GEE-PICX: Generating cloud-free Sentinel-2 and Landsat image composites and spectral indices for custom areas and time frames - a Google Earth Engine web application

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Abstract

1. Earth observation satellites are collecting vast amounts of data that are both free and openly accessible. These data have immense potential to support environmental, economic, and social fields. However, along with the increasing availability of remotely sensed data, challenges are also increasing in accessing and processing these data. In particular, easy-to-use solutions for accessing and computing cloud-free image composites from often cloudy satellite data are lacking, preventing researchers and practitioners without in-depth training in remote-sensing techniques to use the accessible satellite data.
2. We developed GEE-PICX, a web application with an intuitive user interface in the cloud computing platform Google Earth Engine to overcome these challenges and to create cloud-free and analysis-ready image composites for user-defined areas and time steps based on Sentinel-2 and Landsat 5, 7, 8, and 9 images. Data coverage is global and image composites can be aggregated annually or seasonally. The earliest available data are from 1984 (launch of Landsat 5).
3. The workflow automatically filters all available satellite data according to user input and removes clouds, cloud shadows, and snow. It returns spectral band information, calculates a variety of spectral indices and returns the number of valid scenes per pixel as a quality assessment band.
4. GEE-PICX provides researchers with no or little experience in remote sensing for the first time a customizable tool for creating custom data products from freely accessible satellite data with extensive temporal and global spatial coverage. Server-side data processing ensures the tool is usable without hardware limitations. The simple export of time series of ready-to-use rasters including numerous spectral indices can greatly assist environmental programmes and biodiversity research in a variety of disciplines.

Introduction

Understanding environmental changes such as deforestation, desertification, urbanization, or the expansion of croplands over time is of utmost importance to quantify the anthropogenic impacts on earth and to support sustainable development and environmental protection (Chaves et al., 2020; Mallinis & Georgiadis, 2019; Weng et al., 2008). Satellite remote sensing is a widely used method for monitoring such environmental changes due to the multitude of available sensors and platforms providing continuous data of the earth's surface (Cord et al., 2017). Remote sensing data is often freely available (e.g. Landsat since the 1980s), enabling scientists to monitor and quantify short- and long term environmental changes. Optical remote sensing imagery provides (multi-)spectral information, yet the presence of clouds, cloud shadows, and highly reflective surfaces such as snow can adversely affect sensor measurements, posing challenges in acquiring unbiased and gap-free information (Zhu et al., 2015). Opaque clouds cover approximately 31% of the Earth's surface at any time (Guzman et al., 2017), necessitating automatic detection and accurate removal from remote sensing data prior to analysis to prevent data errors at the respective positions. Cloud removal causes gaps in satellite images which can complicate analysis. This can be overcome by merging multiple images from different time points to create cloud-free and gap-free image products. These products can then be used for land cover classifications (Verhoeven & Dedoussi, 2022), land monitoring applications (Carrasco et al., 2019; Parmes et al., 2017), time series analyses (Lasaponara et al., 2022; Yin et al., 2020) or spatial modeling (Guharajan et al., 2021).

After cloud-correction, multi-spectral information can either be used directly (Zhu et al., 2018) or via derived spectral indices, which are combinations of the spectral reflectance from two or more wavelengths (Chaves et al., 2020; Rudd et al. 2021). Spectral indices are often more suitable for specific analyses than the raw spectral information due to more clearly defined and interpretable properties (Rudd et al., 2021). The most popular spectral indices are vegetation indices, but other indices for burned areas, man-made (built-up) features, or water are available, too (Chaves et al., 2020; Petropulos & Kalaitzidis, 2011).

Generating analysis-ready remote sensing data and derived products (e.g. spectral indices) is, however, often challenging, particularly for long-term analyses over larger regions. Creating cloud-free mosaics is often only possible for well-trained remote-sensing scientists. Besides technical expertise, it requires considerable computational resources to process hundreds or thousands of remote sensing data sets. Here, cloud computing platforms such as Google Earth Engine (GEE), powered by the Google Cloud infrastructure, offer new possibilities for big data analysis (Lasaponara et al., 2022; Piao et al., 2019; Yang et al., 2021).

To overcome these challenges, we developed GEE-PICX, a Google Earth Engine web application for generating and exporting cloud-free and analysis-ready composites of satellite images for user-defined areas and time steps with global data coverage. We followed four design principles in developing GEE-PICX:

1. **Flexibility of user input.** Users have control over choice of satellite platform (Landsat or Sentinel-2), study area boundaries, time range, maximum cloud cover (for single images), aggregation mode, and image bands. Relevant images are automatically selected from the data catalog according to user input.
2. **Ease of use.** The application features a self-explanatory interface, requires only a Google account, a web browser and internet connection, and has no hardware or software requirements thanks to server-side processing.
3. **Export of large data sets.** Only limited by Google drive storage capacity.

4. **Generate analysis-ready data.** Generates cloud-free image mosaics with spectral bands, spectral indices, and a quality assessment band (valid scenes per pixel). Export image resolution and coordinate reference system are customizable.

The application allows users without experience in remote sensing to generate cloud-free and analysis-ready image composites for custom study areas and points in time for a multitude of applications in ecology and beyond. Compared to other platforms that allow downloading similar, analysis-ready products it also provides information on data quality or spectral indices which is not provided by EarthExplorer (United States Geological Survey, 2023) and it allows significantly larger downloads than SentinelHub (Sinergise, 2023a).

Workflow description

Overview

Users can access the web application via the provided application link (see Data availability). The script is written in JavaScript and commented to facilitate orientation. No manual code adjustments are necessary. With the application running, users can define parameters according to their requirements in the application interface next to the map. The application then internally processes user inputs, executing functions for satellite image (pre-)processing, visualization, and export preparation. Data visualizations are available directly in the application. The products can be exported at user-defined spatial resolutions and coordinate systems and are ready to use for subsequent analyses.

User input

Below we provide a detailed overview of the choices users can make for creating customized data exports. For advanced information on data processing see Supporting Information S1.

Satellite data: The application can provide image composites based on either the Landsat or the Sentinel-2 mission. Both Landsat and Sentinel-2 datasets consist of atmospherically and topographically corrected Level-2A products that show surface reflectance values with atmospheric correction applied. The dataset choice can be based on either the required spatial resolution or length of the time series. The earliest Level-2A products from Landsat date back to 1984 (at 30m resolution), whereas Sentinel-2 Level-2A products have been available since 2017 (at 10m resolution). The availability of Landsat data from the late 1980s and early 1990s is much lower than in recent years, when more Landsat missions are simultaneously acquiring imagery at a higher temporal frequency. When selecting Landsat as the platform, users have the option to include imagery from all Landsat missions (5-9) to create image composites, or they can choose to include only Landsat-8 and 9 data. The second option is useful to avoid including erroneous Landsat-7 images affected by the Scan Line Corrector failure in 2003 (United States Geological Survey, 2022). However, Landsat-8 data are only available from 2013 and Landsat-9 data from 2022. For more specific information on the satellite missions see Supporting Information S2.

Area of interest: The boundary of the study area can be defined either by uploading a shapefile as an Earth Engine asset (Google Earth Engine, 2021), or by manually drawing a polygon on the Google Earth Engine map. Data coverage is global.

Time period: The time frame can be specified by year- and month range. By default, scenes are aggregated for one year (months 1 - 12). Users can create seasonal image aggregates by narrowing the selection to specific consecutive months (also crossing the year boundary). Users can request export of imagery from multiple years at once.

Cloud cover filter: Optical satellite images may exhibit partial or complete cloud coverage. The pixel-level cloud masks included in scenes cannot perfectly detect and filter out all clouds and cloud shadows (Sanchez et al., 2020). Therefore, the cloud cover percentage per scene is utilized to enhance the quality of image composites by removing scenes exceeding a cloud cover threshold. By default, images with cloud cover exceeding 65% are excluded prior to aggregation. Opting for a 100% threshold includes all images captured within the specified study area and time frame.

Image bands: Users can select single or multiple spectral bands, as well as spectral indices and a valid pixel band, by activating the corresponding checkboxes. Spectral bands convey surface reflectance data and are correlated with chlorophyll and other pigments, vegetation structure and water content (Petropulos & Kalaitzidis, 2012). Key correlations include Green, Red, and Red-edge bands with chlorophyll and pigments, NIR bands with leaf structure, and SWIR with vegetation structure and water content (Chaves et al., 2020; Fernández-Manso et al., 2016). Spectral indices result from mathematical combinations of the spectral bands (see Supporting Information S3 for details on all available indices). The valid pixel band is a quality assessment layer specifying the number of valid scene values that are aggregated at each pixel.

Aggregation mode: The aggregation mode determines which summary statistic is applied to the pixel values of all selected images. Available choices are mean, median and standard deviation.

Coordinate system: The application offers the choice to export rasters in UTM and WGS 84 (EPSG 4326) formats. If UTM is selected, the application automatically identifies the appropriate zone. If the study area spans multiple UTM zones, images can only be exported in WGS 84.

Spatial pixel resolution: The application provides the options to export images at four different spatial resolutions ranging from 10 to 100 meters. Opting for high resolutions in extensive study areas could yield products exceeding several gigabytes, potentially posing challenges for subsequent analyses. Users should choose a resolution that matches their research or monitoring objectives.

Image export

After initiating the export in the application user interface, users can inspect and execute the actual image export(s) within the upper-right window via the Console and Tasks tabs (see Data availability). Two image collections will be automatically added to the Console. The first contains all individual satellite images after filtering, the second contains the image aggregates available for export. Each annual / seasonal image that appears in the *Tasks* manager needs to be exported individually. When clicking "Run", a pop-up window will appear in which the user can optionally modify export names, coordinate reference system, scale, export destination and file format.

The easiest way to save the files on a local computer is to export them to a Google drive folder which is connected to the users' Google account, and then download the data from there. Multiple image exports run in parallel and depending on study area size each export can take from minutes to hours (or even days for study regions measuring hundreds of thousands of square kilometers). When exporting large datasets, Google Earth Engine splits each image into smaller tiles. After downloading them from Google Drive, they can either be merged to a large contiguous mosaic, or be used as a virtual raster.

Except for the "valid-pixel" band, all band values of the export images are multiplied by 10,000. This allows the raster values to be stored as integer values (signed 16-bit) instead of floating point values, thus reducing the file size of exports.

Data visualization

Users can visualize their export data on the map by selecting either a spectral index or various band combinations. Band combinations can highlight certain features (e.g., vegetation types, water bodies, and urban areas) due to correlations between measurable biophysical properties on the Earth's surface and remotely sensed surface reflectance (Price et al., 2002). After choosing the visualization parameter, all aggregated images will be added to the map with default visualization settings. Adjustments to visualization parameters can be made individually within the map's layer panel box (follow instructions on Github link, see Data availability). All indices have a valid value range from -1 to 1 in the application, while the band values of export images are multiplied by 10,000 (except for the valid pixel band). Google Earth Engine may encounter computational problems for visualization if the data is too large due to the size of the study area and/or the length of the time period. This may lead to scaling error messages and some objects would not be displayed on the map (or also *Console*). Visualization problems, however, do not affect image exports, which are always possible and only limited by the storage capacity of the user’s Google drive.

In addition to the visualization options in Google Earth Engine, we provide an interactive R Shiny application for visualizing image time series (see Data Availability).

Case examples

Example A shows deforestation in Brasil using historical Landsat images, while Example B focusses on seasonal land cover changes in the city of Würzburg (Germany), emphasizing the enhanced level of detail provided by Sentinel-2 imagery (Figure 1). In both examples a combination of three spectral bands (SWIR1-NIR-R; NIR-R-G) and a spectral index (NDVI) are shown together with the number of valid pixels (see Fig. 1). The data contain more spectral bands and indices not shown here.

In the Amazon rainforest, deforestation has become a pressing environmental concern over the past several decades. Soy farms, along with other agricultural expansion, have played a significant role in driving deforestation in the Amazon (Nepstad et al., 2006). We used GEE-PICX, to generate and export annual image aggregates for an area in Ariquemes, Rondônia, Brasil for 1991 and 2021, illustrating the magnitude of change over three decades. Such annual aggregates (or composites) are suitable for inferences on broad trends, but average seasonal dynamics or land cover changes within a year, making them unsuitable e.g. for mapping floods.

The second example shows the seasonal changes in land cover/land use in the city center of Würzburg, Germany, and highlights the surrounding ring-shaped park. The region's transition between summer and winter was captured in seasonal satellite image composites and showcases the distinct phenological variations. The higher spatial resolution of Sentinel-2 imagery allows better discrimination of small-scale features and proves particularly valuable in the context of land cover and land use monitoring. Seasonal variation in cloud cover can lead to seasonal bias in the available data. Snow cover can also affect the quality of seasonal image compositions because the applied cloud mask algorithm (see Supporting Information S1) does not perfectly mask highly reflective surfaces such as clouds or snow in individual scenes. Cloud masking leads to data gaps in all affected images. If all scenes have data gaps at the same pixels, the image composite will also have data gaps at this location. During the export to Google drive Google Earth Engine assigns a value of zero to data gaps in image composites, potentially biasing subsequent analyses. Zero values at these locations should be converted to NA prior to further analyses (see Data availability).

Conclusion

The use of satellite imagery is essential for many environmental and conservation studies. However, the broad use of freely available satellite products currently requires expertise in data selection and pre-processing, as well as computational resources. Many environmental and conservation studies therefore primarily rely on pre-packaged thematic products (Wong et al., 2022). However, these datasets often lack the necessary detail to address specific research questions, despite the wealth of information present in satellite data. GEE-PICX provides a solution for users across various domains by significantly simplifying access to the creation of cloud-free satellite image composites. It effectively addresses problems of cloud cover, which are particularly challenging in tropical or mountainous regions (Sanchez et al., 2020; Hribljan et al., 2017). Through the intuitive and user-friendly GEE-PICX application, users can easily generate and export (multi-)temporal cloud-free satellite images for any region and any time period starting from 1984 (availability varies by region).

The multispectral information in the generated products are complemented by additional information on spectral indices and data quality. These are typically not present in the generated output of other platforms. GEE-PICX is further set apart by allowing data generation of extensive areas with very large download sizes. By making the freely available archives of Landsat and Sentinel-2 accessible for non-remote-sensing scientists and practitioners, GEE-PICX strongly supports integrating these archives in environmental and conservation projects of various fields.

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Conflict of Interest statement

The authors declare no conflicts of interest.

Author contributions

Jürgen Niedballa and Andreas Wilting conceived the idea, Luisa Pflumm led the development of the GEE script and Hyeonmin Kang led the development of the GEE App user interface. Luisa Pflumm developed the case examples. Luisa Pflumm, Jürgen Niedballa and Andreas Wilting led the writing of the manuscript, and Hyeonmin Kang contributed to the drafts. All authors gave final approval for publication.

Data availability

The link to the GEE-PICX application is provided on this Github page: https://github.com/Luisa-del/GEE-PICX. The GitHub page also contains a detailed user guide.

In order to use the GEE-PICX application, users need to log in to Google Earth Engine using their Google account. The application opens in JavaScript code editor mode to allow for data export. From the application, user inputs are specified and products can be exported to users' Google drive for download.

An R script to convert null values of an exported raster to NA is provided on Github. We furthermore provide an R Shiny app to visualize and query time series of annual images downloaded via GEE-PICX on GitHub.

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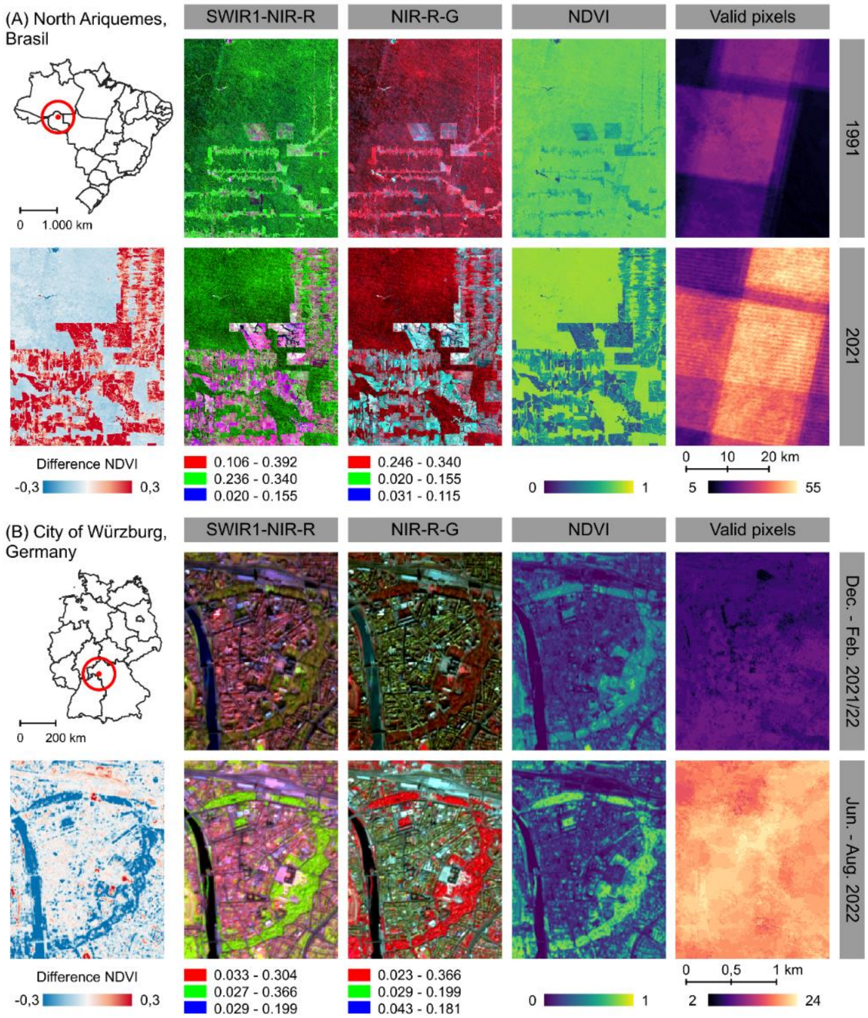
Figures



Options	(A) North Ariquemes (Brasil)	(B) City of Würzburg (Germany)
Satellite platform	Landsat-5,7,8,9	Sentinel-2
Study area	Polygon coordinates (in degree): -63.1 to -62.6 °W, -9.7 to -9.3 °S	Polygon coordinates (in degree): 49.78 to 49.8 °E, 9.92 to 9.94 °N
Month, year, max. cloud cover (per scene)	(1) 1-12, 1991, 65% (2) 1-12, 2021, 65%	(1) 12-2, 2022-23, 65% (winter) (2) 6-8, 2022, 65% (summer)
Number of selected scenes	(1) 44 scenes (2) 97 scenes	(1) 9 scenes (2) 26 scenes
Band selection	B, G, R, NIR, SWIR1, SWIR2, NDVI, valid pixels	
Aggregation mode	median	
Spatial resolution	30 meter	10 meter
CRS	UTM (EPSG: 32620)	UTM (EPSG: 32632)

***Figure 1**: Example GEE-PICX products. A: Annual aggregates based on Landsat scenes for 1991 and 2021. B: Seasonal aggregates based onSentinel-2 scenes for summer (June 2022 - August 2022) and winter (December 2021 - February 2022). The maps show a subset of the available band information. The striking pattern in the valid-pixel scenes results from the orbital path overlap of the Landsat satellites and does not affect image composites. Absolute difference in NDVI was calculated for both areas, with positive values indicating an increase of NDVI compared to the earlier scene.*

Supporting Information

Supporting Information S1

Data processing in GEE-PICX

***Table S1**: Functional setup of GEE-PICX application script.*

Functionality	Description
Image selection and filtering	Select Landsat / Sentinel-2 surface reflectance (SR) products (Level-2). Filter single scenes by study area, time frame and maximum cloud cover.
Cloud masking *	Landsat SR data: mask clouds, cloud shadows and snow from the Cloud Quality Assessment band (QA_PIXEL bitmask). Sentinel-2 SR data: mask clouds, cloud shadows and highly reflective surfaces with auxiliary S2 cloud probability dataset (s2cloudless).
Band selection	Select and rename S2 bands according to spectral wavelength range Select and rename LS 8 & 9 bands according to spectral wavelength range Select and rename LS 5 & 7 bands according to spectral wavelength range
Scale factor application	Apply scale factor for Landsat SR data (0.0000275 + (- 0.2)) before usage Apply scale factor for Sentinel-2 SR data (0.0001)
Spectral indices calculation	Calculate indices with respective formulas and add as band information to each individual scene

Image aggregation & data quality assessment	Aggregate filtered scenes from year or season by median, mean or standard deviation. Count valid pixels at each pixel location for data quality assessment
Visualization	Aggregated scenes can be added to the map. Users can choose spectral indices as single bands or choose from various 3-band combinations. Further changes can be applied manually in the layer panel box. May fail if data size or area of interest are too large (limitations in Google Earth Engine).
Export preparation	Create a batch task to export images as raster to Google Drive. All image band values are multiplied by 10,000 in advance and converted to signed 16-bit integer to reduce output file size (except for valid-pixel band)

* Additional information on s2cloudless:

The development of the s2cloudless algorithm (Zupanc, 2019) has allowed researchers to refine cloud masking, resulting in greater confidence in the final analysis. There is currently no equivalent method for images from the Landsat collection. While the QA60 band is limited to a binary classification of thick and cirrus clouds (European Space Agency, 2020), s2cloudless generates an image with cloud presence probabilities ranging from 0 to 100 percent, at 10 meter scale (Braaten et al., 2020). This provides the opportunity to customize the cloud masking process to better suit the specific requirements of a project. Higher values of the s2cloudless layer are more likely related to clouds or highly reflective surfaces such as snow or roof tops (Google Earth Engine, 2023).

The s2cloudless layer is a separate data set from which matching scenes are automatically selected and filtered. The default cloud probability threshold in the application is 50 % to define cloud / non-cloud masks, which generally allows a very good cloud masking performance (Braaten et al., 2020). The optimal value for the best performance can depend on factors such as cloud type, cover type, location, etc. Users who wish to further customize the cloud mask need to adjust the variable “isNotCloud” in the application script where cloud masking is applied to the selected Sentinel-2 images. In this case, we suggest experimenting with a few different values to better understand the distribution of cloud probability values. For example, thin clouds may not be detected at 90 % cloud probability threshold, but are detected at 10 % (Braaten et al., 2020). The single scenes from the cloud-masked image collection in the *Console* tab could be used to investigate changes due to cloud mask tuning. Nevertheless, for proper inspection and evaluation, basic knowledge of using the Google Earth Engine API is beneficial. For most use cases it is not necessary to modify the cloud probability threshold.

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Supporting Information S2

Satellite data available in GEE-PICX.

Table S2: *Information on satellite data accessible from GEE-PICX web application.*

Platform	**Sentinel-2**		**Landsat**			
Mission	**Sentinel-2A**	**Sentinel-2B**	**Landsat-5**	**Landsat-7**	**Landsat-8**	**Landsat 9**
Mission Launch	2015-06-23	2017-03-07	1984-03-01	1999-04-15	2013-02-11	2021-09-27
Data availability in GEE-PICX app	2017-03-28 - present		1984-03-16 - 2012-05-05	1999-05-28 - present	2013-03-18 - present	2021-10-31 - present
Sensor*	MSI		MSS + TM	ETM+	OLI + TIRS	OLI + TIRS
Temporal resolution	10-days each, 5-days combined constellation		16-days each, 8-days combined constellation Landsat-8 and 9			
Spatial resolution	10-meter		30-meter			
Spectral resolution**	*Bands 2-5, 8, 8A, 11-12:* visible, NIR, red-edge, SWIR		*Bands 1-5, 7* visible, NIR, SWIR		*Bands 2-7*	
Spectral & spatial resolution (bands, in meter)	*Bands 2-5, 8, 8A, 11-12:* 10 m: R, G, B, NIR; 20 m: Red-edge, SWIR		*Bands 1-5, 7:* 30 m: B, G, R, NIR, SWIR	*Bands 1-5, 7:* 30 m: B, G, R, NIR, SWIR	*Bands 2-7:* 30 m: B, G, R, NIR, SWIR	*Bands 2-7:* 30 m: B, G, R, NIR, SWIR

Additional information	-	-	-	Scan Line Corrector (SLC) failure since 2003-05-31 (22 percent of each image affected by data gaps)	-	-
Operator* **	ESA		NASA & USGS			

* OLI, Operational Land Imager; TIRS, Thermal Infrared Sensor; ETM+, Enhanced Thematic Mapper Plus; TM, Thematic Mapper; MSS, Multispectral Scanner; MSI, Multispectral Instrument

** Visible: blue, green, red; NIR: near-infrared; SWIR: shortwave-infrared

*** ESA, European Space Agency; NASA, National Aeronautics and Space Administration; USGS, United States Geological Survey

Supporting Information S3

Spectral Indices available in GEE-PICX

***Table S3**: Available spectral indices derived from Landsat or Sentinel-2 imagery.*

Band name	Full name	Formula	Interpretation
NDVI	Normalized Difference Vegetation Index	$\frac{(NIR - Red)}{(NIR + Red)}$	Highlights density and health of photosynthetically active vegetation. Tends to saturate in densely vegetated areas. Sensitive to the contribution of soil brightness and atmospheric effects..
EVI2	Enhanced Vegetation Index 2	$2{,}4 * \frac{(NIR - Red)}{(NIR + Red + 1)}$	Highlights photosynthetically active vegetation, but does not saturate in densely vegetated areas. Accounts for soil brightness variation. Less affected by atmospheric effects than NDVI and EVI.
SAVI	Soil-Adjusted Vegetation Index	$\frac{(NIR - Red)}{(NIR + Red + L)} * (1 + L)$	Highlights photosynthetically active vegetation and accounts for soil brightness variation.
MSAVI	Modified Soil-Adjusted Vegetation Index	$\frac{(NIR - Red)}{(NIR + Red + L_0)} * (1 + L_0)$	Modified version of SAVI to further minimize the soil background influences on the vegetation signal.

NDMI	Normalized Difference Moisture Index	$\frac{(NIR - SWIR1)}{(NIR + SWIR1)}$	Sensitive to moisture levels in vegetation and soil. Useful for vegetation analyses, for identifying areas prone to drought stress or excess moisture.
NBR	Normalized Burn Ratio	$\frac{(NIR - SWIR2)}{(NIR + SWIR2)}$	Detects and quantifies burnt areas. In general, low NBR values indicate recently burnt areas and bare ground.
NBR2	Normalized Burn Ratio 2	$\frac{(SWIR1 - SWIR2)}{(SWIR1 + SWIR2)}$	A modification of the NBR, useful in postfire recovery studies, highlights vegetation with high water content.
BSI	Bare Soil Index	$\frac{(SWIR1 + Red) - (NIR + Blue)}{(SWIR1 + Red) + (NIR + Blue)}$	Highlights bare ground and rock surfaces. Useful in identification of soil erosion, land degradation, and urbanization processes.
NDWI	Normalized Difference Water Index	$\frac{(Green - NIR)}{(Green + NIR)}$	Sensitive to water bodies. Useful for water resource management, wetland monitoring, and flood assessment.

For more information on spectral indices see: Petropoulos & Kalaitzidisz (2012), Zeng et al. (2022), United States Geological Survey (2022), Qi et al. (1994), Keeley (2009).

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