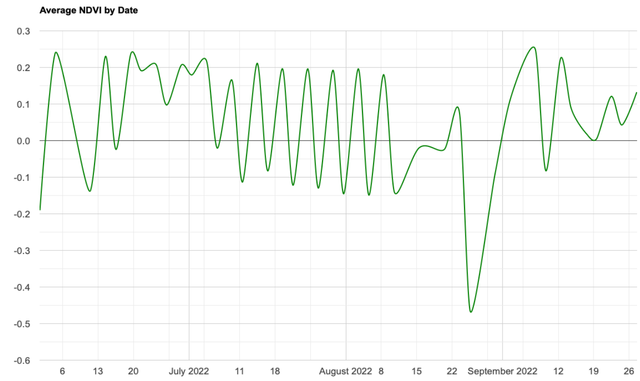


Figure 1: NDVI time serie plot in 2022

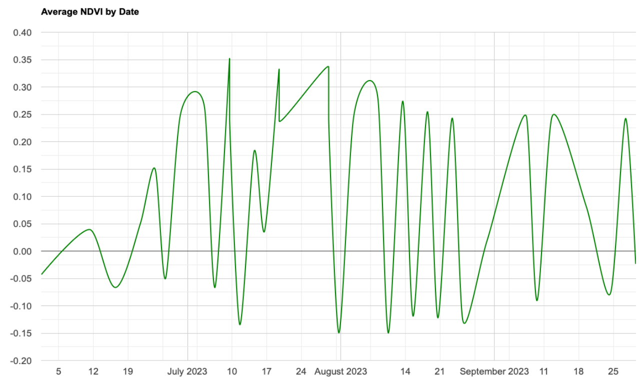


Figure 2: NDVI time serie plot in 2023

A slight reduction in the extent of surface water was observed in 2023, with a decrease of about 69.7 km^2 compared to the previous year. The Greenest Pixel Composite highlighted the spatial distribution of peak vegetation activity during the summer. A visual comparison between 2022 and 2023 revealed a more intense and widespread vegetation pattern in 2023, in agreement with the statistical increase in NDVI-derived surface coverage. The NDVI time series plots confirmed that 2023 (See Figure 2) exhibited more pronounced peaks in vegetation activity compared to 2022 (See Figure 1), with a more dynamic and variable trend. This may indicate a more responsive vegetative cycle to climatic events or variability in crop growth stages throughout the season.

V. CONCLUSION

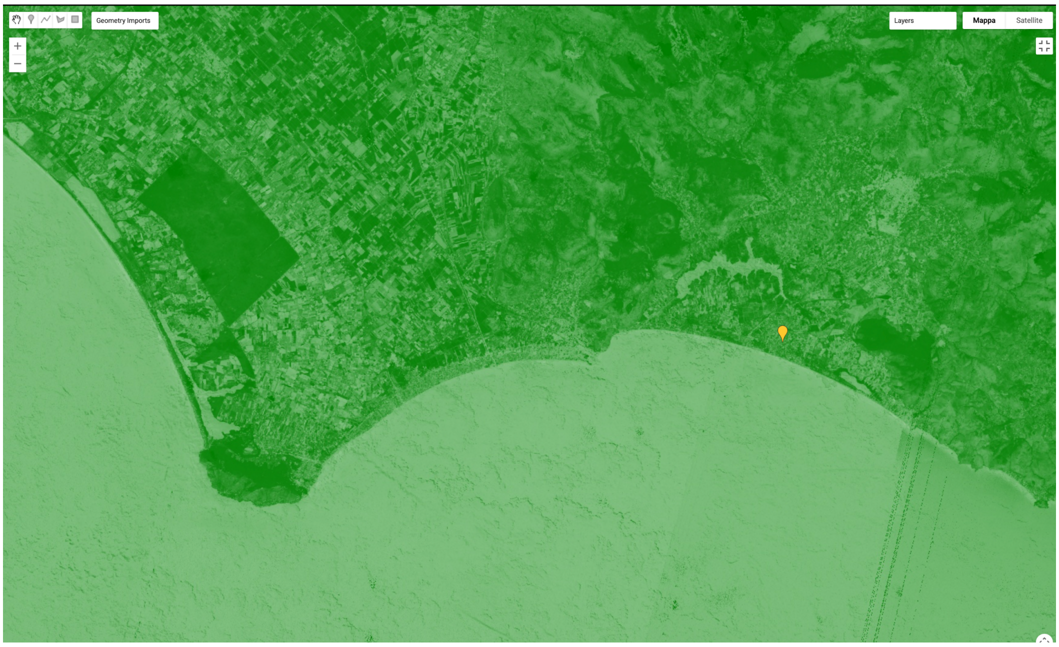
The results reveal clear differences between the two agricultural seasons analyzed (2022 and 2023), both in terms of healthy vegetation coverage (NDVI > 0.3) and surface water extent (MNDWI > 0). Specifically, 2023 shows an increase of approximately 47 km^2 in healthy vegetation compared to the previous year, while water-covered areas decreased slightly by around 69 km^2. This combination of indicators suggests an agriculturally favorable scenario. The higher NDVI values observed in 2023 may reflect a more productive or efficient growing season, supported by better climatic conditions (temperature, solar radiation, absence of extreme events) or improved agricultural practices such as localized irrigation or optimized water management. The slight reduction in MNDWI values does not contradict this trend, and could instead indicate a more targeted use of water resources or reduced seasonal rainfall. The Greenest Pixel Composite visually confirmed a greater photosynthetic activity in 2023, while the NDVI temporal series exhibited a more dynamic pattern, with multiple peaks in vegetation activity. This behavior could be attributed to staggered crop cycles or plant responses to intermittent rainfall events. Overall, the study demonstrates the value of integrating spectral indices with temporal analysis for monitoring agriculture in Mediterranean environments. The extracted information can support local decision-making in irrigation management, crop planning, and the assessment of climate change impacts on seasonal cropsespecially cherry tomatoes, which represent a key agricultural product in the study area.

Appendix A: Images Visualization

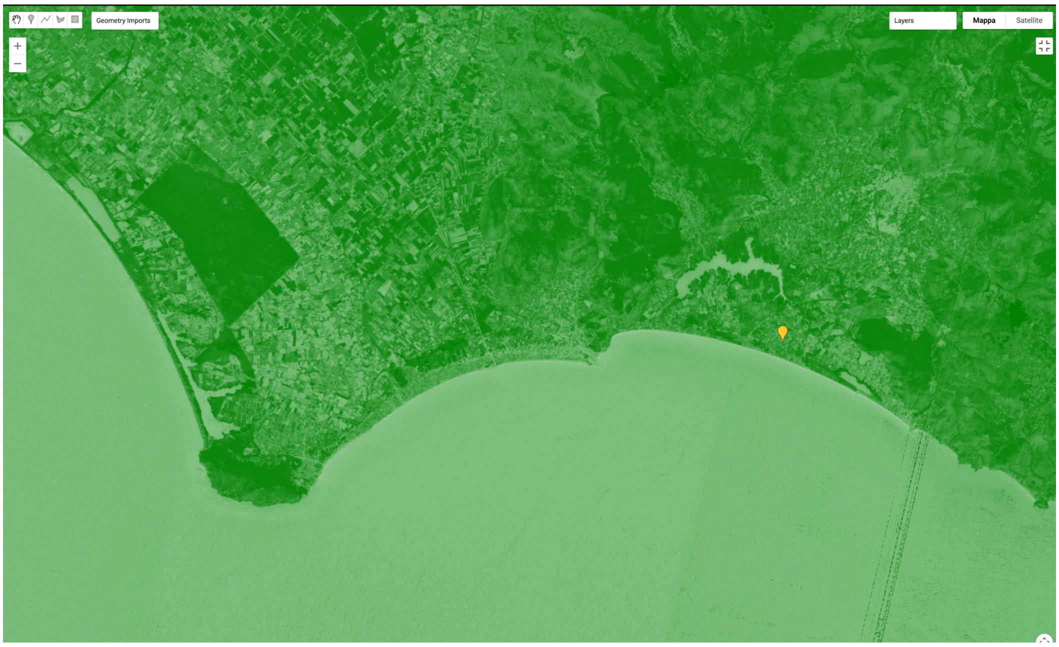
(a) False Color Composite (NIR-RED-GREEN) layer in 2022

(b) False Color Composite (NIR-RED-GREEN) layer in 2023

Figure 3: The bright red areas indicate healthy and active vegetation due to the high reflectance in the near-infrared (NIR) band. This type of composite effectively highlights vegetative cover, making it easily percitible from bare soil, urban areas, and water surfaces.

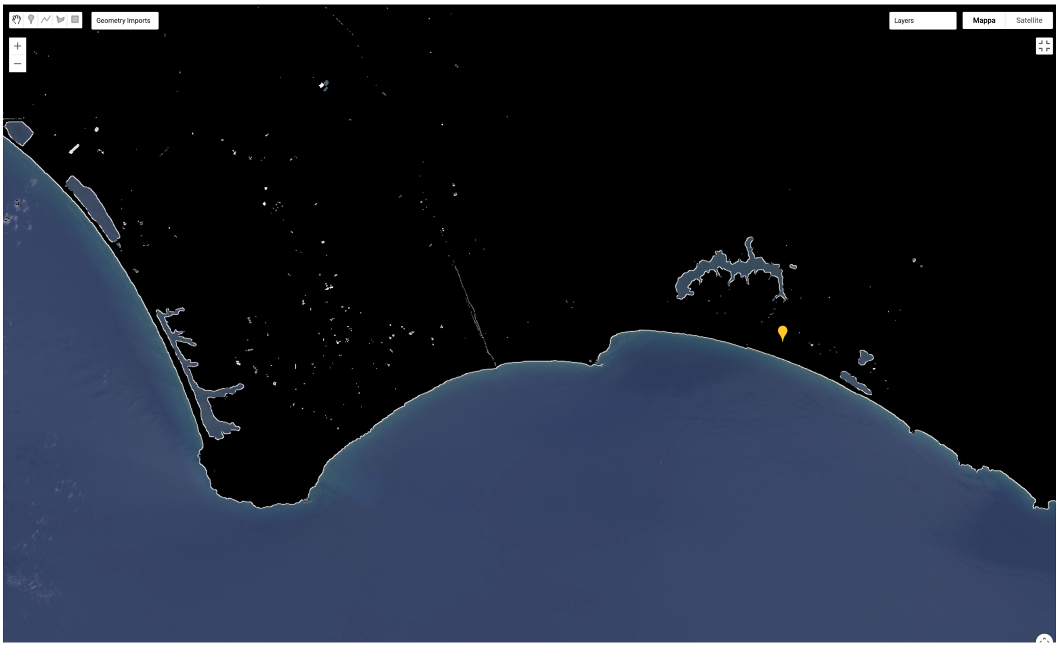


(a) NDVI Greenest layer in 2022

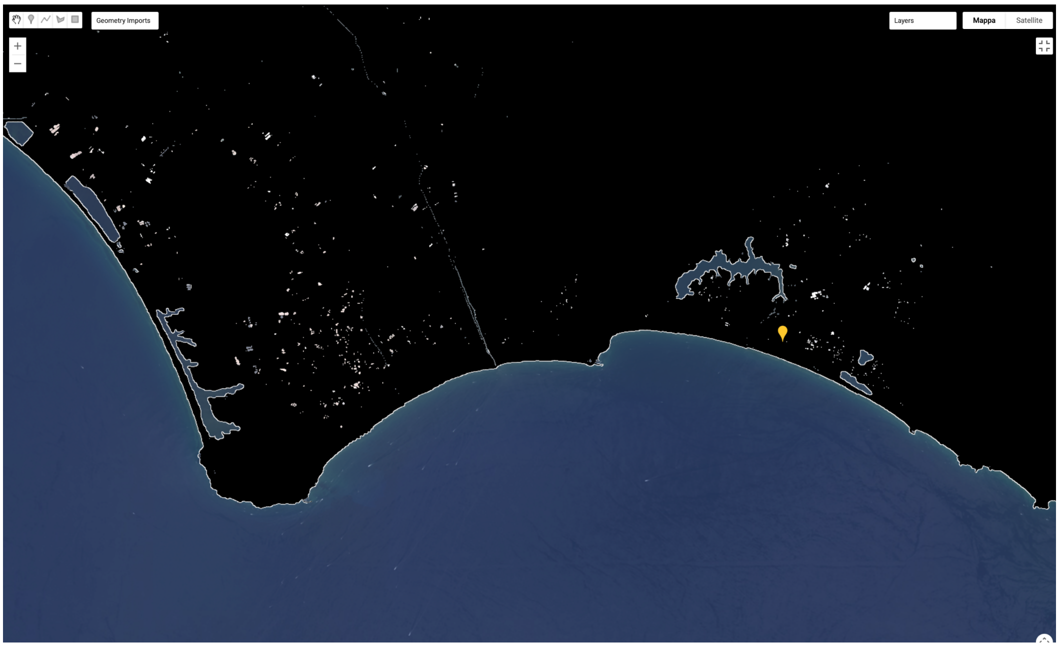


(b) NDVI Greenest layer in 2023

Figure 4: The maximum NDVI value recorded for each pixel between June and September. Greener areas indicate denser and healthier vegetation, while white regions represent low or no vegetation.



(a) Reservoir Edge, Masked Image (RGB) e Mask_MNDWI layers in 2022



(b) Reservoir Edge, Masked Image (RGB) e Mask_MNDWI layers in 2023

Figure 5: The composite visualization highlights surface water within the region of interest using three complementary layers: the true color image masked by MNDWI > 0 reveals only water-covered areas; the binary MNDWI mask outlines the spatial extent of detected water; and the Canny edge detection emphasizes the precise boundaries of the reservoir. This combined view provides both thematic and geometric insight into water body distribution.

Appendix B: Script on Google Earth Engine

1. Selected Point and Area

```
//step 0 to remember the same area
var geometry = ee.Geometry.Point([13.362276168948117, 41.29197659948001]);
var ROI = ee.Geometry.Polygon([
  [
    [12.984277816896697, 41.203689889789345],
    [13.455831619386931, 41.203689889789345],
    [13.455831619386931, 41.38657292751031],
    [12.984277816896697, 41.38657292751031],
    [12.984277816896697, 41.203689889789345]
  ]
]);
```

2. Example of Normalized Difference Vegetation Index (NDVI)

a. Filtering for June-September 2022

```
// step 1
var sentinel_S2 = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED");
// step 2
var filtered_S2 = sentinel_S2
                            .filterDate ('2022-06-01', '2022-09-30')
                            .filterBounds(geometry)
                            .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 50));
print('filtered_S2', filtered_S2);
print('filtered_S2 size',filtered_S2.size());
```

b. Filtering for June-September 2023

```
// step 1
var sentinel_S2 = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED");
// step 2
var filtered_S2 = sentinel_S2
                            .filterDate ('2023-06-01', '2023-09-30')
                            .filterBounds(geometry)
                            .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 50));
print('filtered_S2', filtered_S2);
print('filtered_S2 size',filtered_S2.size());
```

c. Script in common for both 2022 and 2023 period

```
// step 3
function maskS2clouds(image) {
  // Function to mask clouds using the Sentinel-2 QA60 band
  // @param {ee.Image} image Sentinel-2 image
  // @return {ee.Image} cloud masked Sentinel-2 image
  var qa = image.select('QA60');
  // Bits 10 and 11 are clouds and cirrus, respectively
  var cloudBitMask = 1 << 10;
  var cirrusBitMask = 1 << 11;
  // Both flags should be set to zero, indicating clear conditions
  var mask = qa.bitwiseAnd(cloudBitMask).eq(0)
      .and(qa.bitwiseAnd(cirrusBitMask).eq(0));
  return image.updateMask(mask);
}
var cloud_masked_filtered_S2 = filtered_S2.map(maskS2clouds);
// step 4
var apply_radiometric_scale = function (image)
{
  return image.multiply(0.0001);
};
var radiometrically_scaled_filtered_S2 = cloud_masked_filtered_S2.map(apply_radiometric_scale);
// step 5
var image = radiometrically_scaled_filtered_S2.median().select( ['B2', 'B3', 'B4', 'B8']);
// step 6
var RED = image.select('B4');
var NIR = image.select('B8');
var numerator = NIR.subtract(RED);
var denominator = NIR.add(RED);
var NDVI = numerator.divide(denominator);
print('NDVI',NDVI);
// step 7
NDVI = NDVI.rename('ndvi');
print('NDVI',NDVI);
// NDVI alternative computation
var NDVI_bis = image.normalizedDifference(['B8', 'B4']);
// step 8
Map.addLayer(image, {'bands': ['B4', 'B3', 'B2'], min: 0,   max: 0.3},
    'image (RGB - true color)');
Map.addLayer(NIR, {'bands': ['B8'], min: 0,   max: 0.3}, 'NIR');
Map.addLayer(RED, {'bands': ['B4'], min: 0,   max: 0.3}, 'RED');
Map.addLayer(NDVI, {min:-1, max:1}, 'NDVI');
Map.addLayer(NDVI_bis, {min:-1, max:1}, 'NDVI_bis');
Map.centerObject(geometry);
// step 9
Map.addLayer(image, {bands: [ 'B8','B4', 'B3'], min:0, max:0.3},
    'NIR-RED-GREEN false-color composite');
// step 10
var mask_NDVI = NDVI.gt(0.3);
Map.addLayer(mask_NDVI,{}, 'mask_NDVI');
// step 11
var masked_image = image.updateMask(mask_NDVI);
Map.addLayer(masked_image, {'bands': ['B4', 'B3', 'B2'], min: 0,   max: 0.3},
```

```
    'masked image (RGB)');
// step 12
var nominal_spatial_resolution = radiometrically_scaled_filtered_S2.first()
    .select('B8').projection().nominalScale();
print('nominal_spatial_resolution B8',nominal_spatial_resolution);
// step 14
var n_pixels_from_reducer = masked_image.reduceRegion(
        {
          reducer: ee.Reducer.count(),
          maxPixels: 1e29,
          scale: nominal_spatial_resolution,
          bestEffort: false,
          geometry: ROI,
          tileScale:1//default is 1
        });
print('n_pixels_from_reducer',n_pixels_from_reducer);
print('number of pixels with healty vegetation (B8-> NIR)',n_pixels_from_reducer.get('B8'));
// step 15
var area_m2 =ee.Number(n_pixels_from_reducer.get('B8'))
    .multiply(nominal_spatial_resolution).multiply(nominal_spatial_resolution);
var area_km2 = area_m2.divide(1000).divide(1000);
print('healty vegetation area (km2)', area_km2);
Map.centerObject(ROI);
```

3. Example of Greenest pixel composite

a. Filtering for June-September 2022

```
var sentinel_S2 = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED");
var filtered = sentinel_S2.filterDate('2022-06-01', '2022-09-30')
                          .filterBounds(ROI)
                          .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 50));
```

b. Filtering for June-September 2023

```
var sentinel_S2 = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED");
var filtered = sentinel_S2.filterDate('2023-06-01', '2023-09-30')
                          .filterBounds(ROI)
                          .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 50));
```

c. Script in common for both 2022 and 2023 period

```
print('filtered collection', filtered);
function maskS2clouds(image) {
  // Function to mask clouds using the Sentinel-2 QA60 band
```

```
  // @param {ee.Image} image Sentinel-2 image
  // @return {ee.Image} cloud masked Sentinel-2 image
  var qa = image.select('QA60');
  // Bits 10 and 11 are clouds and cirrus, respectively
  var cloudBitMask = 1 << 10;
  var cirrusBitMask = 1 << 11;
  // Both flags should be set to zero, indicating clear conditions
  var mask = qa.bitwiseAnd(cloudBitMask).eq(0)
      .and(qa.bitwiseAnd(cirrusBitMask).eq(0));
  return image.updateMask(mask);
}
function apply_radiometric_scaling_factor_and_addNDVI_band(image) {
  image =  ee.Image(image.multiply(0.0001).copyProperties(image, ['system:time_start']));
  var ndvi = image.normalizedDifference(['B8', 'B4']).rename('ndvi');
  return image.addBands(ndvi);
}
var with_ndvi = filtered.map(maskS2clouds).map(apply_radiometric_scaling_factor_and_addNDVI_band);
print('with_ndvi collection', with_ndvi);
var greenest = with_ndvi.qualityMosaic('ndvi');
print('greenest image', greenest);
var rgb_vis = {
  min: 0,
  max: 0.3,
  bands: ['B4', 'B3', 'B2']
};
Map.addLayer(greenest, rgb_vis, 'greenest pixel composite');
// https://developers.google.com/earth-engine/apidocs/ui-chart-image-series
var chart = ui.Chart.image.series({
  imageCollection: with_ndvi.select('ndvi'),
  region: ROI,
  reducer: ee.Reducer.median(),
  scale: 10, //m
  xProperty: 'system:time_start'
})
.setSeriesNames(['NDVI'])
.setOptions({
  title: 'Average NDVI by Date',
  hAxis: {title: 'Date', titleTextStyle: {italic: false, bold: true}},
  vAxis: {
    title: 'NDVI index ',
    titleTextStyle: {italic: false, bold: true}
  },
  lineWidth: 2,
  colors: ['green'],
  curveType: 'function'
});
print(chart);
Map.centerObject(ROI);
var greenest_ndvi = greenest.select('ndvi');
Map.addLayer(greenest_ndvi, {min: -1, max: 1, palette: ['white', 'green']}, 'NDVI greenest');
```

4. Example of Modified Normalized Difference Water Index (MNDWI)

a. Filtering for June-September 2022

```
// step 1
var L8 = ee.ImageCollection("LANDSAT/LC08/C02/T1_TOA");
// step 2
var L8_filtered = L8.filterDate('2022-06-01', '2022-09-30')
                    .filterBounds(geometry)
                    .sort('CLOUD_COVER');
```

b. Filtering for June-September 2022

```
// step 1
var L8 = ee.ImageCollection("LANDSAT/LC08/C02/T1_TOA");
// step 2
var L8_filtered = L8.filterDate('2023-06-01', '2023-09-30')
                    .filterBounds(geometry)
                    .sort('CLOUD_COVER');
```

c. Script in common for both 2022 and 2023 period

```
// step 3
var image = L8_filtered.first();
print(image);
// step 4
var mndwi = image.normalizedDifference(['B3', 'B6']);
// step 5
Map.addLayer(image, {'bands': ['B4', 'B3', 'B2'],min: 0, max: 0.3},
    'landsat 8 true color image (RGB)');
Map.addLayer(mndwi, {min:-1, max:1}, 'MNDWI');
Map.centerObject(geometry,12);
// step 6
Map.addLayer(image, {'bands': ['B6', 'B5', 'B3'],min: 0, max: 0.3},
    'landsat 8 false color image (SWIR1-NIR-G');
// step 7
var mask_MNDWI = mndwi.gt(0.0);
Map.addLayer(mask_MNDWI,{}, 'mask_MNDWI');
// step 8
var masked_image = image.updateMask(mask_MNDWI);
Map.addLayer(masked_image, {'bands': ['B4', 'B3', 'B2'], min: 0,   max: 0.3},
    'masked image (RGB)');
// step 9
var edge = ee.Algorithms.CannyEdgeDetector(mndwi, 0.99);
Map.addLayer(edge.updateMask(edge), {palette:['ffffff']}, 'reservoir edge');
// step 10
var nominal_spatial_resolution = image.select('B3').projection().nominalScale();
```

```
print('nominal_spatial_resolution B3',nominal_spatial_resolution);
// step 11
var image_bounding_box = image.geometry().bounds(nominal_spatial_resolution);
Map.addLayer(image_bounding_box, {}, 'image bounding box', false);
// step 12
var n_pixels_from_reducer = masked_image.reduceRegion(
        {
          reducer: ee.Reducer.count(),
          maxPixels: 1e19,
          scale: nominal_spatial_resolution,
          bestEffort: false,
          geometry: image_bounding_box,
          tileScale:1//default is 1
        });
print('n_pixels_from_reducer',n_pixels_from_reducer);
print('number of pixels with healty vegetation (B3-> G)',n_pixels_from_reducer.get('B3') );
// step 13
var area_m2 =ee.Number(n_pixels_from_reducer.get('B3'))
    .multiply(nominal_spatial_resolution).multiply(nominal_spatial_resolution);
var area_km2 = area_m2.divide(1000).divide(1000);
print('Extension water area (km2)', area_km2);
Map.centerObject(ROI);
```

R. Ravanelli. Remote sensing and geo big data: Spectral indexes, 2023. Lecture slides, Sapienza University of Rome, Geodesy and Geomatics Division (DICEA).

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