SEN4LDN

LAND DEGRADATION NEUTRALITY

D8.3

Final Report

Version 1.1

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Key takeaway messages

- SEN4LDN developed a novel approach to improve the spatial and temporal resolution of products to monitor LDN for reporting on UN SDG indicator 15.3.1. Apart from the one-out-all-out integration also a continuous sub-integration method was tested, allowing for a more nuanced assessment of land degradation risks and trends.
- National demonstration output products were generated for three countries – Uganda, Portugal and Colombia – showing the applicability of the algorithms at global scale. The national demonstration products have been made openly accessible, together with user documentation (PUG, ATBD and PVR).
- Living labs were established with Early Adopters in the three use case countries, as collaborative spaces where stakeholders could engage actively, ensuring that user needs and real-world feedback directly informed the development and validation of project outputs.
- The SEN4LDN team collaborated successfully, with responsibilities assigned to ensure efficient workflow and accountability throughout the project's duration. The project outlined clear milestones and deliverables, supporting effective project management and enabling robust outreach activities to disseminate results to a wide audience. Regular milestone meetings were conducted to monitor progress, address challenges, and align the consortium on objectives and next steps.
- Outreach activities were carried out to raise awareness, share knowledge, and promote the adoption of SEN4LDN outputs within the broader land degradation and Earth Observation communities.

Summary

This final report of the SEN4LDN project provides a complete description of all the work done during the project. It covers the whole scope of the report, including a description of the programme of work and report on the activities performed, the main results achieved, and the sustainability roadmap for a successful transfer into user practices and processes.

The SEN4LDN project delivered a novel solution for monitoring Land Degradation Neutrality (LDN) in support of UN SDG indicator 15.3.1, advancing both spatial and temporal resolution of Earth Observation-based products. In addition to the standard one-out-all-out integration method, a continuous sub-integration assessment method of the sub-indicators for LDN monitoring was explored, to enable more refined detection of land degradation risks and trends. National demonstration products were produced for Uganda, Portugal, and Colombia, showing the algorithms' global applicability. Output products and user documentation were made openly available. The establishment of living labs with Early Adopters in each demonstration country fostered collaboration, ensuring that the evolving solutions directly addressed user needs and benefited from stakeholder feedback.

The project team maintained robust collaboration and accountability, guided by well-defined milestones and deliverables. Regular milestone meetings supported progress tracking and effective decision-making. Extensive outreach activities promoted awareness of SEN4LDN outputs to encourage the adoption within the land degradation and Earth Observation communities. Overall, the project's results demonstrate significant progress in the operational monitoring of LDN, contributing valuable tools and knowledge to global efforts in land degradation assessment and reporting.

List of abbreviations

AGB	Above Ground Biomass
BU	Busitema University
CDR	Critical Design Review
D	Deliverable
DAR	Demonstration Assessment Review
EU	European Union
EO	Earth Observation
FR	Final Review
GFZ	GeoForschungsZentrum Hemholtz Centre for Geosciences
ICNF	Institute for Conservation of Nature and Forests
KO	Kick-Off
LC	Land Cover
LD	Land Degradation
LDN	Land Degradation Neutrality
LL	Living Lab
MESD	Ministry of Environment and Sustainable Development
OSLL	Open Stakeholder Living Lab
PDR	Preliminary Design Review
PRR	Production Readiness Review
RR	Requirement Review
SDG	Sustainable Development Goal
SEN4LDN	Sentinels for Land Degradation Neutrality
SOC	Soil Organic Carbon
ULUND	Lund University
UNCCD	United Nations Convention to Combat Desertification
VITO	Vlaamse Instelling voor Technologisch Onderzoek
WP	Work Package
WU	Wageningen University

1 Introduction

1.1 Scope and objectives

Anchored in the framework of the 2030 Agenda for Sustainable Development, the 17 Sustainable Development Goals (SDGs) serve as a collective blueprint for tackling pressing global challenges—ranging from eradicating poverty and promoting equitable education, to fostering economic growth and safeguarding terrestrial and aquatic ecosystems. A critical concern emerging from these ambitions is land degradation (LD), a phenomenon that undermines productivity and weakens resilience against the backdrop of mounting climate and environmental pressures. Recognizing this, the United Nations Convention to Combat Desertification (UNCCD) and the SDGs have elevated the fight against land degradation to a global priority.

Central to these efforts is SDG 15, 'Life on Land', and its explicit target 15.3: achieving Land Degradation Neutrality (LDN) by 2030. Realizing LDN requires robust and ongoing monitoring of land's biophysical and biochemical states, as degradation can manifest through abrupt disturbances—such as urban expansion or deforestation—or through gradual declines in soil and land quality [1]. At the scale required for effective intervention, traditional ground-based methods become impractical, thus positioning Earth Observation (EO) technologies at the forefront of global monitoring. Nevertheless, the reliance on EO is not without its hurdles, including the need for higher resolution (both spatially and temporally) and the integration of diverse sensor data [2].

To confront these limitations, the Sentinels for Land Degradation Neutrality (SEN4LDN) project was conceived. This initiative developed innovative methodologies to enhance the spatial and temporal resolution of EO data crucial for land degradation monitoring. Recognizing the diversity in local conditions and degradation drivers, SEN4LDN placed strong emphasis on collaborating with regional partners, so-called 'Early Adopters'. Their involvement was instrumental in defining user requirements and validating the final products for their practical utility in SDG 15.3.1 reporting.

This final report encapsulates the essence of the SEN4LDN project—providing a comprehensive overview, detailing the objectives and activities of each work package, summarizing the principal achievements, and articulating recommendations to guide future advancements in land degradation monitoring using high resolution satellite remote sensing data.

1.2 Document structure

The document is structured as follows:

- Chapter 2: SEN4LDN project overview
- Chapter 3: Work package descriptions and activities
- Chapter 4: Main project results
- Chapter 5: Discussion and future recommendations
- Chapter 6: Conclusions

2 Project overview

2.1 Objective

The primary objective of the Sentinels for Land Degradation Neutrality Monitoring (SEN4LDN) project was to develop, demonstrate and validate a robust and scientifically-sound EO methodology that exploits the high frequency and spatial resolution of open and free-of-charge satellite imagery to increase the spatial details of national assessments of land degradation and restoration, and provide synoptic information for countries to plan LDN interventions at appropriate scales.

2.2 The SEN4LDN consortium

The SEN4LDN project consortium consisted of VITO (Belgium) as the prime contractor, collaborating with Lund University (Sweden), GFZ (Germany), Wageningen University (The Netherlands), and Conservation International (USA). The team comprised of European experts in the domain of LDN monitoring and its sub-indicators such as land cover change mapping, productivity mapping and carbon stocks. Furthermore, the team specializes in cloud agnostic implementation, independent validation, user engagement and production of EO products at continental to global scale. Conservation International joined the team as external service provider bringing in the Trends.Earth open-source software knowledge and its extensive user network. The main responsibilities of and tasks executed by each project partner are listed in Table 1, together with the names of the people most involved.

Table 1: SEN4LDN team and responsibilities

Partner	Main responsibilities and tasks executed	Key personnel
VITO	▪ General project management ▪ Development of trends in land cover workflows ▪ Validation of the trends in land productivity national demonstration products ▪ Implementation of the integrated EO solution ▪ National demonstrations and use cases ▪ Promotion and outreach ▪ Project conclusions and recommendations for future development	Ruben Van De Kerchove Daniele Zanaga Giorgia Milli Carolien Toté
Lund University	▪ Development of trends in land productivity workflows ▪ Follow-up of national demonstrations and results analysis ▪ Support the development of Early Adopter use cases ▪ Support the recommendations for future developments	Lars Eklundh Zhanzhang Cai
GFZ	▪ Lead the user engagement and requirements engineering) ▪ Development of trends in carbon stocks workflows ▪ Follow-up of national demonstrations and results analysis ▪ Support the development of Early Adopter use cases ▪ Support the recommendations for future developments	Martin Herold Katja Berger
Wageningen University	▪ Define requirements for product validation ▪ Lead product validation plan ▪ Validation of trends in land cover national demonstration products ▪ Support promotion and outreach	Nandika Tsendbazar Panpan Xu

Conservation International	▪ Support the development of Early Adopter use cases ▪ Support the recommendations for future developments ▪ Support promotion and outreach	Alex Zvoleff Gabriel Daldegan

2.3 Milestone and review meetings

The SEN4LDN project started with a kick-off meeting on 4 October 2022 at ESRIN, Frascati (IT) and final outcomes were presented at the final review meeting on 21 January 2025 at ESRIN, Frascati (IT). An overview of all project milestone (and review) meetings can be found in Table 2.

Table 2: Overview of SEN4LDN milestone meetings

Milestone	Purpose	Date	Place
MS0	Kick-off (KO)	04/10/2022	ESRIN
MS1	Requirement Review (RR)	07/07/2023	Video conference
MS2	Preliminary Design Review (PDR)	28/11/2023	Video conference
MS3	Critical Design Review (CDR)	06-07/05/2024	ESRIN
MS4	Production Readiness Review (PRR)	06/09/2024	Video conference
MS5	Demonstration Assessment Review (DAR)	17/12/2024	Video conference
MS6	Final Review (FR)	21/01/2025	ESRIN

2.4 SEN4LDN Early Adopters and Living Labs

SEN4LDN engaged with 3 pilot countries to participate to the project as early adopters providing access to local calibration and validation data sets & help defining, validating and assessing the utility of the SEN4LDN EO products and system:

- Ministry of Environment and Sustainable Development (MESD), Colombia
- Busitema University (BU), Uganda
- Institute for Conservation of Nature and Forests (ICNF), Portugal

The project was organized into two distinct phases: (1) User co-creation phase, and (2) User uptake phase. The first phase consisted of designing a continuous feedback interaction with 3 early adopters in a Living lab (LL)[1] approach. This allowed us to identify user and SDG requirements, technical limitations and expectations and to prototype the products and algorithms developed during the project. Prototype products consisted of EO derived datasets for the three land degradation sub-indicators and a combined indicator for a reduced region of interest (i.e. a few Sentinel-2 tiles). These were made available for visual

[1] What are living labs, European Network of Living Labs, https://enoll.org/about-us/what-are-living-labs/

inspection in a web interface and were downloadable by the early adopters for in-depth analysis. The second phase consisted of implementing, delivering and showcasing the EO solution at national scale (see also a description of national demonstration products in §4.3.1) for the early adopters to gather their feedback for iterative development cycles and to inspire and encourage an active engagement with the user community and encourage uptake of the developed EO-solution.

An overview of the LLs is given in Table 3. The first LL focused on collecting user requirements and early adopter expectations using a structured interview approach. These interviews aimed to collect an overview of the LDN activities in the country as well as the user requirements for each of the SDG 15.3.1 sub-indicators. During the second and third rounds of SEN4LDN LLs, we collected the feedback from the three early adopter countries for (i) the prototype products (2nd LLs, March & April 2024) and (ii) final products (National Demonstrations or 3rd LLs in November 2024). In addition, an Open Stakeholder Living Lab (OSLL) was organized on 20 January 2025, to gather the early adopters and the SEN4LDN advisory board and to present and discuss the results of the project.

Table 3: Overview of SEN4LDN living labs for stakeholder engagement

ID	Purpose	Date	Place
LL1	Early Adopter Co-Design Living Lab	08/03/2023 (BU, Uganda) 24/05/2023 (MESD, Colombia) 07/06/2023 (ICNF, Portugal)	Video conference
LL2	Early Adopter Proof of Concept Living Lab	26/03/2024 (BU, Uganda) 08/04/2024 (ICNF, Portugal) 09/04/2024 (MESD, Colombia)	Video conference
LL3	Demonstration Assessment Living Lab	18/11/2024 (ICNF, Portugal) 19/11/2024 (BU, Uganda) 19/11/2024 (MESD, Colombia)	Video conference
OSLL	Open Stakeholder Living Lab	20/01/2025 (all)	ESRIN / Video conference

2.5 Advisory Board

A project Advisory Board was setup, consisting of representatives from authoritative organisations and leading experts in the SDG 15.3.1 application domain, to provide guidance and advice to the project tasks. The members of the SEN4LDN Advisory Board were:

- GEO-Land Degradation Neutrality (GEO-LDN): Neil Sims, Bernd Eversmann
- United Nations Convention to Combat Desertification (UNCCD): Brian O'Connor, Sara Minelli
- World Overview of Conservation Approaches and Technologies (WOCAT): Cesar Luis Garcia
- Universität Bern/Centre for Development and Environment (CDE): Ingrid Teich
- EARSC / SEF: Mónica Miguel Lago

Dedicated meetings were held with the Advisory Board on 28 February 2023, 7 May 2024 (linked with the CDR, see §2.3) and 21 January 2025 (linked with the FR, see §2.3).

3 Work package description and activities

3.1 WP1 – User Characterisation, Engagement and Requirement Engineering

The main objectives of Work Package (WP) 1 were to engage Early Adopters, set-up a Project Advisory board, review the SDG framework, the current technical and user requirements and select test sites, use cases, and national demonstrations. This also encompassed the organization of an Early Adopter Co-Design Living Lab (see §2.4). This resulted in collaboration agreements with the Early Adopters (D1.1, see §4.3.3) and a Requirements Baseline document (D1.2, see §4.3.3, publicly available online). The outcomes of WP1 were presented at the RR meeting on 7 July 2023 (see §2.3).

Partners involved: GFZ (lead), VITO, ULUND, WU

3.2 WP2 – Algorithm Development

Within this WP, all input data sets (satellite, ancillary, and national data) needed for the algorithm trade-off and proof of concept, for the national demonstrations and for the Early Adopter Use Cases were collected, quality checked and pre-processed. In addition, several candidate algorithms for land cover change monitoring and productivity dynamics were selected and benchmarked on the test sites. Automated methods to map land cover, land cover changes and land productivity dynamics at high spatial resolution were developed. Also the feasibility of accessing information on carbon stocks at high spatial resolution was assessed, and an integrated land degradation monitoring system was developed. Methods were adapted to the Good Practice Guidance of SDG Indicator 15.3.1 [3]. Finally, the quality, robustness, scalability and transferability of the selected algorithms were assessed through a Proof of Concept (PoC). The PoC was discussed with the Early Adopters during the Early Adopter Proof of Concept Living Lab (see §2.4).

This resulted in an Input Data Inventory (D2.1, see §4.3.3), PoC results (D3.1, see §4.3.3) and the Algorithm Theoretical Baseline Document (ATBD) (D3.2, see §4.3.3, publicly available online). The (intermediate) results of WP2 were presented at the PDR on 28 November 2023 and the CDR on 6 and 7 May 2024 (see §2.3).

Partners involved: VITO (lead), ULUND

3.3 WP3 – Algorithm Implementation

The aim of WP3 was to develop the EO solution, implement the selected SDG algorithm(s) into end-to-end processing workflows, and integrate the processing workflows into a processing system on a cloud computing / High Performance Computing (HPC) infrastructure for an optimised and scalable processing solution.

In SEN4LDN, workflows were developed and implemented to generate output products to evaluate trends in land cover and trends in land productivity at 10m spatial resolution based on Sentinel-2 L2A inputs and ancillary data. These products were further combined in an indicator for land degradation neutrality that can be used for SDG 15.3.1 reporting. During the course of the project, and in view of the recent developments and broad uptake by the user community, it became clear that it would be highly valuable to integrate the optimized workflows –currently available in Python– into the openEO platform (https://openeo.cloud/) as user defined processes (UDP). However, this was not foreseen in the main contract and the SEN4LDN project budget did not suffice to cover the openEO implementation of complex algorithms and workflows. This means that at this stage the code can in principle be shared with potential external users, but with limited reusability.

However, some first steps were already taken to integrate the SEN4LDN workflows in openEO. A first version of the LC pipeline was implemented (and tested) in openEO, but verification is still lacking, and the last algorithm updates performed within the SEN4LDN contract were not yet included (e.g. recursive post-processing for consistent land cover change mapping). TIMESAT was tested in openEO, but the full Trends in Productivity pipeline was not integrated. In addition, the combination of the sub-indicators into the LDN indicator on SDG 15.3.1 (using the one-out-all-out or the continuous approach) was not yet integrated in openEO.

This means that at this point, only draft deliverables on the Technical Specification (D4.1) and Open source software and associated documentation (D4.2) are available. A mock-up of the EO solution was presented at the CDR on 6 and 7 May 2024, and the final solution, albeit without full openEO integration (see above), was presented at the PRR on 6 September 2024 (see §2.3).

Partners involved: VITO (lead), ULUND

3.4 WP4 – National Demonstrations

The objective of WP 4 was to produce large-scale demonstration products over the selected pilot sites and conduct a comprehensive validation of the output products on each pilot site. In addition, the societal return of the project was maximized by assessing (i) how the novel EO solution developed by the project can be integrated into SDG practices and (ii) the capacity of the target SDG stakeholders to respond to the SDG challenges that the project is addressing can be improved. Finally, SDG-relevant applications were showcased, by conducting several use case studies with the SDG Early Adopters to demonstrate the utility of the EO datasets produced during the national demonstrations.

The results of national demonstrations (D5.1, see §4.3.3, publicly available online) are available for exploration and download. A Google Earth Engine (GEE) web application for national demonstrations products exploration is available at: https://vitorsveg.users.earthengine.app/view/sen4ldn. Products can be downloaded from www.zenodo.org. In addition, a condensed Product User Guide (PUG) is available, with the aim 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 SEN4LDN Early Adopters or other interested users to interpret these products. The 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.

The Product Validation Report (D5.2, see §4.3.3, publicly available online) presents the product validation plan and the qualitative validation results of the output products. Finally, the Demonstration Utility Report (D6.2, see §4.3.3) focused on the suitability and usefulness of the new EO solution developed by the SEN4LDN project, gathering the analysis of the impact and utility of the EO solution, a description of the use cases and related SDG goals, the detailed results of the use cases executed on the demonstration products with practical showcases of their SDG relevance, and the user appraisals on the product utility done by the SDG Early Adopters.

The national demonstrations were presented and discussed with the Early Adopters during the Demonstration Assessment LL and the OSLL (see §2.4).

Partners involved: VITO (lead), ULUND, WU, GFZ

3.5 WP5 – Promotion and Outreach

Promotion and outreach activities are concentrated in WP5, aiming at increasing the awareness of the project as well as the dissemination of results. Here, key SDG stakeholders and international operational programmes will be engaged that can support the appropriation of the developed EO solution by the SDG community. The outreach activities performed during the project and planned for the near future are listed in §4.5.

Partners involved: VITO (lead), ULUND, GFZ, WU

3.6 WP6 – Roadmap

The goal of WP6 was to facilitate the operational uptake of the EO solution by the SDG Early Adopters and promote its adoption within the target SDG community. This includes the elaboration of a roadmap with all necessary steps needed to transfer the EO solution into a sustainable environment.

The SEN4LDN User Handbook (UHB) (D8.1, see §4.3.3, publicly available online) 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). Specific use cases in each use case 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. In addition, a mock-up containing all necessary input for the generation of a Policy Briefs for SDG decision makers (D8.2, see §4.3.3) was prepared and delivered.

We engaged with the user community in an Open Stakeholder Living Lab organized on 20 January 2025 (see §2.3) to assess the adequacy of the EO solution to respond to the needs of the SDG stakeholders and to identify elements for recommendations and outlook analysis.

Partners involved: VITO (lead), GFZ

3.7 WP7 – Project Management

The objective of WP7 was to manage the overall activity of the project to ensure that all tasks are executed in a coherent, consistent, and efficient manner and to ensure communication with ESA. To reach this goal, in addition to the milestone and review meetings (see §2.3), in total 6 consortium progress meetings were organized, for which minutes of meetings were provided. Furthermore, numerous technical sync meetings were held to align technical developments, deliverable preparation etc.

This final report (D8.3, see §4.3.3, publicly available online) provides a complete description of all the work done during the project. The Contract Closure Document (D8.4, see §4.3.3) is still to be delivered.

Partners involved: VITO

4 Main results of the project

4.1 Requirements analysis

For user characterization and aligning the user requirements, SEN4LDN adopted an engagement strategy based on a Living Labs (LL) approach which consists of continuous engagement with potential users and stakeholders during the various phases of the project development. We defined a core group of SDG Early Adopters: BU, Uganda; MESD, Colombia; and ICNF, Portugal (see §2.4). On one side, these early adopters were provided access to prototype versions of the SEN4LDN LDN monitoring data products and were invited to periodically meet and discuss them to provide feedback and insights that were used for product development. On the other hand, they assisted us in identifying areas of interest and relevant data sources that can be used for validating our products in their areas of interest which helped us to demonstrate their applicability and to develop ready-to-use SDG 15.3.1 indicator data products.

The first Early Adopter Co-Design LL aimed to gather an overview of the user requirements and in our view, provided an excellent overview of these. A very significant outcome was that all early adopters provided an insightful overview of what are the drivers of LD in their countries and how diverse the challenges to monitor it can be. For example, both Colombia and Uganda identified illegal activities such as illegal logging or mining as playing a significant impact in LD for their countries. Portugal, on a different note, stated that increasing high intensity greenhouse agriculture is potentially reducing the amount of water availability in other locations which in their view is impoverishing the ecosystem and increasing LD. Another interesting point made by the Portuguese early adopters was that much of the “greening” in Portugal is not necessarily as positive as is expected by the current models because these often reflect growth of monocultures, unmanaged shrubs and forest and potentially invasive alien plants. Another very important outcome from the first LL sessions was that each of the early adopters identified a number of potential “case-studies” in their countries that have both a technical value for SEN4LDN but also a potential scientific value for the field of LD monitoring through EO.

Overall, there was agreement for a need for higher temporal and spatial resolutions products as proposed by SEN4LDN, especially based on Sentinel-2 data. Improving the ability to monitor each of the SDG 15.3.1 sub-indicators have different challenges and opportunities.

Land cover (LC) mapping has seen great improvements in recent years with the advent of novel AI methods and computational solutions alongside new commercial and non-commercial EO sensors. Access to these innovative techniques varies strongly by country, and there is a need for a uniform approach and resulting data products. Improvements in this sub-indicator will affect all other sub-indicators by allowing stakeholders to more accurately discriminate classes and identify areas of negative or positive changes in the landscape. SEN4LDN aimed to address these challenges by improving on the established ESA WorldCover algorithm [4], resulting in accurate and meaningful LC datasets at Sentinel-2 resolutions.

In terms of Productivity, because a continuous monitoring of a vegetation index is required, temporal resolution has been the main bottleneck for long term monitoring, as optical EO data is particularly vulnerable to cloud cover and other atmospheric effects, and temporal frequency of high-resolution satellite data has not been at the same level going backwards in time. From 2018 onwards, Sentinel-2 offers this capability globally. All SDG Early Adopters showed interest in having intra-seasonal estimates of productivity as this is important to identify classes such as crop types, seasonal variations and changes in vegetation covers. Here SEN4LDN offers an integrated approach based on TIMESAT and Sentinel-2 data alongside auxiliar datasets such as rainfall and temperature to generate time series of productivity at resolutions of 10m and sub-annual data products which is in-line with user requirements.

Carbon stocks are the most challenging SDG 15.3.1 sub-indicator to monitor as these can be interpreted as a combination of two different estimates: above-ground biomass (AGB) and soil organic carbon (SOC). Each of these aspects has different challenges to monitor and estimate, for example while AGB can vary greatly within a year, e.g. a crop growing season, it can also be monitored through EO. SOC on the other hand, can be hard to monitor through EO often varies slower than AGB and can remain relatively consistent with big changes in SOC being often caused by human driven LC change (e.g. deforestation or agriculture interventions). AGB monitoring can be improved with using specific satellite mission data and products (i.e. CCI Biomass, GEDI) and higher spatial and temporal resolution of both LC and Productivity monitoring which are both objectives of the SEN4LDN. SOC estimates can benefit both by these higher resolution products by increasing the ability to discriminate between classes and inter-seasonal variations of crops but will necessarily benefit by the integration of field sampling data collected by national authorities, an avenue that SEN4LDN can explore for further improving the estimates of carbon stocks in time and space.

Furthermore, all SDG Early Adopters stated that increasing the temporal resolution would improve their ability to monitor seasonal and possibly sub-seasonal changes which can be critical to effectively identify land degradation and its causes. In this context, examples provided related to the ability to detect events such as seasonal crops or catastrophic events such as fires are very relevant for effective monitoring of LD. Other aspects of the data products, such as validation procedures, delivery mode, data formats, licensing and documentation were discussed and detailed in the Requirements Baseline document (D1.2, see §4.3.3, publicly available online).

4.2 Technical developments and achievements

SEN4LDN aimed to improve LDN monitoring using high resolution Sentinel data. A novel approach was developed and showcased to improve both the spatial and temporal resolution of the data required. The Good Practice Guidance for SDG indicator 15.3.1. involves three sub-indicators: (1) assessment of land cover and land cover changes; (2) analysis of land productivity and trends; and (3) Determination of carbon stocks values and changes.

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.

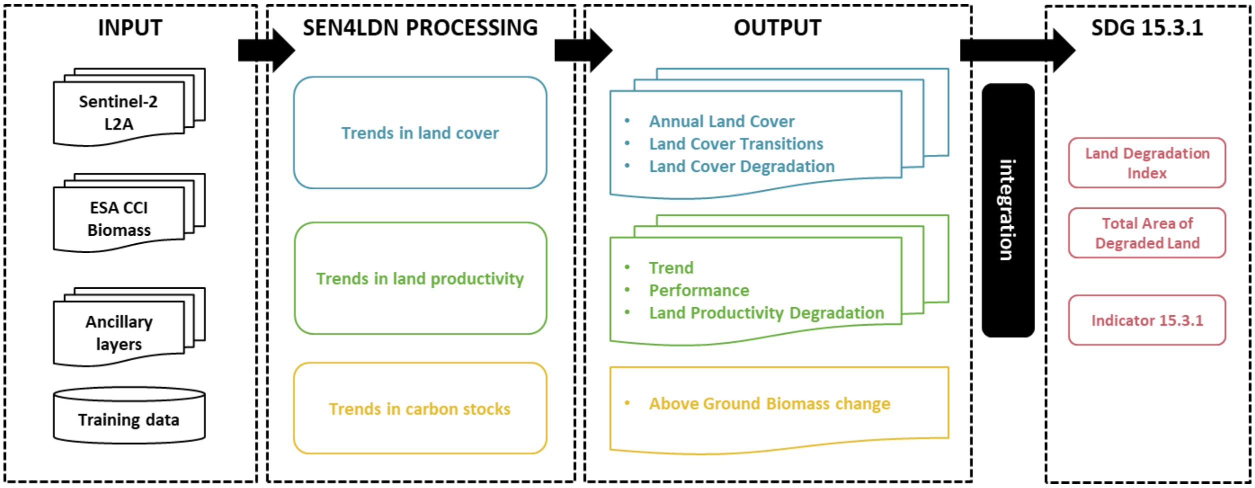

Figure 1: General concept of the SEN4LDN EO solution for reporting on SDG indicator 15.3.1

For the first sub-indicator, trends in land cover between 2018 and 2023 are evaluated based on an automated algorithm to map land cover dynamics at 10 m resolution that combines deep learning and a pixel classifier on pre-processed Sentinel-2 imagery and ancillary input layers. Post-processing is performed to mitigate class fluctuations, resulting in consistent annual land cover maps. Land cover probabilities are used to generate land cover transition (probability) layers, that are further processed to discrete and continuous land cover degradation products. The final output products in the SEN4LDN national demonstrations are annual land cover maps for the time series 2018 to 2023, 2018-2023 land cover transition map, 2018-2023 land cover degradation (LCD) map, and 2018-2023 land cover degradation probabilities (LCD-PROB).

To evaluate trends in land productivity, the seasonal accumulated production of green biomass is estimated from a Sentinel-2 derived vegetation index, which is an indicator for photosynthetic activity and overall ecosystem functionality. The performance of vegetation productivity is based on comparison of the local productivity to similar land units over a larger area. Discrete and continuous land productivity degradation maps at 10m spatial resolution are generated based on the combination of the former two. Besides intermediate products on trends and performance, the final output products in the SEN4LDN national demonstrations are a land productivity degradation (LPD) map and a continuous land productivity degradation index (LPD-INDEX).

The concept of carbon stocks in terms of LDN assessments is primarily related to the soil carbon pool and related changes. However, since soil organic carbon (SOC) stock change estimates from remote sensing are not readily available (yet), SEN4LDN explored the use of above-ground biomass (AGB) changes as a proxy for carbon stock changes to provide an estimate at 100m spatial resolution, independent of the other two sub-indicators. Two research demonstration approaches were combined into a hybrid method to quantify trends in carbon stocks: a stock change approach based on ESA CCI biomass maps, and a gain-loss approach based on a carbon flux model.

The output products for the first two sub-indicators were validated. Land cover validation used national and global datasets with 70-90% accuracy. Land cover change was validated for Uganda collaborating with national experts while for Portugal and Colombia, a comparison with similar national datasets was conducted. Validation of land productivity trends indicated high internal consistency, particularly in

Portugal and Uganda, with some challenges in Colombia due to atmospheric and topographical factors. Details on the validation process and outcomes are available in the Product Validation Report (PVR) (see §4.3.2).

Finally, the outputs of the trends in land cover and trends in land productivity sub-indicators were integrated 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 (Figure 2). Since the trends in carbon stocks output products cover a different time frame and are provided at a different spatial resolution, the integration was performed on the trends in land cover and trends in land productivity sub-indicator products only. In SEN4LDN two methods were tested: (1) the so-called one-out-all-out (1OAO) in which a significant reduction or negative change in any one of the sub-indicators is considered to comprise land degradation, resulting in a discrete land degradation (LD) neutrality map, and (2) 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 (LD-index). This allows for a more in-depth interpretation of the combined product, including an assessment of the magnitude or probability of degradation and improvement, and for an interpretation of possible contrasting sub-indicators.

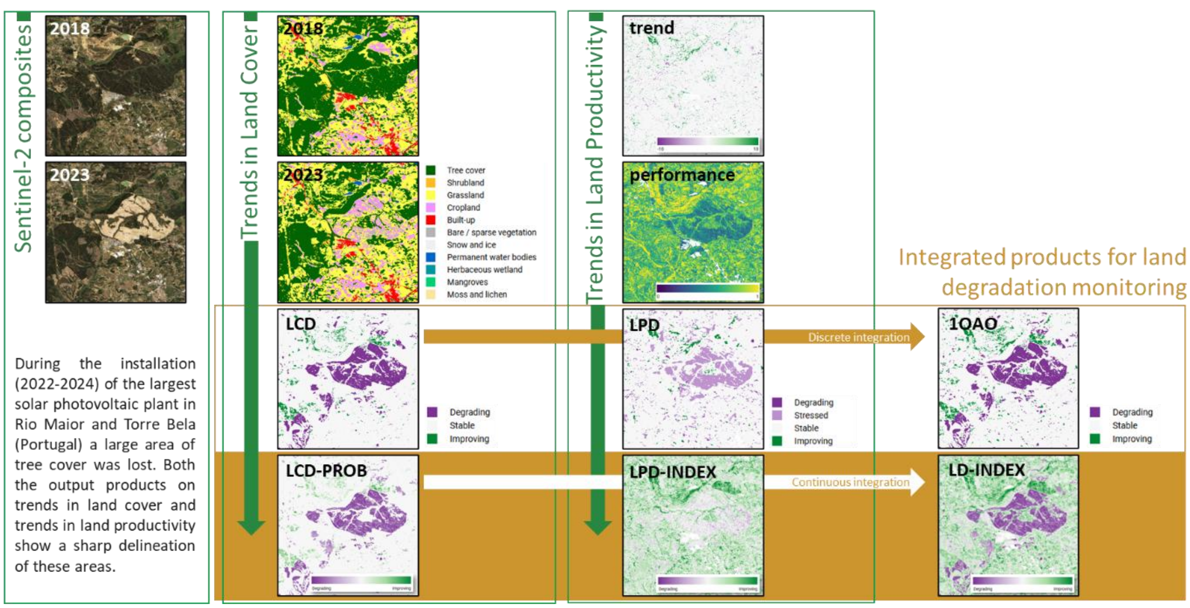

Figure 2: Example of the SEN4LDN workflow to generate integrated products for land degradation monitoring

4.3 National demonstrations and Use cases

4.3.1 National demonstration products

National demonstration products were generated over the three use case countries: Uganda, Portugal and Colombia (see e.g. Figure 3). These products, including a Product User Guide (PUG), Algorithm Theoretical Baseline Document (ATBD) and Product Validation Report (PVR), are available for download as digital datasets.

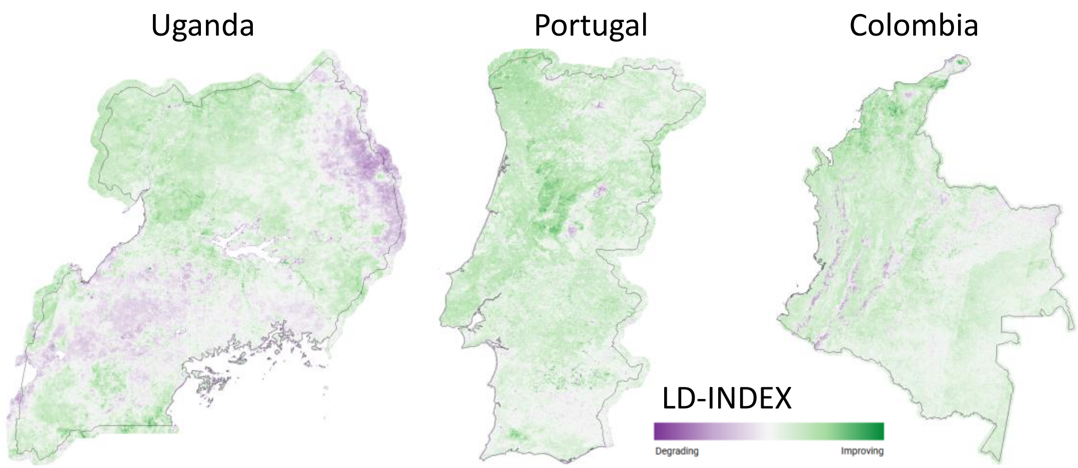

Figure 3: One of the SEN4LDN national demonstration products: Continuous Land Degradation probability index (LD-index) over Uganda, Portugal and Colombia. The LD-index is based on a continuous sub-indicator integration method that combines the continuous land cover degradation and land productivity degradation products.

The Google Earth Engine (GEE) web application for national demonstrations products exploration is available at: https://vitorsveg.users.earthengine.app/view/sen4ldn. Users are encouraged to read the condensed PUG, available online. The objective is to provide the necessary background information on the national demonstration products that are provided in the GEE web application, to allow the SEN4LDN Early Adopters or other interested users to interpret these products. The 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, some guidance on the usage of the GEE web application is provided.

The national demonstration output products are published and available for download on www.zenodo.org.

Table 4: SEN4LDN national demonstration output products download links

Product family	Products	Link
Trends in Land Cover	Annual Land Cover Maps (LCM) Land Cover Transition (LCT) Land Cover Degradation (LCD) classes Land Cover Degradation Probabilities (LCD-PROB)	https://doi.org/10.5281/zenodo.14223152
Trends in Land Productivity	Values of trend coefficient of productivity Classes indicating trend / no trend Maximum performance over the land cover class reference Classes of performance indicating degradation / no degradation Land productivity degradation classes	https://doi.org/10.5281/zenodo.14230324
Trends in Carbon Stocks	Hybrid AGB Average Hybrid AGB Standard Deviation	https://doi.org/10.5281/zenodo.14274475
Indicator for SDG 15.3.1	Land Degradation Neutrality indicator	https://doi.org/10.5281/zenodo.14283566

4.3.2 Product validation

The validation methodology and results for the SEN4LDN products, focusing on land cover (LC) and land productivity trends in Uganda, Portugal, and Colombia, is summarized in the Product Validation Report (PVR) (D5.2, see §4.3.3, publicly available online). The validation of SEN4LDN products focuses on land cover and land cover change (LCC) maps, as well as trends in land productivity. The validation procedures include several aspects. For the validation of land cover, the primary validation data is derived from the global land cover validation dataset, initially generated for the Copernicus Land Monitoring Service (CLMS). This dataset employs stratified random sampling and includes 21,752 primary sampling units (PSUs) globally. For Uganda, a separate validation dataset was collected due to insufficient samples in the global dataset. Land cover change was validated directly in Uganda using a stratified random sampling design and indirectly in Colombia and Portugal by comparing SEN4LDN LCC maps with national products (MapBiomas in Colombia and COSc in Portugal). The validation of trends in land productivity focuses on the trend and performance products, including visual checks, internal consistency analysis, and indirect validation through qualitative cross-comparison with global products derived from CLMS GDMP 300m.

The SEN4LDN land cover maps showed varied performances across the three countries. The highest overall accuracy was achieved in Colombia (90.1% ± 3.4%), with high accuracies in mapping trees, low vegetation, and wetlands. The overall accuracy in Portugal was 87.0% ± 6.5%, with good performance in mapping crops and low vegetation. The lowest accuracy was observed in Uganda (69.6% ± 5.5%), with significant confusion between low vegetation, trees, and crops. The map performed well in mapping wetlands but had low accuracy for built-up areas and other classes due to limited validation data.

In Uganda, the land cover change map achieved an overall accuracy of 73.7% at the change vs. no change level and 72.9% for specific transition classes. The map performed well in detecting forest-related changes (deforestation and reforestation) but underestimated other changes.

Indirect validation over Colombia and Portugal showed that SEN4LDN LCC maps had a higher percentage of stable/unlikely change areas compared to national products. In Colombia, the SEN4LDN map estimated a more logical change area compared to MapBiomas, while in Portugal, it was more conservative compared to COSc.

The validation of trends in land productivity included visual checks, internal consistency analysis, and indirect validation. Systematic visual analysis indicated no significant spatial artefacts, except for the effect of persistent cloud coverage in some areas of Colombia and Uganda. High internal consistency was found for the products over Portugal and Uganda, with slightly lower consistency in Colombia due to atmospheric and topographical factors. Qualitative cross-comparison with CLMS GDMP 300m showed good agreement between the temporal profiles of TPROD and GDMP, confirming the trend coefficient and trend class.

Overall, the SEN4LDN products demonstrated strong performance in monitoring land degradation neutrality, providing valuable insights for SDG 15.3.1 reporting. The PVR highlights the importance of local stakeholder involvement in product development and validation, ensuring that the final products meet user requirements and are usable for sustainable development monitoring.

4.3.3 Feedback from the early adopters

During the Early Adopter PoC LL (LL2) and the Demonstration Assessment LL (LL3), we collected the feedback from the three early adopter countries for (i) the prototype products (LL2, March-April 2024) and (ii) final products (LL3, November 2024). In addition, an Open Stakeholder Living Lab (OSLL) was organized on 20 January 2025, to gather the early adopters and the SEN4LDN advisory board and to present and discuss the final results of the project.

4.3.3.1 Uganda

From the presentations of the 2nd Living Lab, the Uganda team appreciated the direction and data provided by the new products. However, they raised key issues such as misclassifications in specific areas, like Mount Elgon, and the need for clarification on certain transition categories, such as “inundation” and “agricultural expansion”. They also emphasized the importance of incorporating ground truth data and local knowledge into the product development process and expressed a desire for an interactive tool to facilitate stakeholder input. To address these concerns, possible next steps were discussed, such as a validation exercise for the land cover and change maps involving Ugandan stakeholders, further exploration of Net Primary Productivity (NPP) and Gross Primary Productivity (GPP) to assess productivity trends, investigation of incorporating ground truth data for Aboveground Biomass (AGB) and Soil Organic Carbon (SOC) assessments, and the development of a combined indicator for LDN status in Uganda.

During LL3, the Uganda team expressed overall satisfaction with the improvements in the new SEN4LDN products. While there are still challenges to address, such as misclassifications in areas like banana and coffee plantations and difficulties in classifying wetlands, especially seasonal ones, these issues highlight the complexity of land cover classification. Additionally, the current algorithm's conservative approach to change estimation and the limitations of EO-based products for soil organic carbon estimation pose further challenges.

To enhance the usability of our products, the team emphasized the need for tools to extract data for specific areas, like Uganda, and a user-friendly interface to clip products to specific boundaries. While these requests are beyond the scope of our current project, they offer valuable insights for future developments.

Finally, during the OSLL, the Uganda early adopters stressed the importance of the SEN4LDN project in presenting an opportunity to access and use high spatial resolution datasets, in near-real time. It remains a challenge to match the land cover legend that is commonly used in Uganda, with the broader land cover classes that are used in the SEN4LDN national demonstration products on trends in land cover: (i) plantations and woodlots, tropical high forests, woodland etc. are combined in a more general 'tree cover' class; (ii) the ‘cropland’ class is too general, as it involves both subsistence (mixed) farmland and more uniform mono-cropped commercial farmland; (iii) it would be interesting to differentiate grasslands or shrubs on seasonal wetlands from grasslands or shrubs on the uplands; (iv) similarly, floating vegetation on water bodies should be differentiated from permanent wetlands. It may be necessary to create subclasses that better portray the ecosystem functions of these classes. Reconciling the land cover map legends will have implications for the definition of the transition matrix.

4.3.3.2 Portugal

The Portuguese team provided valuable feedback on the prototype products during LL2. There was some clarification requested on the land cover change methodologies. Mainly, they expressed interest in more detailed land cover classifications and the possibility of identifying non-native invasive species. Portugal is a special case as the natural vegetation is not, or not only forest, but shrubland which also provides a much better protection from fires. We acknowledged the need for a balance between global and national-specific needs. Also, the project's potential to improve upon UNCCD guidelines was highlighted. The Portuguese partners critiqued the UNCCD methodology for not capturing diverse realities, particularly in the case of shrubland loss in Portugal. One user inquired about the use of a full Landsat time series with Sentinel-2 data, while others raised concerns about the limitations of EO data in directly attributing change to degradation.

Finally, it was agreed upon that in possible future developments – beyond the SEN4LDN project – the land cover production team would further explore the disaggregation of crop classes and the feasibility of incorporating national data. The productivity team will consider alternative land productivity indices.

During LL3, the Portuguese partners expressed overall satisfaction with the final products and the progress made. They particularly appreciated the improved land cover classification, although they requested more detailed classes to better represent the diversity of Portuguese landscapes. Additionally, they emphasized the need for more accurate classification of land cover changes and related degradation/restoration processes, especially in croplands and forests/shrublands. Regarding land productivity, they suggested considering a state-based approach for calculations and discussed the limitations of using short-term changes to assess long-term trends. For carbon stock, they requested more information on the methodology and offered to share sample data.

In terms of UNCCD reporting, the partners suggested reconsidering the one-out-all-out methodology and called for more detailed land cover classes and transition matrices. They also emphasized the importance of better representing small-scale regeneration.

Finally, they provided feedback on data access and visualization, suggesting improvements to the GEE app legend and requesting more detailed information on validation methodology and statistical information on land cover degradation, productivity changes, and the final LDN indicator.

During the Open Stakeholder Living Lab, the Portuguese early adopters raised concerns about (i) the spreading of solar panels that jeopardize soil health and future sustainability, (ii) the spreading of irrigated crops in drylands, (iii) increased productivity in areas of hyper intensive monoculture, leading to soil erosion and land degradation, (iv) the need to more clearly identify the degradation or restoration processes and a more reliable land cover transition matrix. Also for monitoring trends in land cover in Portugal, there is a need for more detailed land cover (sub-)classes to analyse land degradation: (i) separate irrigated cropland from non-irrigated cropland; (ii) identification of fruit trees; (iii) differentiate native species and invasive alien species, which are likely to increase the risk and effects of forest fires. On trends in land productivity, there are limitations related to the length of the SEN4LDN demonstration products time series, which is not in line with the UNCCD criteria. For trends in carbon stocks, the Portuguese early adopter is happy with the final result, since they don’t have experience of systematic SOC monitoring.

4.3.3.3 Colombia

The Colombian team provided valuable feedback on the prototype products during LL3. Overall, they expressed enthusiasm for the project and provided valuable feedback. However, they raised concerns about the representation of páramos and wetlands in the carbon stock maps, highlighting the degradation of these ecosystems. They offered to provide an ecosystem map to aid in identifying unrealistic estimations. Furthermore, they inquired about the differentiation between natural and managed grasslands and offered access to Colombian ground reference points for potential improvements. They also highlighted the importance of accurately representing the occidental savannas, which are experiencing significant land cover changes. The importance of high spatial and temporal resolution data and products for effective monitoring in Colombia was emphasized. Besides, they stressed the need for ground validation to fully understand the degradation processes. Regarding soil organic carbon, they expressed concerns about the complexity of the data and suggested collaboration with the International Soil Alliance.

During LL3, the Colombian partners provided valuable feedback on the final land cover classification product. They suggested distinguishing between tree cultivations, agroforestry, and plantations within the tree cover class. They again recommended differentiating between managed pastures and natural grasslands (although this is difficult with EO data). Additionally, they pointed out misclassifications of sugar cane fields and offered a detailed national land cover map for validation purposes. While acknowledging the limitations of the current validation database and land cover classes, the partners expressed overall satisfaction with the project's achievements, particularly the high spatial and temporal resolution of the products.

During the OSLL, the Colombia early adopters stressed the usefulness of the SEN4LDN products, both for SDG reporting and for promotion and implementation of restoration efforts. There are however limitations on land cover classes: for monitoring land degradation, it would be important to differentiate (i) between pastures and natural grasslands, and (ii) between commercial plantations and other land cover classes. Nevertheless, the SEN4LDN demonstration products are very useful to monitor the restoration strategy of the country and to use as baseline to identify and evaluate the impact of restoration projects.

4.3.4 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 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. Use of longer time-series from e.g. Landsat imposes some constraints, because of the coarser acquisition frequency.

There are also **country-specific processes** that are hard to monitor with a globally 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 with the global model and further improve the national scale model training 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 us to evaluate land cover **transition probabilities**, which provide a measure of transition 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 (see §4.3.3) 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, SAR) 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 [3]. 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 on 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 overcome 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.

4.4 Project deliverables

Table 5 provides an overview of the SEN4LDN project deliverables. Publicly available deliverables are available on https://esa-sen4ldn.org/en/deliverables.

Table 5: SEN4LDN project deliverables

Ref.	Deliverable	Publicly available?	Description
D1.1	Early Adopter Collaboration Agreements	No	Signed memorandum of cooperation or exchange of letters between the Contractor and each Early Adopters, which specifies the conditions of the collaboration and the respective contributions from both parties
D1.2	Requirement Baseline (RB)	Yes	Comprehensive review and analysis of the underlying SDG framework addressed by the project, a characterisation of the target SDG User Group and of the SDG needs and challenges, an assessment of how EO can help addressing these needs, a collection and analysis of the SDG requirements to be addressed by the project, a complete list of the technical requirements for the EO solution to be developed and validated, the specifications of the national demonstrations and Use Case studies to be conducted to demonstrate the adequacy, robustness, scalability and usefulness of the proposed solution.
D2.1	Input Data Inventory (IDI)	No	Shared project database (with associated Metadata description) of all the “quality checked” and “pre-processed” input data (i.e., satellite, ancillary and national data) needed for the algorithm development and testing, national demonstrations (including product validation) and Early Adopter Use Cases.
D3.1	Proof of Concept (PoC) results on test sites	No	Outputs of the algorithm cross-comparisons and experimental analyses performed during the algorithm benchmarking, and the results of the selected algorithm(s) generated on the test sites during the Proof of Concept.

D3.2	Algorithm Theoretical Baseline Document (ATBD)	Yes	Detailed specification of all the processing algorithms of the EO solution developed by the project. The ATBD shall include a description of the problem, a summary of the trade-off analyses performed on algorithm and implementation choices, the results of the algorithm benchmarking, testing and proof of concept, a functional description of each selected algorithm with a mathematical specification, and a summary of the algorithm validation.
D4.1	Technical Specification (TS)	No	Technical document that provides the specifications and the architectural design of the EO solution, and of the integration of the processing workflows in an end-to-end processing system on a cloud computing / HPC infrastructure.
D4.2	Open-source software and associated documentation including Software Reuse File (SRF)	No	Software of the EO data processing algorithms published on an open-source repository hosting service (to be agreed with the Agency), with open-source licensing scheme and associated documentation, including a Software Reuse File (SRF).
D5.1	Results of national demonstrations	Yes	The results of the national demonstrations shall contain in a unique dataset all the output products (i.e., SDG maps and derived statistics/indicators) generated on each of the national pilot areas, with an accompanying dataset description document.
D5.2	Product Validation Report (PVR) (validation plan and results on pilot sites)	Yes	Report of the product validation performed on the pilot sites during the User Uptake phase (Phase 2). The PVR shall contain the detailed results of the product validation done during the national demonstrations, with the validation protocols and metrics, the results of the product validation and the cross-comparisons with existing datasets.
D6.1	Demonstration Utility Report	No	Main project deliverable on the suitability and usefulness of the new EO solution developed by the project. The report shall gather in a unique document the analysis of the impact and utility of the EO solution, a description of the use cases and related SDG goals, the detailed results of the use cases executed on the demonstration products with practical showcases of their SDG relevance, and the user appraisals on the product utility done by the SDG Early Adopters.
D7.1	Promotion Material	Yes	Graphically appealing communication material (e.g. brochures, flyers, videos) on project objectives and results.
D7.2	Peer-reviewed scientific publications	Yes	Scientific papers in high impact international scientific journals to maximise the scientific return of project.
D8.1	User Handbook (UHB) (for SDG practitioners)	Yes	Tutorial 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 shall include some references to pilot products (single SDG maps and aggregated statistics/indicators) developed during the project, with the products specifications (including metadata documentation).
D8.2	Policy Briefs (for SDG decision makers)	Yes	Short graphical documents, with a summary of the project objectives, of the relevance for the Sustainable Development Goals, a summary of the results achieved for SDG decision

			makers, and practical showcases of their relevance for the SDG community.
D8.3	Final Report	Yes	Complete description of all the work done during the study and shall be self-standing, not requiring to be read in conjunction with reports previously issued. It shall cover the whole scope of the study, i.e., a comprehensive introduction of the context, a description of the programme of work and report on the activities performed, the main results achieved, and the sustainability roadmap for a successful transfer into user practices and processes.
D8.4	Contract Closure Document (CCD)	No	Deliverable, due at the end of the Contract. For the avoidance of doubt, "end of the Contract" shall mean the finalisation of a series of tasks as defined in a self-contained Statement of Work. The contents of the Contract Closure Summary shall conform to the layout provided in Annex F hereto.

4.5 Outreach activities

Table 6 lists outreach activities to promote the SEN4LDN project and its outcomes.

Table 6: Outreach activities in the frame of the SEN4LDN project

Date	Event	Link
21/02/2024	Blog post entitled "Towards mapping land degradation at high resolution"	https://blog.vito.be/remotesensing/mapping-land-degradation
19/11/2024	UNCCD COP16 Day 8: Science, Technology, and Innovation Day	https://www.youtube.com/watch?v=SkJdTdKi13Q
05/02/2025	EO Africa R&D Facility Webinar on "Mapping Our Planet in High Resolution: Advancing Land Cover and Degradation Monitoring with Sentinel Data"	https://www.eoafrica-rd.org/space-academy/webinars/#webinar18
19/02/2025	Presentation to the EEA Copernicus team	/
04/03/2025	SEN4LDN published as use case on the Earth Observation for Sustainable Development Goals (EO4SDG) website	https://eo4sdg.org/get-more-information/country-use-cases/
23/04/2025	EU Space Support Office Webinar on "Copernicus for Land Degradation, Agriculture and Food Security"	https://www.copernicus.eu/en/events/events/copernicus-land-degradation-agriculture-and-food-security
14/05/2025	UNGGIM:Europe Webinar on "The contribution of Earth Observation to 15.3.1. indicator"	https://un-ggim-europe.org/events/un-ggim-europe-webinar-series-sdg-15-3-1/
06/06/2025	Blog post on "High-Resolution Land Degradation Neutrality Monitoring: Achievements of the ESA SEN4LDN Project"	https://blog.vito.be/remotesensing/high-resolution-land-degradation-neutrality-monitoring-achievements-of-the-esa-sen4ldn-project
24/06/2025	Presentation at the ESA Living Planet Symposium entitled "High Resolution Land Degradation Neutrality Monitoring – Achievements of the ESA SEN4LDN Project" in session F.04.03 Desertification, land degradation and soil management	https://lps25.esa.int/programme/programme-session/?id=A9E20134-C56E-49C1-AA1D-AD7029C5A147
tbd	Journal Paper in preparation, tentative title: "High-resolution land degradation neutrality monitoring with Sentinel-2 – Case studies over Colombia, Portugal and Uganda"	https://onlinelibrary.wiley.com/journal/1099145x

5 Discussion, recommendations and future evolutions

The ESA SEN4LDN project has made significant developments in advancing high-resolution monitoring of land degradation neutrality (LDN) through the innovative use of Sentinel-2 data. 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. By implementing detailed case studies across Colombia, Portugal, and Uganda, the project has demonstrated both the technical feasibility and the practical value of integrating EO into national and regional LDN monitoring strategies. Key achievements include the development of robust methodologies for detecting subtle land degradation trends, improved spatial and temporal resolution of degradation assessments, and enhanced engagement with local stakeholders to refine algorithms.

However, there are still some challenges that require further research and development efforts in the future:

(i) An important limitation of the evolution towards 10m spatial resolution with Sentinel-2 is the lack of a historical archive to respond to UNCCD methodology demands. To expand the time series for monitoring trends in land cover and land productivity backwards in time with e.g. harmonized Landsat input data was not yet explored.

(ii) For some country or region-specific land degradation processes, monitoring with globally applicable methodologies and resulting data products is challenging. Algorithms could be deepened to reach specific thematic detail based on adaptable schemes at country scale, starting from the global dataset, by integration of national (training) data in the process. Disaggregation into more narrow land cover classes is required to respond to specific needs, e.g. monitoring of tree plantations, managed or natural grasslands, commercial farmland, invasive species etc.

(iii) Incorporation of Sentinel-1 SAR data in the workflows would improve the quality of temporal composites that are used as input for land cover mapping and land productivity estimation, since good quality passive satellite observations often lack over areas with persistent cloud cover. This was especially noticeable for specific areas in the Colombia and Uganda national demonstrations.

(iv) Regarding the evaluation of trends in carbon stocks, a drawback of algorithm developed in SEN4LDN based on AGB 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. Further research should also focus on the combination of AGB and SOC products to achieve a measure to monitor total carbon stocks.

6 Conclusion

In summary, SEN4LDN has showcased substantial advancements in the high-resolution monitoring of land degradation neutrality, leveraging the capabilities of Sentinel-2 data and pioneering new approaches to sub-indicator integration and uncertainty quantification. Through targeted case studies in Colombia, Portugal, and Uganda, the project has effectively demonstrated the potential for scalable, robust EO-based methodologies to support LDN monitoring. Continued efforts to address current limitations—such as adapting algorithms to country-specific needs, refining land cover classifications, integrating additional satellite data sources, and harmonizing carbon stock assessments—will be essential for further progress. With ongoing research and collaboration, these developments will contribute to more effective land management in support of SDG 15.3.1.

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