SEN4LDN

LAND DEGRADATION NEUTRALITY

User Handbook

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Key takeaway messages

- SEN4LDN developed a novel Earth Observation (EO) solution to enhance spatial and temporal resolution for monitoring land degradation neutrality (LDN), supporting SDG indicator 15.3.1 reporting. High-resolution National Demonstration Products were created for Uganda, Portugal, and Colombia, showcasing trends in land cover, land productivity, and carbon stocks.
- This User Handbook is a tutorial for technical practitioners of the target SDG community on the concept and usage of the EO solution developed during the project, with a summary of the national demonstrations and associated use cases. The UHB includes some references to pilot products (single SDG maps and aggregated statistics/indicators) developed during the project, with the products specifications (including metadata documentation).
- Stakeholders, so-called SEN4LDN Early Adopters, in Uganda, Portugal, and Colombia provided valuable insights, emphasizing the need for localized classifications, ground truth data integration, and improved usability of EO tools. Specific use cases in each country highlighted the utility of EO products in addressing diverse land degradation processes, including deforestation, agricultural expansion, and wetland drainage.
- Product strengths and limitations were listed based on feedback from the early adopters and evaluation of SEN4LDN demonstration products at national level and over specific use case areas.
- Recommendations for future developments include incorporating Sentinel-1 data, extending the time series for productivity trends, refining carbon stock methodologies, and developing customizable workflows for country-specific applications.

List of abbreviations

1OAO	One-out-all-out
AGB	Above Ground Biomass
EU	European Union
EO	Earth Observation
LCD	Land Cover Degradation
LD	Land Degradation
LDN	Land Degradation Neutrality
PROB	Probability
SDG	Sustainable Development Goal
SEN4LDN	Sentinels for Land Degradation Neutrality
SOC	Soil Organic Carbon
UHB	User Handbook
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
WP	Work Package

1 Introduction

1.1 Scope and objectives

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.

Efficient monitoring of 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 several challenges and opportunities to address particularly related with increasing spatial and temporal resolution and diversity of sensor types [2]. Sentinels for Land Degradation Neutrality (SEN4LDN) 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 will provide insights on the user requirements and feedback on the final product and its actual usability for SGD 15.3.1 reporting.

The objective of SEN4LDN Work Package 6 (WP6) is to facilitate the operational uptake of the EO solution by the SDG Early Adopters and to promote its adoption within the target SDG community.

This User Handbook is a tutorial for technical practitioners of the target SDG community on the concept and usage of the EO solution developed during the project, with a summary of the national demonstrations and associated use cases. The UHB includes some references to pilot products (single SDG maps and aggregated statistics/indicators) developed during the project, with the products specifications (including metadata documentation).

1.2 Document structure

The document is structured as follows:

- Chapter 2 provides a general description of the EO solution developed in SEN4LDN
- Chapter 3 lists the product specifications
- Chapter 4 provides a summary of the national demonstrations and use cases

1.3 Related documents

- **SEN4LDN D1.2 Requirements Baseline**

- SEN4LDN D2.1 Input Data Inventory
- SEN4LDN D3.1 Proof of Concept results on test sites
- **SEN4LDN D3.2 Algorithm Theoretical Baseline Document**
- **SEN4LDN D5.1 Results of National Demonstrations**
    - Product User Guide
    - Zenodo records for
        - Trends in Land Cover: https://zenodo.org/records/14223153
        - Trends in Land Productivity: https://zenodo.org/records/14230325
        - Trends in Carbon Stocks: https://zenodo.org/records/14274476
        - Indicator for SDG15.3.1: https://zenodo.org/records/14283567
    - Google Earth Engine online Application for product exploration, available at https://vitorsveg.users.earthengine.app/view/sen4ldn
- **SEN4LDN D5.2 Product Validation Report**
- SEN4LDN D6.1 Demonstration Utility Report

Public deliverables are available on https://esa-sen4ldn.org/en/deliverables.

2 The SEN4LDN EO solution

2.1 Concept

The extent of land degradation for reporting on SDG Indicator 15.3.1 is in principle calculated using three sub-indicators [3]. The general concept of the workflow used in SEN4LDN to provide the necessary inputs to the indicator is illustrated in Figure 1. The input data consist of Sentinel-2 Level 2A products, ESA CCI Biomass products, Ancillary layers, and training data. The following chapters provide a detailed specification of the SEN4LDN processing algorithms for

(i) Trends in land cover, yielding annual land cover maps, information on land cover transition and a land cover degradation product;
(ii) Trends in land productivity, yielding information on land productivity trends, performance and a land productivity degradation product; and
(iii) Trends in carbon stocks, yielding information on above ground biomass change.

In the following chapter, the output products that are generated are listed. Since the trends in carbon stocks output products cover a different time frame and are provided at a different spatial resolution, the integration is performed on the trends in land cover and trends in land productivity sub-indicator products only.

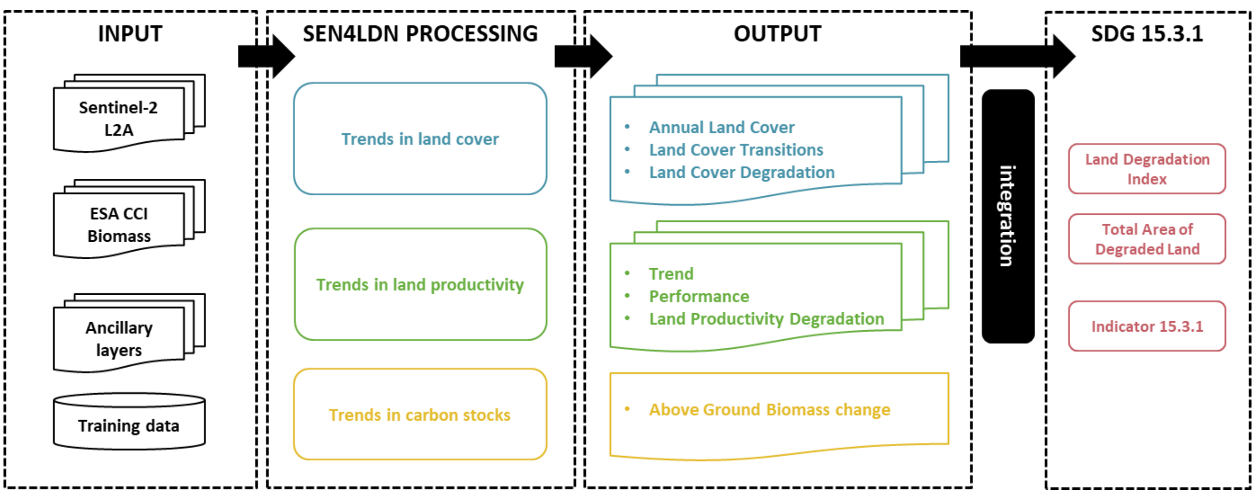

Figure 1: General concept of the SEN4LDN algorithm to feed into SDG indicator 15.3.1

2.2 General description of the algorithms

2.2.1 Trends in land cover

The intention of the SDG 15.3.1 trends in land cover sub-indicator is to identify where degradation has occurred specifically because of land cover change. Within SEN4LDN an automated method to monitor land cover dynamics at high spatial resolution, i.e. 10m, based on Sentinel-2 observations, was developed.

The land cover classification algorithm developed in the framework of the SEN4LDN project aims to extend the capabilities of the current state-of-the-art algorithms for global land cover classification. The new system was designed as an evolution of the ESA WorldCover classification system, as this proved to be one of the best global land cover algorithms published in recent years [4], [5], [6].

The key limitation of ESA WorldCover algorithm is the poor generalization across different years. The development and calibration of the algorithm is performed on single years, and when the algorithm is applied to a different year, the prediction reliability is reduced, leading to errors. This limits the ability of using this algorithm for studying land cover changes and degradation events, and a solution needed to be designed.

The objective of the SEN4LDN design is to overcome this problem by adopting two key solutions. As a first step, the new models are trained on features computed from Sentinel-2 and AgERA5 data of multiple years (2018-2022). This ensures robustness against phenological fluctuations due to different meteorological conditions in different years. The second solution is to combine the advantages of single pixel classifiers with the generalization capabilities of deep learning semantic segmentation algorithms used for example by ESRI Land Cover and Google Dynamic World, thus preserving high spatial accuracy, but improving the generalization capabilities.

The land cover classification workflow is summarized here and illustrated in Figure 2. The algorithm starts from the input data which are used to produce features through a pre-processing step. The features are then used to train first a deep learning semantic segmentation algorithm. Due to technical constraints, only a subset of the computed features is used for the deep learning algorithm. The full set of features is then merged with the probabilities obtained from the deep learning model and fed into a CatBoost classifier. The output probabilities of the CatBoost classifier, computed for several years, are ingested in a post-processing routine, which optimizes consistency of the predictions while preserving changes, yielding the final land cover time-series.

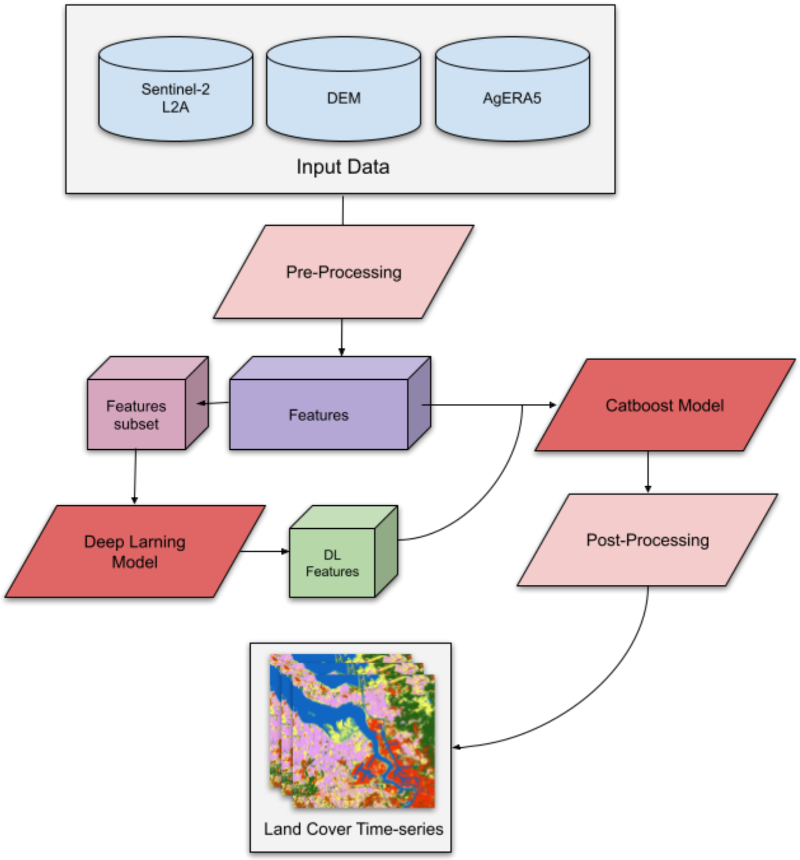

Figure 2: Summarized scheme of the Land Cover classification model

An overview of the workflow to monitor trends in land cover as a sub-indicator for land degradation is illustrated in Figure 3. The main input data source is Sentinel-2 L2A surface reflectances. In a pre-processing step, the Sentinel-2 time series are cleaned (including improved cloud detection), and a compositing algorithm is applied to extract features. Together with the training dataset and ancillary layers, this feeds into the land cover classification algorithm (LC model, see Figure 2), which has been developed as an evolution of the ESA WorldCover 2021 classification algorithm. In total 11 land cover classes are predicted starting from yearly time-series of reflectance data for the Sentinel-2 L2A products bands. These 11 classes are considered adequate to allow monitoring of key degradation processes, although some of the land use changes might remain undetected. A post-processing routine is applied to the LC probabilities obtained by the model predictions across different years, to stabilize them and reduce classification errors due to noise and phenological fluctuations of the input features. To determine changes for a given location, a combination of the LC probabilities is performed for each type of transition, obtaining continuous transition probabilities, which are then used to produce a discrete LC transition maps by means of a transition matrix. Land cover changes are specified as being either degradation, improvements, or neutral transitions, summarized in the Land Cover Degradation (LCD) output products.

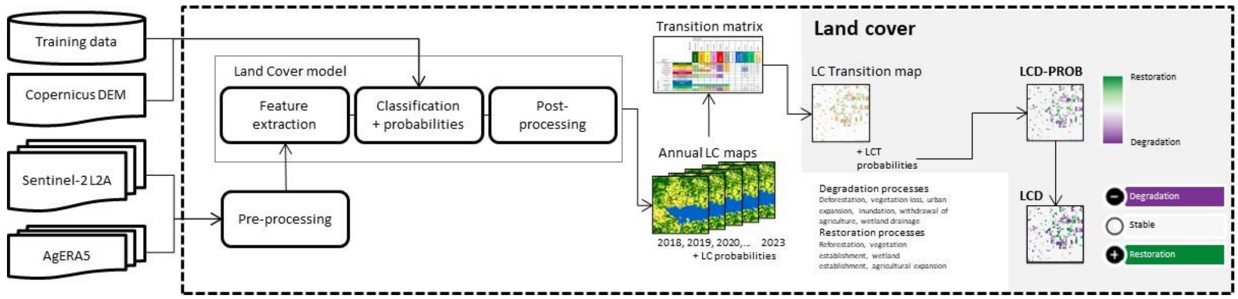

Figure 3: Overview of the workflow for the trends in land cover sub-indicator

2.2.2 Trends in land productivity

The aim of this component is to develop an automated method to monitor trends in land productivity dynamics at high spatial resolution. The biological production provides a fundamental resource in the form of food, fodder, fuel and fibre for sustaining human economy and wellbeing. Negative trends in this production can be an indicator of land degradation. Land productivity can be estimated from satellite-observed vegetation index data over growing seasons, summarized into annual values. Frequently, the Normalized Difference Vegetation Index (NDVI) is used as a proxy for this plant growth. However, since this index saturates over high biomass areas, we are here assessing also alternative indices with better dynamic range.

Optical observations from satellite are constrained in cloudy areas. Since this limits data coverage and frequency, a data processing method that is robust to noise and short-term variability is necessary. Therefore, while it is possible to develop trend estimates directly from raw satellite sensor data, we here first implement robust data processing methodology to handle gaps in time series, then aggregate data seasonally, and finally derive trends from the aggregated data.

For data aggregation and smoothing, we are using the TIMESAT software system. TIMESAT has been used since ca. 2000 [33] for pre-processing of satellite time-series and was recently upgraded to work with high-spatial resolution data [34]. TIMESAT is the core algorithm in the High-Resolution Vegetation Phenology and Productivity (HR-VPP) portfolio of the Copernicus Land Monitoring System (CLMS)[1]. The software system fits mathematical functions over time to each pixel location of a stack of vegetation index data to generate smooth seasonal trajectories. From these trajectories, seasonal parameters are derived that describe the vegetation phenology and productivity. Vegetation productivity is the aggregated smoothed seasonal vegetation index across the growing season. We focus on changes in the sum of vegetation productivity between years.

Apart from deriving the trend in the annual productivity parameters, we generate data on the productivity performance, which is a measure of the productivity of a particular land area in comparison to other land areas with similar characteristics. Finally, we generate an aggregate measure termed Land Productivity Degradation that combines aspect of trend and performance. The methodology in this chapter broadly follows the suggestions in the UNCCD Best Practice Guidance [9], but with necessary modifications due to the use of high-resolution data.

[1] https://www.eea.europa.eu/en/datahub/datahubitem-view/b6cc3b37-0686-4bb1-b8c3-3c08520743c3

Land productivity parameters are generated from the same workflow on Sentinel-2 TOC data as used for the trends in land cover. Figure 4 outlines the general methodology. Following pre-processing of the data, vegetation indices (VIs) are calculated. Then, time-series for each pixel are fed into TIMESAT for fitting smooth functions and outputting phenological parameters. Out of these, productivity is used as the main parameter in the ensuing process. Trend estimation and performance estimation are done for each pixel, generating sub-indicators Trend and Performance. Finally, an aggregated sub-indicator, Land Productivity Degradation (LPD), is developed.

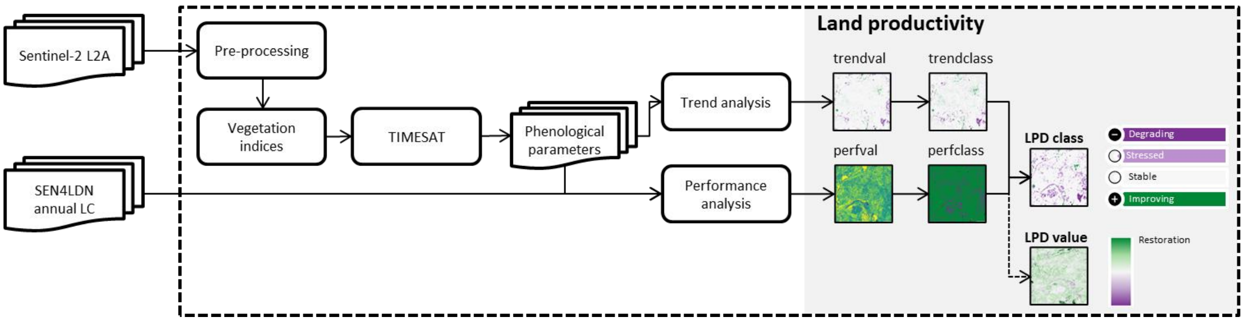

Figure 4: Overview of the workflow for the trends in land productivity sub-indicator

2.2.3 Trends in carbon stocks

The aim of this component is to develop an automated method to monitor carbon stocks dynamics at high spatial resolution. Currently, carbon stocks are estimated using a combination of land cover and SOC data within the Trends.Earth application. This means that only changes in SOC are considered for LDN monitoring, which is, however, difficult to observe with multi-spectral data alone (such as Sentinel-2) due to coverage of the soil with vegetation and lack of spectral information (imaging spectroscopy is better suited for SOC prediction). In addition, SOC storage is highly variable across sites depending on soil-forming factors, including time, parent material, topography, climate, organisms and impact by humans. Accurate predictions of SOC stocks require therefore detailed data on site properties and management, which are often not available. Those factors inhibit the establishment of SOC time series preventing the estimation of trends that would be needed. Hence, we propose the exploration of above-ground biomass (AGB) maps and derived trends as a first feasibility study in this context.

Two research demonstration approaches are used for mapping changes in AGB based on Earth observation data and combined [52]:

- **Stock change approach**: This method directly calculates ΔAGB by differencing biomass maps created at different points in time, available from the European Space Agency's Climate Change Initiative (CCI). This collection offers forest AGB estimates for the years 2010, 2017, 2018, 2019, and 2020. Maps are provided at a spatial resolution of 100 m.
- **Gain-loss approach**: This approach focuses on land-use specific carbon fluxes, utilizing pre-determined emission and removal factors to estimate ΔAGB from an initial biomass estimate for a specific timeframe. The Word Resources Institute (WRI) carbon flux model incorporates spatial datasets to characterize carbon emissions and removals based on activity data (forest gains and losses) combined with biomass maps information.

- **Hybrid approach**: The final optimal solution is to average the resulting maps from stock change and gain-loss methods, and the resulting standard deviation is considered as absolute uncertainty measure. See also Figure 5.

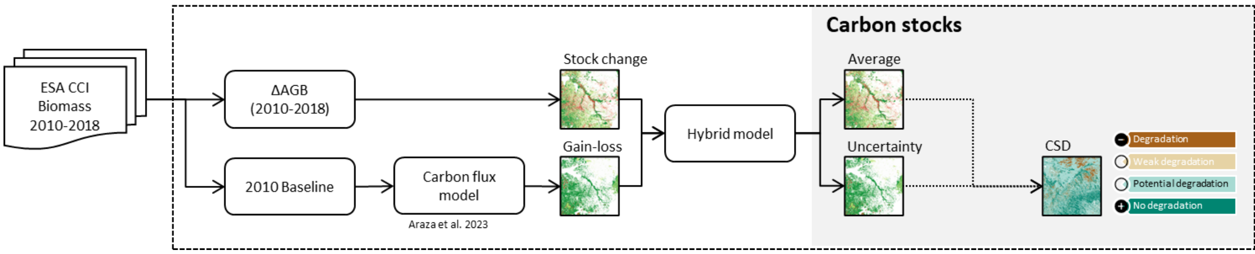

Figure 5 Overview of the workflow for the trends in carbon stocks sub-indicator

2.2.4 Integration

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 SEN4LDN, we aim to test two different algorithms:

- The default one-out-all-out (1OAO) integration method, as described in [9].
- A continuous sub-indicator integration method, that combines the continuous Land Cover Degradation and Land Productivity Degradation products into a continuous Land Degradation Probability Index. This allows for a more in-depth interpretation of the combined product, including an assessment of the magnitude or probability of degradation and an interpretation of uncertainties or possible contrasting sub-indicators.

3 SEN4LDN product specifications

3.1 Trends in land cover

3.1.1 Products definition

3.1.1.1 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” [11]. Land cover is typically described as a set of hierarchical classes, each denoting the dominant biotic and abiotic assemblages occupying the Earths’ surface [12]. 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.	

3.1.1.2 Land cover transitions

The land cover transitions map provides information on the degradation and improvement 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 improvement processes) are based on the land cover transition matrix.

Map code	Degradation / Improvement 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 an improvement process that refers to the establishment or restoration of tree cover.	
102	Vegetation establishment	Vegetation establishment is the improvement 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 improvement process refers to the conversion of grasslands or other land in cropland.	

3.1.1.3 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 / Improvement process	Definition	Colour	Map code
Stable	Stable Land Cover		0
Improvement	Land Cover Improvement 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 (improvement).

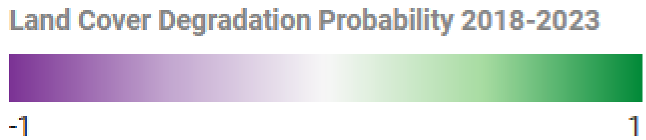

Figure 6: Colour scale of Land Cover Degradation Probability (LCD-PROB)

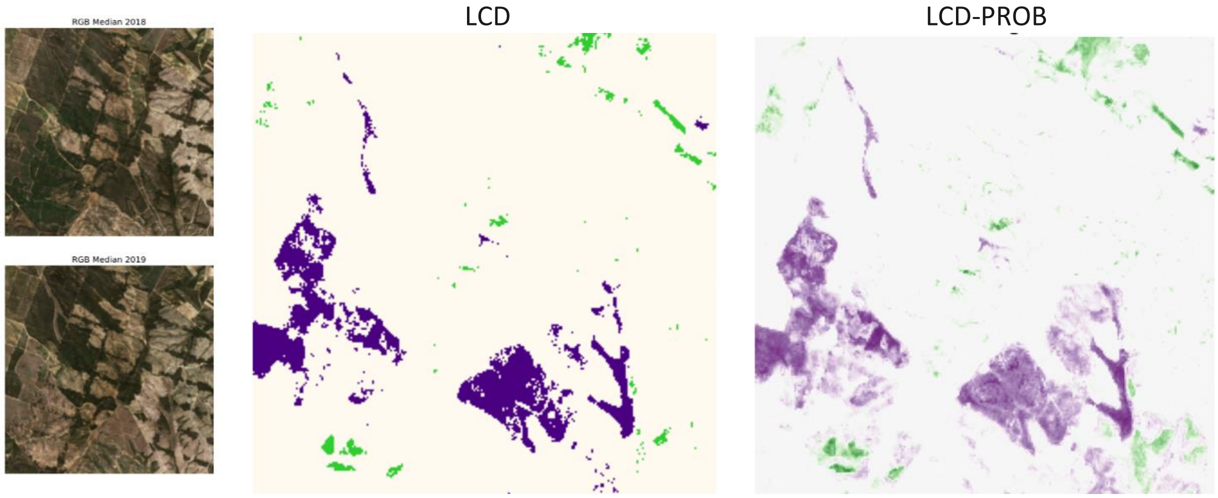

Figure 7: Example of LCD and LCD-PROB output products of Trends in Land Cover

3.1.2 Output products specifications

The final output products of the trends in land cover algorithms are:

- Annual Land Cover Maps (LCM) (timeseries 2018 – 2023)
- Land Cover Transition map (LCT) (between year 2018 and year 2023)
- Land Cover Degradation Map (LCD) (between year 2018 and year 2023)
- Land Cover Degradation Probabilities (LCD-PROB) (between year 2018 and year 2023)

The products (see details in Table 4) are delivered as single band Cloud Optimized Geotiffs (COGs) in a 3x3 degree lat/lon (WGS84) tiling grid. The aim of the operational workflow would however be to make the spatial extent and projection grid to be user customizable.

The products naming will follow the scheme:

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

For example, for a tile of the annual land cover maps:

SEN4LDN_LCM_V100_2018_N09W075_MAP.tif

The date identifier for transition and degradation maps include the starting and ending years (for example 2018-2023).

The metadata included with the products follows the scheme delineated in Table 5.

Table 4: Output products of trends in land cover algorithms

Product	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), Improved (1), Degraded (2)	UINT8 [0,1,2]	255	-	See Table 3
LCD-PROB	Land Cover Degradation Probabilities scaled between -1 (degradation) and 1 (improvement)	UINT8 [0-250]	255	0.008 -1	-

Table 5: Metadata fields of the output COG products

Field	Description
copyright	SEN4LDN project 2024 / Contains modified Copernicus Sentinel-2 data for the year/years {year/years} processed by the SEN4LDN consortium.
product_crs	EPSG:4326
product_grid	3x3 degrees lat/lon (WGS84) tiling grid
product_tile	{tile_id}. For example W003N21 or E120S12
version	{product version}
reference	Products DOI
time_start	Interval starting time for the products used in the generation.
time_end	Interval ending time for the products used in the generation.
creation_time	File creation time
title	Product title
product_type	Product type
license	CC-BY 4.0 - https://creativecommons.org/licenses/by/4.0/
legend	Product legend (if applicable, e.g. for discrete maps)
bands	Product bands (if applicable, e.g. for probabilities)

3.2 Trends in land productivity

3.2.1 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.

Land productivity, and losses of productivity in connection with land degradation, can be estimated based on the trend, state and performance of vegetation productivity ([9], [13], [14]) 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. Since no historical satellite series of the same spatial resolution exists, and because comparing trends at different resolutions would be misleading, the state indicator has not been computed in SEN4LDN.

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. The performance indicator is computed by comparing local pixel values with the average across large areas. Finally, we generate an aggregate measure termed Land Productivity Degradation that combines aspect of trend and performance. The methodology in this chapter broadly follows the suggestions in the UNCCD Best Practice Guidance [9], but with necessary modifications due to the use of high-resolution data and a shorter available time-series.

3.2.2 Output products specifications

The datasets in Table 6 are generated as part of the Productivity Trends sub-indicator.

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
- <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 6: Datasets 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	-
LPD Index*	Land productivity degradation	Continuous values of land productivity degradation [-1 - 1]	UINT8	255	1/100 -1

* The LPD Index sub-indicator is currently not available to users.

3.3 Trends in carbon stocks

3.3.1 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. [15], using Earth observation data and models.

1) The stock change approach directly calculates ΔAGB by comparing ESA CCI biomass maps [16] from two different points in time.

2) The gain-loss approach uses a carbon flux model[2], 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.

3.3.2 Output products specifications

The final output products of the carbon stocks algorithms are:

- Stock change AGB map (time span 2010 – 2018)
- Gain-loss Land AGB map (time span 2010 – 2018)
- Hybrid AGB change map (time span 2010 – 2018)
- Uncertainty AGB change map (standard deviation of hybrid approach, time span 2010-2018)

Note that the carbon stock change product serves rather as a prototype demonstration case. The data availability does not correspond to the same time span and resolution as the products generated to monitor trends in land cover and productivity.

The products naming will follow the scheme:

SEN4LDN_<PRODUCT_ID>_<VERSION>_<DATE_ID>_<ROI>.tif

with ROI the region of interest (e.g. country name).

Table 7: Output products of trends in carbon stocks

Product name	Content	Data type and range	No data value	Scale Offset	Unit
Stock change map*	ESA CCI Biomass mapping approach	FLOAT32	-9999	-	mg/ha
Gain-loss map*	WRI Flux model approach	FLOAT32	-9999	-	mg/ha
Hybrid map	Average of stock change and gain-loss maps	FLOAT32	-9999	-	mg/ha
Uncertainty layer	Standard deviation between stock change and gain-loss maps	FLOAT32	-9999	-	mg/ha

* The Stock change map and Gain-Loss map are currently not distributed to users.

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

3.4 Integrated indicator on LDN

3.4.1 Products definition

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.

In contrast to the 1OAO integration method, for the continuous sub-indicator integration method continuous maps of LCD-PROB and LPDval (see above) are considered as input. The LD-index is defined as the absolute maximum of LCD-PROB and LPDvalue (either positive for improving pixels, or negative for degrading pixels). The output variable is a continuous map delineating the probability of the pixel to have experienced a positive or negative evolution in the reporting period. A user customizable threshold can be used to convert this map into a discrete map and to delineate $A(recent)_n$ and $A(improved)_n$, similar to the output of the 1OAO.

3.4.2 Output products specifications

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 8.

Table 8: SEN4LDN products 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), Improved (1), Degraded (2)	UINT8 [0,1,2]	255	-
LD-INDEX*	Land Degradation Neutrality Index map scaled between -1 (degradation) and 1 (improvement)	UINT8 [0-250]	255	0.008 -1

* The LD-Index is currently not available to users.

4 Summary of the national demonstrations and use cases

4.1 Product strengths and limitations

The SEN4LDN project focused on developing an EO method for the national assessment of land degradation and improvement at **high temporal frequency** (annual) and **high spatial resolution** (10m) that is **applicable at global scale**. In addition, SEN4LDN developed continuous sub-indicators and explored a **continuous sub-indicator integration** method that allows to provide (a proxy for) uncertainties in the identification of ongoing degradation or improvement processes. In this respect, SEN4LDN has provided tangible results to support the UNCCD and GEO-LDN in defining the next steps to increase the spatial and thematic detail of national assessments of land degradation and improvement.

An important limitation of the evolution towards high spatial resolution by using Sentinel-2 10m input products – available since 2017 – is the lack of a **historical archive** to respond to UNCCD methodology demands. This is especially relevant for the trends in productivity sub-indicator, where long term consistent datasets are necessary to (better) evaluate state and trends in vegetation productivity.

There are also **country-specific processes** that are hard to monitor with a global applicable methodology and resulting datasets. In this respect, algorithms should be deepened to reach specific thematic detail based on adaptable schemes at country scale, starting from the global dataset. This could be done by integration of national data, such as local training data or detailed maps, in the process. The process is to start from the global dataset and further improve the national scale map with local data. For land cover classification, this would require an evolution to an on-demand dynamic land cover mapping service that can rely on specific reference data, in which each country can apply its own typology of land cover and land use classes.

The land cover mapping algorithm that was developed within SEN4LDN built upon a combined solution of deep learning with a pixel classifier, resulting in continuous land cover probability products. The resulting annual land cover maps show **high interannual consistency**, which is important for evaluating changes. The continuous scale in the annual output products allows to evaluate land cover **transition probabilities**, which provide an idea on probabilities and thus also uncertainties. Although the algorithm to derive land cover transitions starting from the land cover probability maps for the 11 classes as defined in the land cover algorithm allows to apply a user-specified land cover transition matrix, the feedback from the early adopters clearly shows that **disaggregation into more narrow land cover classes** is required to respond to specific needs. This includes the following sub-classes: (i) tree plantations vs. natural tree cover vs. fruit orchards; (ii) managed pastures vs. natural grasslands; (iii) subsistence cropland vs. mono-cropped commercial farmland or plantations; (iv) irrigated cropland vs. non-irrigated cropland; (v) native vs. invasive alien tree species; etc. These developments – on the boundary of mapping land cover vs. mapping land use – are becoming more feasible with the evolution towards high spatial resolution, but further research is required. Another limitation is related to the lack of good satellite observations over areas with **persistent cloud cover**, leading to artefacts in the temporal composite features that are used as input for land cover mapping. This problem could be tackled through the incorporation of Sentinel-1 (synthetic aperture radar) data in the workflow.

SEN4LDN developed automated, global algorithms to generate **discrete and continuous land productivity degradation products** and land productivity degradation classes and continuous values at 10m resolution. However, for monitoring trends in land productivity, the period for which Sentinel-2 data is available is a strong constraint, as this adds uncertainties to the monitoring of trends in land productivity. The proposed methodology is therefore not completely in line with the UNCCD Good Practice Guidance [11]. The **time series length is limited** and going backwards in time with other sensors is difficult, because of the inconsistency in the frequency of observations, resulting in temporal inconsistencies. Fixing the baseline period to 2000-2015 puts a strong constraint to the reporting based on newly developed products and algorithms. As a result, it is not possible to integrate new datasets with higher spatial resolution that are only available more recently. More research is needed to look at ways to by-pass these constraints. Alternatively, at some point in the future the baseline period definition could be revised. Another limitation is the lack of good satellite observations over areas with **persistent cloud cover**, leading to unrealistic low productivity performance values, as was shown in the Colombia national demonstration products. As for the land cover algorithm, this problem could be tackled through the incorporation of synthetic aperture radar (SAR) Sentinel-1 data in the workflow. The use of **land cover as input** to the land productivity workflow introduces uncertainty to the output products, as possibly errors are propagated from one sub-indicator to another. In addition, **land cover change** complicates direct comparisons of seasonal trajectories over the years. Finally, the performance estimation is currently based on country-wide reference statistics. This could be tackled by using fine-grained **bioclimatic zonation** as production ecosystem functional units to calculate the reference input for the performance algorithm.

For the evaluation of trends in carbon stocks, SEN4LDN explored the use of **aboveground biomass** (AGB). This is a challenging sub-indicator because it is difficult to observe carbon stocks – especially soil organic carbon (SOC) – with optical EO data. SEN4LDN therefore focused on a research demonstration approach to evaluate trends in aboveground biomass based on a combination of the stock change approach and a gain-loss approach at lower spatial resolution (100m). A drawback of the developed algorithm is the different time scale and spatial resolution that hinders integration with the products that were developed for trends in land cover and trends in land productivity. The integration with the other sub-indicators needs further investigation. Further research could also focus on the **combination of AGB and SOC** products to achieve a measure to monitor total carbon stocks. This would require further developments in both the AGB and SOC products.

4.2 Conclusions from the demonstration utility analysis

The SEN4LDN project developed an EO method for national assessments of land degradation neutrality with high temporal frequency and spatial resolution. The SEN4LDN national demonstration products for Uganda, Portugal and Colombia provided insights into land stability, improvement, and degradation from 2018-2023. In the demonstration utility analysis, we have assessed the utility of SEN4LDN products in addressing country-specific challenges and improving SDG reporting, providing insights into the Land Degradation Neutrality (LDN) targets, efforts, and challenges faced by Uganda, Portugal, and Colombia, as well as the use cases developed under the SEN4LDN project.

Uganda formulated ambitious LDN targets aim for "no net loss" of land quality by 2030 compared to 2015. The main challenges include deforestation, overgrazing, poor land management, urbanization, and weak governance. The SEN4LDN national demonstration products show an estimated additional 1.6% of the country degraded between 2018 and 2023, mostly related to degradation in land productivity. The products were tested over specific use case areas to analyse the drivers or land degradation, including areas affected land productivity decline, deforestation and reforestation, wetland drainage and industrial expansion.

The main challenges for Portugal include desertification and the fact that increase of vegetation or forest cover may not reflect true land health as large-scale monoculture plantations or invasive plant growth not necessarily correspond to ecosystem restoration. The national demonstration products were evaluated over several use case areas to study the effects of conservation agriculture, forest restoration after wildfires, and deforestation linked to solar panel installations.

The national and sub-national LDN targets for Colombia include restoring 100,000 hectares of degraded land and promoting sustainable practices. Land degradation is caused by a complex set of factors, including inadequate agricultural practices, lack of knowledge about soil health, government policies that promote unsustainable practices, and climate change. The use case areas focused on mining expansion, reforestation, deforestation in the Amazon, and agricultural expansion.

The feedback from the Early Adopters can be summarized as (i) a general consent on the utility of the SEN4LDN products for SDG reporting and restoration strategy formulation, mainly because of the high spatial and temporal resolution of the products; (ii) concerns about misclassifications and the need for local ground truth data integration in land cover mapping; (iii) requests for more detailed land cover classes (e.g. native vs. invasive species, irrigated vs. non-irrigated cropland, natural vs. managed grasslands, natural forest vs. commercial plantations); and (iv) challenges related to soil organic carbon estimation and methodologies.

As for the roadmap towards future evolutions in possible follow-up activities, this includes:

(i) Related to trends in land cover:
   a. Provide land cover maps with additional disaggregated classes to respond to local needs.
   b. Provide an on-demand mapping service that allows inclusion of local (training) data to better characterize the local conditions, on top of a general classification mechanism that is applicable at global scale.
   c. Incorporate SAR products derived from Sentinel-1 to mitigate the effect of persistent cloud cover in land cover mapping.

(ii) Related to trends in productivity:

a. Develop methodologies to expand the time series using complementary datasets backwards in time to respond to UNCCD methodology demands, especially relevant for evaluation of the state and trends in vegetation productivity.
b. Apply ecosystem functional units (bioclimatic zonation) for performance estimation.
c. Incorporate SAR products derived from Sentinel-1, relevant in areas with high cloud cover.

(iii) Related to trends in carbon stock:

a. Develop a combined approach on aboveground biomass and soil organic carbon to monitor evolution of total carbon stocks.
b. Provide carbon stock sub-indicator products at the same spatial and temporal resolution as the other two sub-indicators.

(iv) Related to integration of sub-indicators:

a. The continuous sub-indicator integration method needs further testing and discussion.
b. Integration of all three sub-indicators, once all are available at the same spatial and temporal resolution (see above).

(v) To maximize user uptake, integration of the EO solution into an operational customizable workflow is required.

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