SEN4LDN

LAND DEGRADATION NEUTRALITY

PUG

Product User Guide

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Table of contents

List of figures

List of tables

List of abbreviations

AGB	Above-ground biomass
AOI	Area of Interest
CCI	Climate Change Initiative
EA	Early Adopter
EO	Earth Observation
EOS	End of season
EU	European Union
ESA	European Space Agency
EVI2	2-band Enhanced Vegetation Index
FAO	Food and Agriculture Organization
GEE	Google Earth Engine
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LC	Land Cover
LCCS	Land Cover Classification System
LCD	Land Cover Degradation
LCT	Land Cover Transitions
LD	Land Degradation
LDN	Land Degradation Neutrality
LPD	Land Productivity Degradation
MAXV	Maximum seasonal value
NDVI	Normalized Difference Vegetation Index
PP	Productivity Performance
PROB	Probability
PUG	Product User Guide
SAR	Synthetic Aperture Radar
SDG	Sustainable Development Goal
SEN4LDN	Sentinels for Land Degradation Neutrality
SOC	Soil Organic Carbon
SOS	Start of season
ST	Smoothed timeseries
TPROD	Total Productivity
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification

1 Introduction

1.1 Introduction to the SEN4LDN project

The 2030 Agenda for Sustainable Development is fundamentally based on 17 Sustainable Development Goals (SDG) which are targets agreed upon by the UN members regarding various interlinked objectives that must be ensured to achieve sustainable development. These range from combating poverty, ensuring access to education, to economic development and the protection of life on water and land.

Diminished overall productivity and reduced resilience in the face of climate and environmental change, have made addressing land degradation a global priority formalized by the United Nations Convention to Combat Desertification (UNCCD) and the SDG. To this end, the 2030 Agenda for Sustainable Development defined target 15.3 of SDG 15, called '*Life on Land*', that strives to reach Land Degradation Neutrality (LDN) by 2030. SDG indicator 15.3.1 serves as the primary measure in this process as it quantifies the spatial extent of degraded land, making it a crucial tool for monitoring and assessing efforts to combat land degradation on a national scale.

Efficient monitoring of Land Degradation (LD) requires constant monitoring of various biophysical and biochemical characteristics of the land. These disturbances can range from rapid land cover change (e.g., fire or logging) to continuous and slower degradation of soil and land quality [1]. While monitoring these at larger scale becomes a logistical impossibility if not using Earth Observation (EO) data, there are still a number of challenges and opportunities to address particularly related with increasing spatial and temporal resolution and diversity of sensor types [2]. The European Space Agency (ESA) Sentinels for Land Degradation Neutrality (SEN4LDN) project aims to address these two limitations by developing and showcasing a novel approach for improving both the spatial and temporal resolution of the data required for LD monitoring. While LDN is agreed between the SDG signatories, each region/country will have its own specific challenges and drivers of LD and therefore the inclusion of local partners in the product development is extremely important. These stakeholders (or Early Adopters) will provide insights on the user requirements and feedback on the final product and its actual usability for SGD 15.3.1 reporting.

1.2 Objective of the condensed Product User Guide

A first proof-of-concept version of the land degradation sub-indicators is presented to the SEN4LDN Early Adopters (EA) during the second round of Living Labs (March-April/2024). The national demonstration products are presented to the same audience during the third round of Living Labs (November 2024). The objective of this condensed Product User Guide is to provide the necessary background information on the national demonstration products that are provided in a Google Earth Engine (GEE) web application, to allow the EAs to interpret these products.

This PUG contains information on the products and a brief summary of the algorithms used to generate the products. Also the limitations of the products are described. Finally, also some guidance on the GEE web application is provided.

It has to be noted that, although improvements have been implemented to the product algorithms in the last phase towards generation of the national demonstration products, the products may still suffer from some limitations and/or quality issues. Those are listed in the following chapter.

2 Land degradation neutrality sub-indicators

2.1 Trends in land cover

2.1.1 Products definition

2.1.1.1 Annual land cover (2018-2023)

Annual land cover maps for the years 2018 to 2023 are provided at 10m resolution for the three EA countries: Uganda, Portugal and Colombia.

Land cover (LC) as defined by the Food and Agriculture Organization (FAO) is the "observed (bio)physical cover of the earth's surface" and is a synthesis of the many processes taking place on the land" [3]. Land cover is typically described as a set of hierarchical classes, each denoting the dominant biotic and abiotic assemblages occupying the Earths' surface [4]. The discrete LC classification maps provide 11 classes (see Table 1), as defined using the Land Cover Classification System (LCCS) developed by the UN and FAO.

Table 1: Coding of the Land cover layer and definition of the classes

Map code	Land Cover Class	IPCC LC class	Definition	Color
10	Tree cover	Forest land	Any geographic area dominated by trees with a cover of 10% or more. Other land cover classes (shrubs and/or herbs in the understory, built-up, permanent water bodies, …) can be present below the canopy. Areas planted with trees for afforestation purposes and plantations (e.g. oil palm, olive trees) are included in this class.	
20	Shrubland	Other (Shrubland)	Any geographic area dominated by natural shrubs having a cover of 10% or more. Shrubs are defined as woody perennial plants with persistent and woody stems and without any defined main stem being less than 5 m tall. Trees can be present in scattered form if their cover is less than 10%. Herbaceous plants can also be present at any density. The shrub foliage can be either evergreen or deciduous.	
30	Grassland	Grassland	Any geographic area dominated by natural herbaceous plants (Plants without persistent stem or shoots above ground and lacking definite firm structure): (grasslands, prairies, steppes, savannahs, pastures) with a cover of 10% or more, irrespective of different human and/or animal activities, such as: grazing, selective fire management etc. Woody plants (trees and/or shrubs) can be present assuming their cover is less than 10%.	
40	Cropland	Cropland	Land covered with annual cropland that is sowed/planted and harvestable at least once within the 12 months after the sowing/planting date. The annual cropland produces an herbaceous cover and is sometimes combined with some tree or woody vegetation. Note that perennial woody crops will be classified as the appropriate tree cover or shrub land cover type. Greenhouses are considered as built-up.	
50	Built-up	Settlement	Land covered by buildings, roads and other man-made structures such as railroads. Buildings include both residential and industrial building. Urban green (parks, sport facilities) is not included in this class. Waste dump deposits and extraction sites are considered as bare.	
60	Bare / sparse vegetation	Other (Sparse vegetation)	Lands with exposed soil, sand, or rocks and never has more than 10 % vegetated cover during any time of the year	
70	Snow and ice	/	This class includes any geographic area covered by snow or glaciers persistently.	
80	Permanent water bodies	Other (Water)	This class includes any geographic area covered for most of the year (more than 9 months) by water bodies: lakes, reservoirs, and rivers. Can be either fresh or salt-water bodies. In some cases the water can be frozen for part of the year (less than 9 months).	
90	Herbaceous wetland	Wetland	Land dominated by natural herbaceous vegetation (cover of 10% or more) that is permanently or regularly flooded by fresh, brackish or salt water. It excludes unvegetated sediment (see 60), swamp forests (classified as tree cover) and mangroves (see 95).	
95	Mangroves	Forest	Taxonomically diverse, salt-tolerant tree and other plant species which thrive in intertidal zones of sheltered tropical shores, "overwash" islands, and estuaries.	

100	Moss and lichen	Other (Sparse vegetation)	Land covered with lichens and/or mosses. Lichens are composite organisms formed from the symbiotic association of fungi and algae. Mosses contain photo-autotrophic land plants without true leaves, stems, roots but with leaf-and stemlike organs.	

2.1.1.2 Land cover transitions

The land cover transitions map provides information on the degradation and restoration processes that have taken place between 2018 and 2023, based on the annual LC maps for 2018 and 2023 at 10m resolution. Class definition and colour coding is specified in Table 2.

Table 2: Coding and definition of the Land cover transitions layer. Land cover transitions (degradation and restoration processes) are based on the land cover transition matrix (see Table 5).

Map code	Degradation / Restoration process	Definition	Colour
1	Deforestation	Deforestation refers to the intentional clearing of forested land, i.e. conversion of tree cover (or mangroves) to grassland, cropland or built-up areas.	
2	Vegetation loss	Vegetation loss refers to the reduction or decline in vegetation cover, e.g. conversion from tree cover to shrubland, or conversion from other land to bare / sparse vegetation.	
3	Urban expansion	Urban expansion refers to the physical extension settlements into the surrounding countryside, i.e. conversion from other land to built-up.	
4	Inundation	Based on the annual LC maps, prolonged inundation can be detected. This involves the conversion of grassland or cropland to herbaceous wetland.	
5	Withdrawal of agriculture	This degradation process refers to the conversion of cropland to shrubland or grassland.	
6	Wetland drainage	This degradation process refers to the conversion of wetland to grassland, cropland, or other land.	
0	Stable / Unlikely change		
101	Reforestation	Reforestation is a restoration process that refers to the establishment or restoration of tree cover.	
102	Vegetation establishment	Vegetation establishment is the restoration process of introducing vegetation cover, i.e. conversion of bare / sparse vegetation to other vegetation classes.	
103	Wetland establishment	Wetland establishment refers to the conversion of shrubland, built-up areas or other land to wetlands.	
104	Agricultural expansion	This restoration process refers to the conversion of grasslands or other land in cropland.	

2.1.1.3 Land Cover Degradation (LCD) products

The LCD product consist of a discrete LCD map, using coding as specified in Table 3.

Table 3: LCD classes

Degradation / Restoration process	Definition	Colour	Map code
Stable	Stable Land Cover		0
Restoration	Land Cover Restoration as defined by Table 2		1
Degradation	Land Cover Degradation as defined by Table 2		2

The LCD-PROB provides continuous land cover degradation probabilities, scaled between -1 (degradation) and 1 (restoration).

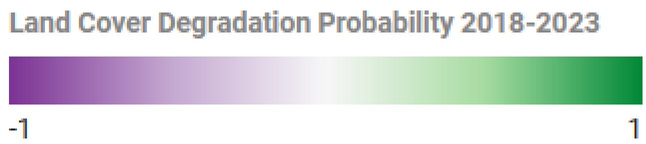


Figure 1: Colour scale of Land Cover Degradation Probability (LCD-PROB)

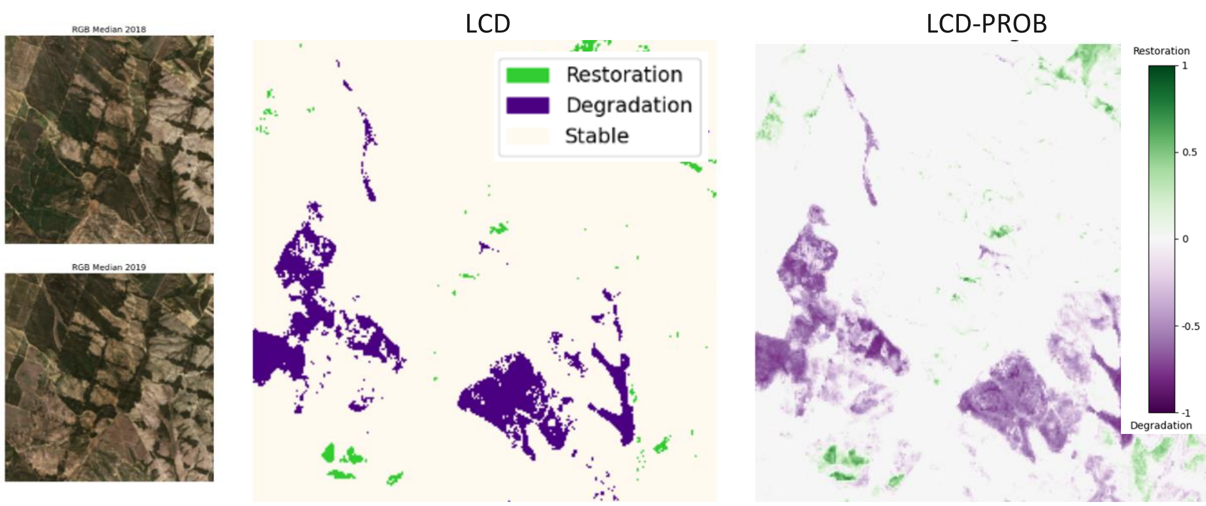


Figure 2: Example of LCD and LCD-PROB output products of Trends in Land Cover

2.1.2 File naming, format and characteristics

The SEN4LDN products on trends in land cover follow this naming standard:

SEN4LDN_<PRODUCT>_V100_<PERIOD>_<LATLON_TILE_3>_MAP.tif

where:

- <PRODUCT> refers to the different sub-indicator products (see Table 4)
- <PERIOD> refers to the temporal range of the product:
  - YYYY for annual LCM
  - 2018-2023 for LCT, LCD and LCD-PROB
- <LATLON_TILE_3> indicates the spatial coverage of the file, composed of the 3-digit longitude and 2-digit latitude of the bottom-left corner of the 3° x 3° tile (e.g. S03E030 covering the area with latitude [-3°, 0°] and longitude [30°, 33°]).

The SEN4LDN products on trends in land cover are provided as fully compliant single band Cloud Optimized GeoTIFF (COG) files with standard metadata attributes. The products are delivered on a regular latitude/longitude grid with 3° x 3° tiles (EPSG:4326). The resolution of the grid is 0.3 arcsec (1°/12,000) or approximately 10 m at the equator. The <LATLON_TILE_3> indicated in the file name refers to the spatial coverage of the file, composed of the 3-digit longitude and 2-digit latitude of the bottom-left corner of the 3° x 3° tile.

Table 4: SEN4LDN products on trends in land cover

Layer name	Content	Data type and range	No data value	Scale Offset	Legend
LCM	Time series of Annual Land Cover Maps	UINT8 [10-100]	0	-	See Table 1
LCT	Land Cover Transition Map	UINT8 [1-104]	0	-	See Table 2
LCD	Land Cover Degradation Map with classes indicating Stable (0), Restoration (1), Degradation (2)	UINT8 [0,1,2]	255	-	See Table 3
LCD-PROB	Land Cover Degradation Probabilities scaled between -1 (degradation) and 1 (restoration)	UINT8 [0-250]	255	0.008 -1	-

2.1.3 Summary of the retrieval methodology

Copernicus Sentinel-2 Level 2A (L2A) surface reflectance data for 2018-2023 are used as input to a LC classification algorithm. Yearly timeseries of L2A observations are pre-processed to remove clouds, composited into 10-daily median composites and used to derive yearly percentiles (10th, 25th, 50th, 75th, and 90th) of the Sentinel-2 spectral bands (B02, B03, B04, B08, B11 and B12) and the Normalized Difference Vegetation Index (NDVI).

A selection of computed Sentinel-2 features is used to train a deep learning semantic segmentation algorithm. Together with a training dataset and ancillary layers, this feeds into the land cover classification algorithm, which is used to derive classification probabilities. These are ingested in a post-processing routine, which optimizes consistency of the predictions while preserving changes, resulting in yearly predictions (2018-2023) of land cover. The discrete land cover classification map provides 11 classes (see Table 1). These 11 classes are considered adequate to allow monitoring of key degradation processes, although some of the land use changes might remain undetected.

To determine trends in land cover between 2018 and 2023 for a given location, a combination of the land cover probabilities is performed for each type of transition, obtaining continuous transition probabilities, which are then used to produce a discrete land cover transition (LCT) map by means of a transition matrix (Table 5). Land cover changes are specified as being either degradation, improvements, or neutral transitions, summarized in the Land Cover Degradation (LCD) output products.

Note that this land cover transition matrix is a general starting point. Specific transitions can be re-evaluated per use case, to adopt to local conditions and requirements.

*Table 5: General land cover transition matrix using the 11 land cover classes (see Table 1). Land cover change processes are colour coded as positive **P**, stable **S** or negative **N**. Unlikely transitions are put within brackets.*

	Final class										
IPCC LC class	Forest land	Other	Grassland	Cropland	Settlement	Other	/	Other	Wetland	Forest	Other

IPCC LC class	Original class	Tree cover	Shrubland	Grassland	Cropland	Built-up	Bare / sparse vegetation	Snow and ice	Permanent water bodies	Herbaceous wetland	Mangroves	Moss and lichen
Forest	Tree cover	S	N	N	N	N	N	-	-	(N)	(S)	(N)
Other	Shrubland	P	S	N	P	N	N	-	-	P	(P)	(N)
Grassland	Grassland	P	P	S	P	N	N	-	-	N	(P)	(N)
Cropland	Cropland	P	N	N	S	N	N	-	-	N	(P)	(N)
Settlement	Built-up	(P)	(P)	(P)	(P)	S	(P)	-	-	(P)	(P)	(P)
Other	Bare / sparse vegetation	P	P	P	P	N	S	-	-	P	(P)	(P)
/	Snow and ice	-	-	-	-	-	-	-	-	-	-	-
Other	Permanent water bodies	-	-	-	-	-	-	-	-	-	-	-
Wetland	Herbaceous wetland	N	N	N	N	N	N	-	-	S	(P)	S
Forest	Mangroves	(S)	N	N	N	N	N	-	-	(N)	S	(N)
Other	Moss and lichen	P	P	P	P	N	N	-	-	P	(P)	S

2.1.4 Limitations

There are a number of limitations related to the land cover products:

- First of all, the LC model and LC change model outputs are highly dependent on the quality of the input data. Residual cloud contamination or artefacts in the Sentinel-2 L2A input data affects the product quality. The pre-processing steps (i.e. cloud removal, compositing and percentiles generation) are designed to minimize these effects. In areas with persistent cloud cover, too few good quality input satellite images might be available to generate annual LC maps. Residual (undetected) clouds may lead to artefacts in the land cover products.
- For some land cover transition processes, the recognition based on yearly LC maps is not straightforward and it is subject to debate whether these represent positive or negative processes. For example, plantations (e.g. palm oil, coffee, sugar cane, tea, cacao, banana) will be recognised by the LC algorithm as 'tree cover', and as such the conversion from any LC type to plantations will probably be labelled as vegetation establishment or reforestation.

2.2 Trends in land productivity

2.2.1 Products definition

Vegetation productivity is defined as the seasonal accumulated production of green biomass as estimated from a satellite-derived index, the 2-band Enhanced Vegetation Index (EVI2). This index expresses the density and health of plant life, providing indicators of photosynthetic activity and overall ecosystem functionality. We use the total sum of this index between the start and end of seasons (TPROD) to indicate the green biomass production. In addition, we use the maximum seasonal value (MAXV) to indicate the potential productivity as a basis for the performance estimation.

Land productivity, and losses of productivity in connection with land degradation, can be estimated based on the **trend, state** and **performance** of vegetation productivity ([5], [6], [7]) The trend measures the rate and direction of change of land productivity over a time period. The state compares the productivity to historical productivity, and the performance compares the local productivity to similar land units over a large area.

In SEN4LDN, the **trend** is estimated for the period 2018-2023 at 10 m spatial resolution. The resulting map product displays the value of the slope coefficient of this trend, thus the amount of change over time. Apart from the trend values a map of classes of trend values is generated that shows areas of strong negative trend, weak negative trend, no trend, weak positive trend and strong positive trend.

A **state indicator** would depend on comparing current productivity with historical values. However, no historical satellite series of the same spatial resolution exists. While theoretically, historical estimates could be derived from low-resolution data (kilometre scale), comparing trends at such different resolutions would be misleading, and therefore the state indicator has not been computed in SEN4LDN.

The **performance** indicator is computed by comparing local pixel values with the average across large areas, e.g., a country. From these input data, we produce the datasets in Table 4.

Table 6: Indicators of land productivity

Name	Sub-Indicator of land productivity	Content	Data type and range	No data value	Scale Offset
trendval	Trend	Values of trend coefficient of productivity over the period 2018-2023 ($day.year^{-1}$) [-10, 10]	UINT8	255	1/10 -10
trendclass	Trend	Classes indicating trend / no-trend: Degrading (1), Stable (2), Improving (3)	UINT8 [1,2,3]	0	-
perfval	Performance	Maximum performance 2021-23 over the land cover class reference [0.0 – 2.0]	UINT8	255	1/100 0
perfclass	Performance	Classes of performance indicating Degradation or No degradation	UINT8 [1,2]	0	-
LPD	Land productivity degradation	Classes of degradation or no degradation by combining slope and performance: No data (0), Degrading (1), Stressed (2), Stable (3), Improving (4)	UINT8 [1,2,3,4]	0	-

2.2.2 File naming, format and characteristics

The SEN4LDN products on trends in land productivity follow this naming standard:

SEN4LDN_<PRODUCT>_V100_2018-2023_<LATLON_TILE_3>_MAP.tif

where:

- <PRODUCT> refers to the different sub-indicator products (see Table 7)
- <LATLON_TILE_3> indicates the spatial coverage of the file, composed of the 3-digit longitude and 2-digit latitude of the bottom-left corner of the 3° x 3° tile (e.g. S03E030 covering the area with latitude [-3°, 0°] and longitude [30°, 33°]).

The SEN4LDN products on trends in land productivity are provided as fully compliant single band Cloud Optimized GeoTIFF (COG) files with standard metadata attributes. The products are delivered on a regular latitude/longitude grid with 3° x 3° tiles (EPSG:4326). The resolution of the grid is 0.3 arcsec (1°/12,000) or approximately 10 m at the equator. The <LATLON_TILE_3> indicated in the file name refers to the spatial coverage of the file, composed of the 3-digit longitude and 2-digit latitude of the bottom-left corner of the 3° x 3° tile.

Table 7: SEN4LDN products on trends in land productivity

Layer name	Sub-Indicator of land productivity	Content	Data type and range	No data value	Scale Offset
trendval	Trend	Values of trend coefficient of productivity over the period 2018-2023 (day.year^{-1}) [-10, 10]	UINT8	255	1/10 -10
trendclass	Trend	Classes indicating trend / no-trend: Degrading (1), Stable (2), Improving (3)	UINT8 [1,2,3]	0	-
perfval	Performance	Maximum performance 2021-23 over the land cover class reference [0.0 – 2.0]	UINT8	255	1/100 0
perfclass	Performance	Classes of performance indicating Degradation or No degradation	UINT8 [1,2]	0	-
LPD	Land productivity degradation	Classes of degradation or no degradation by combining slope and performance: No data (0), Degrading (1), Stressed (2), Stable (3), Improving (4)	UINT8 [1,2,3,4]	0	-

2.2.3 Summary of the retrieval methodology

The 2-band Enhanced Vegetation Index (EVI2), derived from Sentinel-2 between the start year (2018) and end year (2023), provides improved sensitivity in capturing canopy structural variations and chlorophyll content. We utilize the TIMESAT software package [8], [9]to smooth and fill gaps in the EVI2 time series for each 10 m x 10 m Sentinel-2 pixel and to extract key phenological parameters such as the start of the season (SOS), end of the season (EOS), maximum VI of the season (MAXV), and total productivity (TPROD, integrated VI from SOS to EOS) (Figure 3). Among these, TPROD (Figure 4) serves as crucial indicators for further trend analysis.

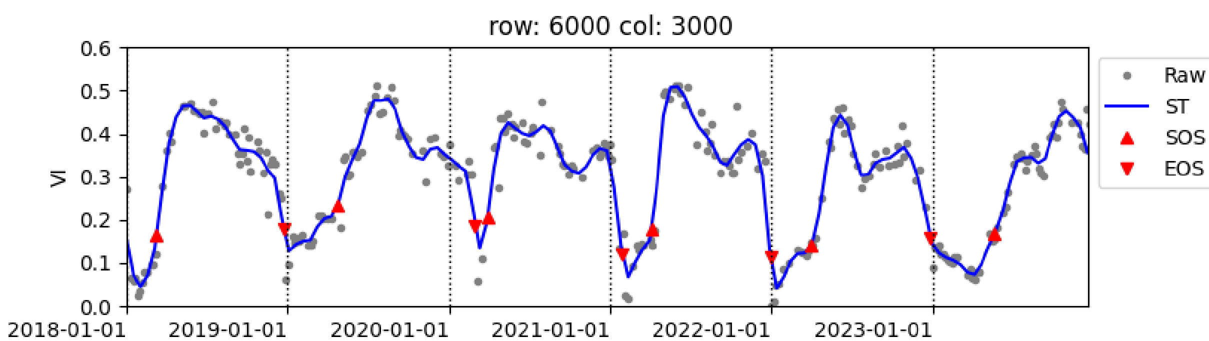


Figure 3: The application of TIMESAT to fit a time series for a specific pixel location (Tile: 36NXG, row: 6000, col: 3000). It displays the raw vegetation index values over time (marked as 'Raw' with grey dots), alongside the smoothed time series ('ST' depicted by the blue line). Key phenological events for each growing season, specifically the start of season (SOS) and end of season (EOS), are highlighted by red upward-pointing and blue downward-pointing triangles, respectively, demonstrating the seasonal patterns and transitions of vegetation over multiple years from 2018 to 2023.

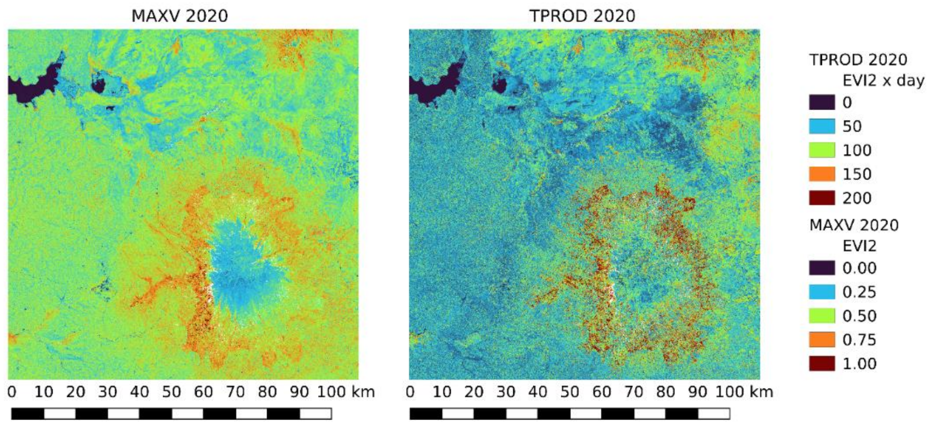


Figure 4: Maximum value of the season (MAXV) and total productivity (TPROD) of Sentinel-2 tile 36NXG in 2020. On the left, the "MAXV 2020" map displays the peak EVI2 values of 2020, indicating the highest level of vegetation greenness achieved during the year, with a colour scale ranging from low (blue) to high (red) values. On the right, the "TPROD 2020" map shows the total productivity, calculated as the cumulative EVI2 over the growing season in 2020, with the productivity scale extending from lower (blue) to higher (red) values.

To compute the **trend** we have used the Theil-Sen robust statistical regression method that computes the median change over time, and the Mann-Kendall test to investigate the statistical probability of finding a trend. The p-value of the Mann-Kendall test indicates the probability of no trend. Thus, a high p-value indicates that the change is not significant and a low p-value that the trend is significant (Figure 5).

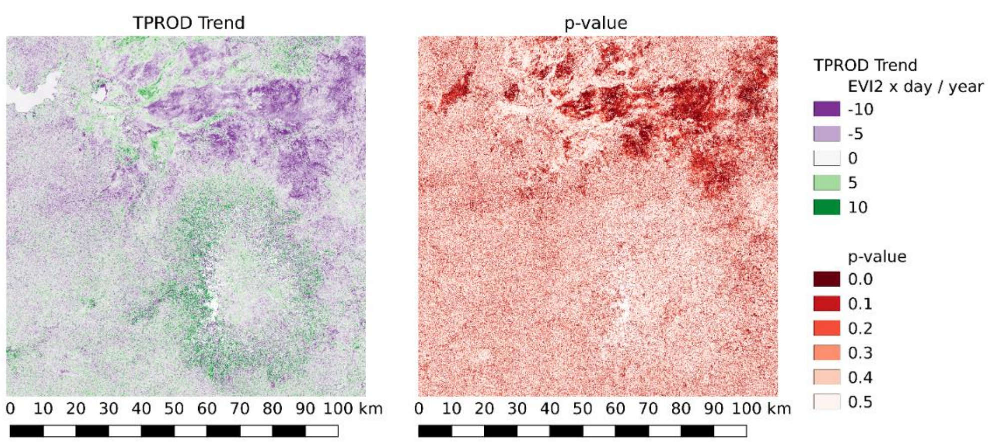


Figure 5: The trend analysis of total productivity (TPROD) from 2018 to 2023 and the statistical significance of the trend, mapped across a regional landscape. On the left, the "TPROD Trend" map visualizes the annual change in the Enhanced Vegetation Index (EVI2) multiplied by the number of days, with values ranging from decrease (purple) to increase (green). On the right, the "p-value" map indicates the statistical significance of these trends, with colour scaling from high significance (dark red) to low significance (white). In the Google Earth Engine (GEE), trends are displayed only if the associated p-value is below 0.1.

The **performance** indicator is based on computing the maximum TPROD for each pixel in relation to the 90th upper percentile TPROD across a large area, e.g., a country or a tile, for the same land cover class as the pixel. The pixel maximum TPROD is derived for the period 2021-2023, and the maximum across area is defined per land cover class and for the full period 2018-2021. Thus, while the performance indicator provides a measure of how an area compares to other areas, there is also an element of change since the indicator focuses the recent years compared to a longer period:

$$PP = \frac{TPROD_{max}^{pixel}}{TPROD_{upper90th}^{class}}, \qquad Eq. 1$$

where PP is productivity performance, $TPROD_{max}^{pixel}$ is the 2021-2023 maximum value for a pixel belonging to a certain land cover class, and $TPROD_{upper90th}^{class}$ is the 2018-2023 90th upper percentile value of the country for the stable landcover class.

Land Productivity Degradation (LPD) is computed following the logic in [5]. The two productivity indicators (trend and performance) are combined into a qualitative LPD map with aggregated classes following simple logical combinations according to Table 5.

Table 5: Lookup table for defining qualitative land productivity degradation (LPD). Both weak and strong trends are included in the trend classes.

Class	Trend classes	Performance classes	LPD classes
0	Missing data	Missing data	Missing data
1	Degrading	Degrading/Stable	Degrading
2	Stable/Improving	Degrading	Stressed
3	Stable	Stable	Stable
4	Improving	Stable	Improving

2.2.4 Limitations

It should be noted that the period for estimating change is rather short, and extreme values may have large impact on the estimates. While we use a robust statistical method to reduce the impact of single outliers, the trend maps and the combined products should be interpreted with caution. The combination of classes in the final LPD map is rather arbitrary and it is useful to consider which of the factors determines the output value.

The effectiveness of LPD products in the context of land cover change needs to be carefully assessed. Even the original input data, i.e. EVI2, has different meanings for different land cover types. Leaf area index and gross primary productivity will be different for forest and grassland simulations with the same EVI2. Therefore, when a land cover change is detected in a pixel, the EVI2 comparison before and after cannot be compared directly, and therefore also affects the validity of the TPROD and hence the LPD. In addition, the use of land cover type as input data to the LPD product will introduce uncertainty in the land cover type into the LPD product.

2.3 Trends in carbon stocks

2.3.1 Products definition

Carbon stocks in terms of LDN assessments is primarily related to soil carbon pool and related changes. Measuring soil carbon stock changes using EO approaches is very challenging and mostly limited to combining a soil organic carbon (SOC) stock estimate with a land cover change/vegetation productivity proxy to estimate the change in stocks. The SEN4LDN consortium reviewed available SOC estimates using

EO data and none of them were suitable beyond what is provided in Trends.Earth. However, above-ground biomass/carbon stock estimations are increasingly possible using EO-approaches, including those from dedicated ESA missions and projects. That is why the focus is on exploring above-ground biomass (AGB) changes as a proxy for carbon stock changes to provide an estimate independent of the other two sub-indicators.

Multi-temporal AGB maps allow us to directly estimate changes in biomass (ΔAGB) and thus carbon stocks. This measurement reflects trends in carbon storage of vegetation, influenced by land-use changes like deforestation but also by natural processes within ecosystems like forest degradation, regrowth, and disturbances. We propose two main approaches to quantifying trends in carbon stocks, following Araza et al. [10], using Earth observation data and models.

1) The **stock change** approach directly calculates ΔAGB by comparing ESA CCI biomass maps [11] from two different points in time.
2) The **gain-loss** approach uses a carbon flux model[1], which takes land-use specific emission and removal factors into account to estimate ΔAGB from an initial biomass estimate.

The **baseline year** for both methods is **2010** and the AGB difference will be calculated to **2018**. **Spatial resolution of the product is 100m** and results are given in discrete values ranging from **-20 to +20 mg/ha**.

2.3.2 File naming, format and characteristics

The SEN4LDN products on trends in carbon stocks follow this naming standard:

SEN4LDN_<PRODUCT>_V100_2010-2018_<COUNTRY>_MAP.tif

where:

- <PRODUCT> refers to the different sub-indicator products (see Table 8)
- <COUNTRY> indicates the spatial coverage of the file.

The SEN4LDN products on trends in carbon stocks are provided as single band GeoTIFF files with standard metadata attributes. The products are delivered on a regular latitude/longitude grid with 3° x 3° tiles (EPSG:4326). The resolution of the grid is 0.00088888° or approximately 100 m at the equator.

Table 8: SEN4LDN products on trends in carbon stocks

Layer name	Content	Data type and range	No data value	Scale Offset
Hybrid_Avg	Average of stock change and gain-loss maps	FLOAT32	-9999	-
Hybrid_Stdev	Standard deviation between stock change and gain-loss maps	FLOAT32	-9999	-

2.3.3 Summary of the retrieval methodology

The **stock change** approach is based on ESA's Biomass CCI project that uses Synthetic Aperture Radar (SAR) data to create multidate forest AGB maps. A model is then applied to separate these signals and estimate canopy density and vegetation height. From these measurements, AGB is derived through allometric equations [12]. Uncertainties are included as standard deviation layers to account for variations in the

[1] Modified carbon flux model: https://github.com/arnanaraza/carbon-budget

model and data retrieval process. The specific satellites used to collect the SAR data vary by year, including Sentinel-1, Envisat ASAR, and JAXA's ALOS missions. The stock change approach is generated through a subtraction of the 2010 and the 2018 map.

The **gain-loss** approach is based on a modified version of the carbon flux model developed by Harris et al. [13]. The gain-loss approach to mapping AGB changes focuses on forest-related land-use conversions and their impact on carbon storage. Pre-determined land use specific emission and removal factors are used to estimate how much carbon is lost or gained due to land use changes. These factors are typically based on existing data and scientific understanding of carbon fluxes in different ecosystems. The initial biomass estimate, which serves as a baseline, comes from the ESA CCI maps 2010.

Finally, we recommend calculating an average map (Fig. 4), calling it **hybrid approach**, from the two methods. This may average out errors from the two individual, relatively independent approaches, and gives the advantage of reducing the variance in the final map, leading eventually to a more robust estimate.

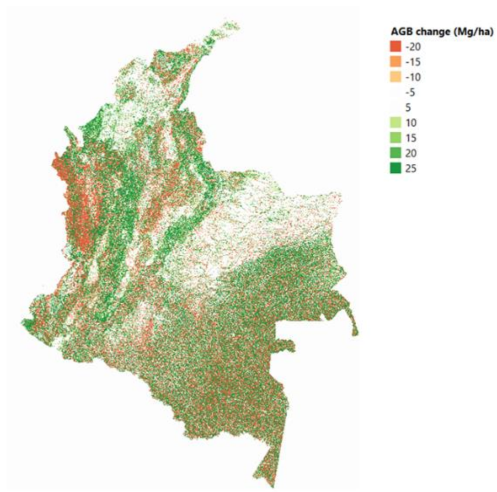


Figure 6: Example of resulting AGB change hybrid map (trends in carbon stocks), calculating the average from stock change and gain-loss methods for Colombia

2.3.4 Limitations

The following limitations of the underlying AGB algorithms and stock change models must be considered:

- **Algorithm accuracy**: The carbon flux model might not capture the full complexity of land cover types within the specific country, since the reference data sources under-represent most eco-zones especially in the tropics. This can lead to under or overestimation of flux changes, particularly in areas with diverse ecosystems or land use practices.
- **Spatial resolution:** The resolution of the satellite imagery (ESA CCI maps) used to train the models may not be fine-grained enough to detect subtle changes in AGB, especially for smaller land-use features.
- **Temporal resolution**: The relatively long time between the two map products used (8 years) may not be sufficient to capture rapid or even medium-term changes in AGB, such as those caused by deforestation and fast regrowth events.

In addition, there are some limits regarding the reference and remote sensing data:

- **Limited coverage of reference data:** Reference data used for validation of global maps, i.e. National Forest Inventory (NFI) plot data, local ΔAGB maps from airborne LiDAR, and selected Forest Resource Assessment country data (see [10]) might not be geographically representative of the specific target country. Therefore, local inaccurate estimates of AGB changes may not be discovered.
- **Remote sensing data quality:** Accuracy and consistency of the baseline map (ESA CCI Biomass 2010) may vary depending on the measurements, which further impact the reliability of model calculation and outputs (error propagation).

Future developments could incorporate country-specific plot-based biomass and biomass change measurements to assess data quality and refine ("recalibrate") biomass changes considering specific national circumstances. While such data exists, the project team has not yet had access to it. Additionally, the carbon flux model could utilize the output from the LC Change model (2.1) as input to ensure alignment with the temporal and spatial resolutions of the other two sub-indicators. Finally, incorporating high-resolution soil organic carbon content maps alongside the AGB change map would provide a more comprehensive picture of trends in carbon stocks.

3 Integrated LDN indicator

3.1 Products definition

The goal of the integration step is to generate a product that allows to calculate the extent of land degradation for reporting on UN SDG indicator 15.3.1, expressed as the proportion (percentage) of land that is degraded over total land area:

$$P_n = \frac{A(Degraded)_n}{A(Total)}$$

Eq. 1

with

$$A(Degraded)_n = A(persistent)_n + A(recent)_n - A(improved)_n$$

Eq. 2

The three sub-indicators – trends in land cover, trends in land productivity, and trends in carbon stocks – are proxies to monitor the essential variables that reflect the capacity to deliver ecosystem services, and are used to delineate $A(recent)_n$, area that is degraded during the reporting period, and $A(improved)_n$, area that has recovered during the reporting period.

In the default one-out-all-out (1OAO) integration process, the UN SDG indicator 15.3.1 is calculated by integrating the three sub-indicators (trends in land cover, trends in land productivity and trends in carbon stocks) using a 1OAO method, in which a significant reduction or negative change in any one of the three sub-indicators is considered to comprise land degradation. In this methodology, the indicator is reported as a binary quantification (i.e. degraded/not degraded). If one of the sub-indicators is declining or negative (or stable when degraded in the baseline or previous reporting period) for a particular land unit, then it may be considered potentially degraded.

3.2 File naming, format and characteristics

The SEN4LDN products on trends in land cover follow this naming standard:

SEN4LDN_LD_V100_2018-2023 _<LATLON_TILE_3>_MAP.tif

where:

- <LATLON_TILE_3> indicates the spatial coverage of the file, composed of the 3-digit longitude and 2-digit latitude of the bottom-left corner of the 3° x 3° tile (e.g. S03E030 covering the area with latitude [-3°, 0°] and longitude [30°, 33°]).

The SEN4LDN LDN product is provided as fully compliant single band Cloud Optimized GeoTIFF (COG) files with standard metadata attributes. The products are delivered on a regular latitude/longitude grid with 3° x 3° tiles (EPSG:4326). The resolution of the grid is 0.3 arcsec (1°/12,000) or approximately 10 m at the equator. The <LATLON_TILE_3> indicated in the file name refers to the spatial coverage of the file, composed of the 3-digit longitude and 2-digit latitude of the bottom-left corner of the 3° x 3° tile.

Details on the product characteristics are listed in Table 9.

Table 9: SEN4LDN product on the LDN indicator

Product	Content	Data type and range	No data value	Scale Offset
LD	Land Degradation Neutrality Map with classes indicating Stable (0), Restoration (1), Degradation (2)	UINT8 [0,1,2]	255	-

3.3 Summary of the retrieval methodology

In the current setup, since the product on trends in carbon stocks are provided for a different time period and at a lower spatial resolution (see §2.3), SEN4LDN uses only two sub-indicators in the 1OAO aggregation method: land cover degradation and land productivity degradation (Table 10).

The input variables for the 1OAO algorithm are discrete maps of LCD (see §2.1) and LPD (see §2.2). The output variable is a discrete map delineating pixels that have a positive, stable or negative evolution in the reporting period.

Table 10: Combination of land cover degradation and land productivity degradation sub-indicators using the 1OAO integration method

Land Cover Degradation	Land Productivity Degradation	⇨	1OAO
Improving	Improving		Improving
Improving	Stable		Improving
Improving	Declining		Declining
Stable	Improving		Improving
Stable	Stable		Stable
Stable	Declining		Declining
Declining	Improving		Declining
Declining	Stable		Declining
Declining	Declining		Declining

Figure 7 shows an example of the 1OAO integration principle applied over a 2.5 x 2.5 km² area in Portugal where deforestation processes and vegetation establishment have occurred in the time frame 2018-2023.

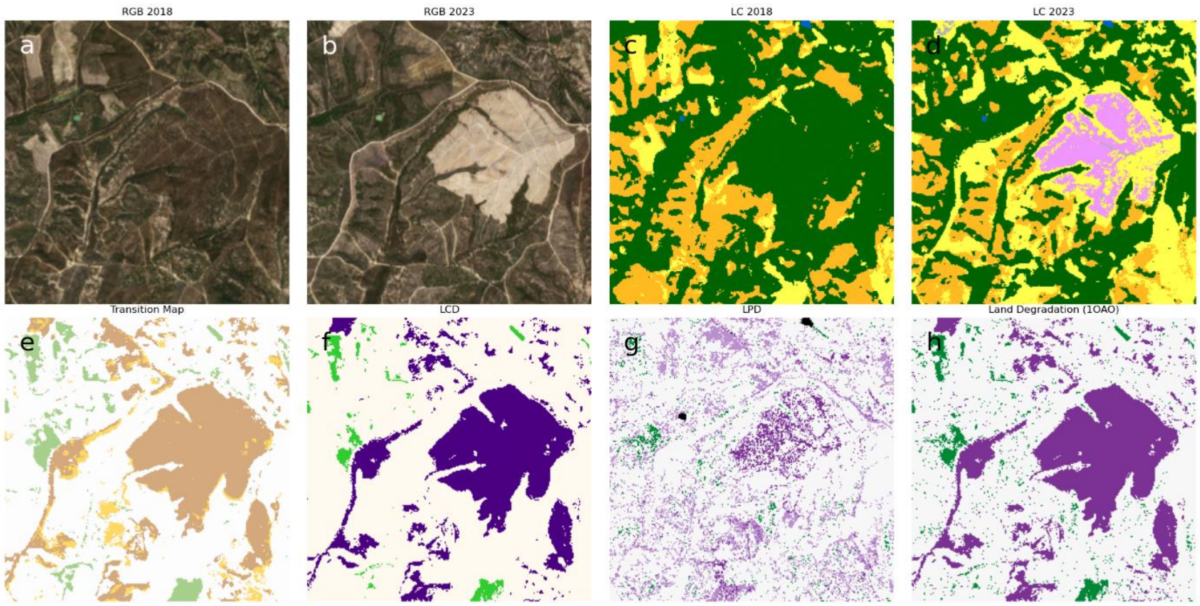


Figure 7: Example on area of 2.5km x 2.5km in Portugal. (a, b) Sentinel-2 RGB Median composite for years 2018 and 2023. (c, d) Land Cover maps 2018, 2023. (e) Land Cover Transition map (LCT). (f) Land Cover Degradation map (LCD). (g) Land Productivity Degradation map (LPD). Land Degradation indicator obtained through integration of LCD and LPD with the 1OAO method, as specified in Table 10. The indicator highlights 'Improved' areas in green, 'Degraded areas in purple, and 'Stable' areas in light grey.

3.4 Limitations

The integrated LDN indicator is based on two sub-indicators only, as the products on trends in carbon stocks are not provided for the same period and at the same spatial resolution as the products on trends in land cover and trends in land productivity. As such, the product is not fully compliant with the UNCCD Good Practice Guidance [5].

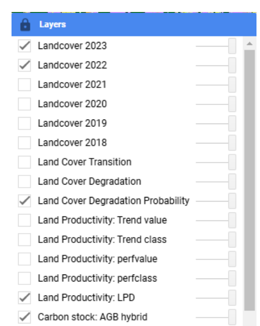
4 Google Earth Engine application

The Google Earth Engine (GEE) web application is available at:

https://vitorsveg.users.earthengine.app/view/sen4ldn

The main view is displayed in Figure 8. The different visualization options are described in more details below.

Figure 8: Main view on the SEN4LDN GEE web application. 1. Layer selection, 2. Map legends, 3. Split panel separator, 4. Zoom options, 5. Zoom to Area of Interest, 6. Product User Guide download link



Which layers are displayed or not, and with which transparency, can be selected from the 'Layers' list (number 1 in Figure 8). By default, only the Landcover transition map, Land Productivity indicators and Carbon stock indicators are displayed. This can be adapted by toggling the checkboxes on and off. Transparency of the layers can be adapted using the sliders at the right. The 'Layers' list can be locked on the view by clicking the lock symbol.

The legend of the different layers are shown in the right pane (number 2 in Figure 8). Scrolling to the bottom of the right pane, the 'Background' option becomes available. This allows changing the background of the left viewing panel (default high resolution satellite data) to another layer. This can e.g. be used to visualize the differences in the LC maps for different years: the wipe-style separator allows to detect differences in both maps (see Figure 9).

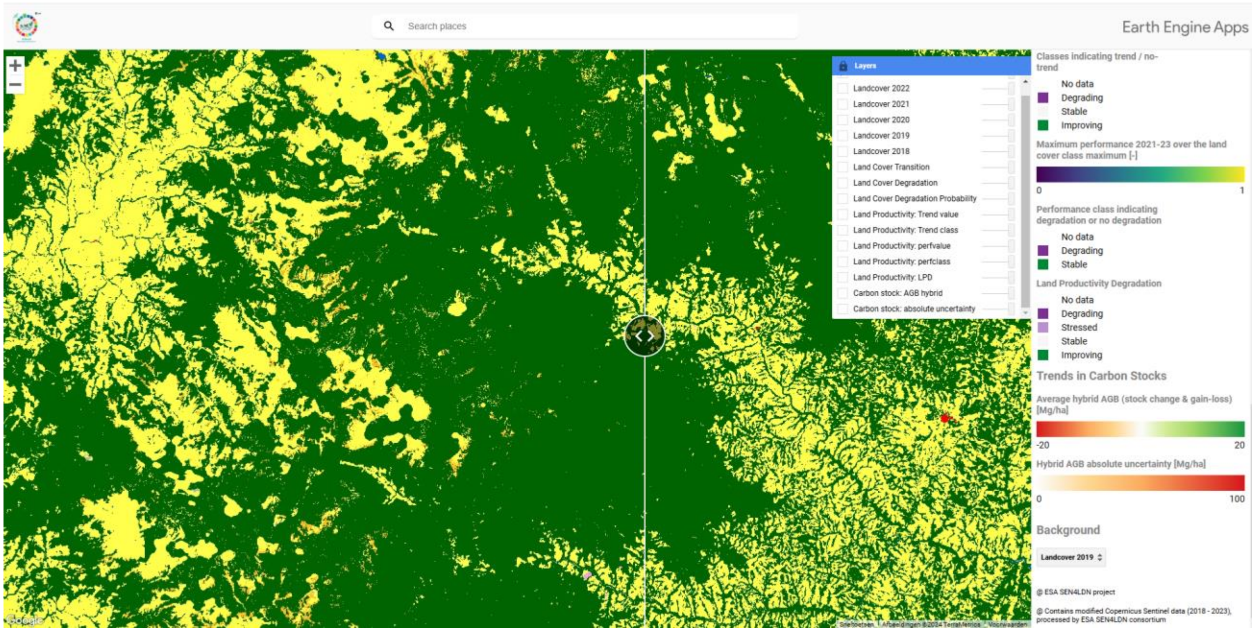


Figure 9: Example on the use of the wipe-style separator between the left and right viewing panel to evaluate land cover changes between 2019 (left) and 2023 (right).

Zooming in and out can be done by the zoom buttons at the top left (number 4 in Figure 8) or by scrolling the mouse wheel. Pan through the map by clicking the right mouse button and moving around. By clicking the zoom button (number 5 in Figure 8) the view switches to the Area of Interest (AOI).

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