

## CarbComply

Towards multi-decade carbon cycle monitoring solutions supporting legal compliance with new EU regulations

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### Projektbeschreibung

Die Europäische Kommission hat mit der Green-Deal-Agenda und dem europäischen Klimagesetz ehrgeizige Klimaziele für 2050 festgelegt. Die Aktivität befasst sich mit mehreren wichtigen Strategien (EU Forest Strategy, EU Soil Strategy) und Verordnungen (z. B. EU-Verordnung über entwaldungsfreie Produkte (EUDR), Überarbeitung der EU-LULUCF-Verordnung), die sich auf neue Anforderungen für den öffentlichen und privaten Sektor konzentrieren. Ein Schlüsselement ist die EUDR, die darauf abzielt, die durch importierte Waren verursachte Entwaldung zu bekämpfen. Ab Ende 2024 dürfen Unternehmen keine Produkte mehr verkaufen, die aus abgeholzten Gebieten stammen, wobei Verstöße mit empfindlichen Strafen geahndet werden.

Um die in diesen Verordnungen festgelegten Umweltziele zu erreichen, sind die Erdbeobachtungsdaten des Copernicus-Programms von entscheidender Bedeutung. CarbComply zielt darauf ab, innovative EO-basierte Nachweisservices zu entwickeln, die sich speziell auf die oberirdische Biomasse (AGB) und den organischen Bodenkohlenstoff (SOC) als primäre Kohlenstoffspeicher konzentrieren. Das Projekt zielt darauf ab, den gesamten Kohlenstoffkreislauf über einen Zeitraum von mehr als 20 Jahren zu erfassen, wobei die neuesten Fortschritte und Datensätze für eine umfassende Bewertung der Kohlenstoffbilanz einbezogen werden.

Die Entwicklung stützen sich auf zwei Säulen, die sowohl privaten als auch öffentlichen Interessengruppen dienen. Die technischen Entwicklungen werden durch eine starke Einbeziehung der Nutzer von Anfang an begleitet, um in einem iterativen Prozess Methoden zu entwickeln, die den Bedürfnissen der Beteiligten entsprechen. Prototypen werden auf Basis definierter Anwendungsfälle entwickelt, die eine Prüfung und Validierung der Konzepte durch interaktives Feedback ermöglichen. Ein weiterer Schwerpunkt ist das Verständnis der rechtlichen Anforderungen. Die Anwaltskanzlei Cerha Hempel wird dabei helfen, die rechtlichen Anforderungen in technische Spezifikationen für einen EO-Prototyp-Compliance-Dienst umzusetzen.

CarbComply wird sich auf technische Innovationen im Zusammenhang mit dem Kohlenstoffkreislauf konzentrieren, insbesondere auf die oberirdische Biomasse (AGB). Das Projekt wird einen Konzeptnachweis für eine langfristige, konsistente und harmonisierte Zeitreihe der AGB-Dichte (AGBD) unter Verwendung bestehender und neuer Copernicus-Missionsdaten erbringen, u.a. BIOMASS, ROSE-L und CHIME. Die Methodik umfasst Fusionsverfahren für mehrere Satellitensensordaten und die Kalibrierung anhand von Felddaten.

Der zweite Schwerpunkt von CarbComply ist die Verbesserung einer EO-basierten Methode zur Modellierung des

Bodenkohlenstoffs, die ursprünglich für Ackerland in Österreich entwickelt wurde. Die Hauptfaktoren für Veränderungen des organischen Kohlenstoffs im Boden (SOC) werden untersucht und ein Dienst zur kontinuierlichen Überwachung der Bodenqualität und des SOC-Gehalts in Europa entwickelt. Dazu gehört die Analyse von hyperspektralen Satellitendaten. Die daraus resultierende Innovation wird ein Dashboard-Prototyp für die Berichterstattung über die Einhaltung der Vorschriften sein. Das Dashboard wird über einfache Veränderungen der Bodenbedeckung hinausgehen, die Bewertung von AGBD-Trends einbeziehen und eine detaillierte parzellenbasierte Bewertung und Überwachung spezifischer Eigenschaften ermöglichen, um den Bedürfnissen von Interessengruppen in Branchen wie der Holzverarbeitung gerecht zu werden.

## **Abstract**

The European Commission has set ambitious climate targets for 2050 through the Green Deal Agenda and the European Climate Law. The activity addresses several important strategies (EU Forest Strategy, EU Soil Strategy) and regulations (e.g, EU Regulation on Deforestation-Free Products (EUDR), 2023-revision of EU LULUCF Regulation) focusing on new requirements for public stakeholders and the private sector. A key component, among others, is the EUDR which aims to combat deforestation caused by imported goods. Starting from the end of 2024, EU companies cannot sell products originating from deforested areas, with significant penalties for violations.

To meet the environmental goals set forth in these regulations, Earth Observation (EO) data from the Copernicus program is crucial. CarbComply seeks to develop innovative EO-based compliance evidence services, specifically focusing on above-ground biomass (AGB) and soil organic carbon (SOC) as the primary carbon storage pools, constituting over 90% of carbon content. The project aims to address the entire carbon cycle over a period exceeding 20 years, incorporating the latest advancements and datasets for a comprehensive carbon balance assessment.

The project's development will be structured around two pillars, serving private and public stakeholders alike. The technical developments will be guided by a strong involvement of the users from the very beginning to develop methods in an iterative process that fit the needs of the stakeholders. Prototypes will be developed based on defined use cases, allowing for testing and validation of concepts through interactive stakeholder feedback. The development process also includes a focus on understanding the legal requirements relevant to the addressed industry. The law firm Cerha Hempel will help to translate legal requirements into technical specifications for an EO prototype compliance service.

CarbComply will concentrate on technical innovations related to the carbon cycle, particularly above-ground biomass (AGB). The project will provide a proof of concept for a long-term, consistent, and harmonized AGB density (AGBD) time series using existing and new Copernicus mission data. This includes missions such as BIOMASS, ROSE-L, and CHIME. The methodology involves fusion methods for multiple satellite sensor data and calibration using field data.

The second focus of CarbComply is to improve a satellite-based soil carbon modeling method, initially developed for arable land in Austria. The project will review the main drivers of soil organic carbon (SOC) changes and develop a service for continuously monitoring soil quality and SOC content in Europe. This includes the analysis of hyperspectral satellite data. The resulting innovation will be the design of a dashboard prototype for compliance reporting in compliance with the regulations in support of the Green Deal Agenda. The dashboard will go beyond simple land cover changes, incorporating evaluation of AGBD trends and enabling detailed plot-based evaluation and monitoring of specific properties, addressing the needs of stakeholders in industries like wood processing.

## **Endberichtkurzfassung**

(Also attached as a PDF in the "Attachments" section in the side menu)

## Project Summary

The most significant outcomes of the CarbComply project center on the development of a high resolution “Carbon Intelligence Layer”, designed to transform complex EO data into verifiable evidence supporting regulatory compliance.

The project’s key results can be summarized as follows:

### 1. Harmonized Above-Ground Biomass Time Series

One of the project’s key achievements was the delivery of a harmonized, multi-decadal Above Ground Biomass Density (AGBD) time series spanning 1991 to 2024 for pilot regions in Austria and Bulgaria. Developed and validated within an operational environment, the solution successfully demonstrated Technology Readiness Levels (TRL) 6-7, highlighting its strong potential for future large-scale operational deployment. The resulting dataset provides a consistent and scientifically robust foundation for long-term biomass monitoring, carbon accounting, and regulatory compliance applications.

The following sections provide a detailed technical summary of the components and methodologies developed for the AGB element:

#### 1.1 Multi-Sensor "Era" Approach

To ensure long-term consistency while accounting for the significant evolution of satellite technologies over more than three decades, the CarbComply workflow was structured around two distinct processing “eras.” This approach enabled the integration of historical and modern Earth Observation datasets into a harmonized biomass monitoring framework while maintaining methodological continuity across the full time series.

Era 1 (1991 - 2018): Relied on legacy Landsat optical imagery combined with C-band Synthetic Aperture Radar (SAR) data from ERS-1/2 and Sentinel-1 missions.

Era 2 (2019 - 2024): Utilized high-resolution Sentinel-2 optical imagery (10-20 m) integrated with modern L-band SAR data from ALOS-2/PALSAR-2, alongside spaceborne LiDAR measurements from NASA GEDI.

#### 1.2 Data Harmonization and Normalization

A critical component of the CarbComply methodology was the harmonization and normalization of multi-temporal Earth Observation (EO) datasets to ensure consistency across the full monitoring period.

Given the substantial variation in sensor characteristics, atmospheric conditions, and acquisition parameters over time, the project implemented advanced normalization techniques to minimize systemic temporal biases and improve comparability between years.

The project applied Relative Radiometric Normalization (RRN) to harmonize multi-year EO features against a common 2021 baseline. This approach relied on Pseudo-Invariant Features (PIFs), temporally stable reference pixels, such as mature and undisturbed forest areas, which served as structural anchors for cross-temporal calibration.

In addition, harmonic parameterization was applied to optical datasets to model and capture seasonal vegetation dynamics, including NDVI trajectories. This enabled robust cloud-free gap filling, improved temporal consistency, and more efficient data compression while preserving seasonal information relevant to biomass analysis.

### 1.3 LiDAR Integration and Calibration

A central innovation of the CarbComply project was the integration of high-precision LiDAR and field-based reference data to improve the accuracy and reliability of satellite-derived biomass estimates. By combining local ground-truth measurements with advanced remote sensing products, the project addressed systematic biases commonly associated with large-scale biomass estimation and strengthened the scientific robustness of the resulting datasets.

**Field campaigns:** During field activities conducted in Bulgaria in November 2024, Personal Laser Scanning (PLS) technology was used to collect detailed single-tree measurements, including coordinates, diameter, height, and volume. These observations were used to calibrate and validate reference plots for biomass modeling.

**GEDI recalibration:** Biomass estimates derived from NASA GEDI L4A products were recalibrated using local ground-truth datasets in order to reduce biome-specific overestimation and underestimation effects. The final modeling framework adopted a reduced set of Relative Height (RH) metrics, specifically the 74th and 98th percentiles, resulting in a simplified, cost-effective, and operationally robust model structure.

### 1.4 AGB Modeling and Target Variables

To generate reliable and scalable biomass estimates, the CarbComply project implemented a machine learning-based modeling framework centered on the Random Forest algorithm. This approach was selected due to its robustness, ability to handle high-dimensional EO datasets, and strong performance in capturing complex nonlinear relationships between remotely sensed variables and forest biomass characteristics.

Within the modeling framework, two primary target variables were investigated:

**Direct AGB prediction:** AGB density, expressed in Mg/ha, was predicted directly from EO derived features, including optical, SAR, and LiDAR inputs.

**Merchantable volume estimation:** The project also explored the prediction of growing stock volume, expressed in m<sup>3</sup>/ha, which was subsequently converted into AGB values using species-specific Biomass Expansion Factors (BEFs) and wood density parameters in accordance with Intergovernmental Panel on Climate Change methodologies. This approach demonstrated strong potential, as merchantable volume can often be more accurately captured by structural sensing

technologies such as LiDAR and SAR.

### 1.5 Monte Carlo Uncertainty Framework

A key achievement of the CarbComply project was the integration of a Monte Carlo simulation framework directly into the biomass modeling workflow to quantify, track, and propagate uncertainty from input data through to final pixel-level outputs. This approach enabled a shift from deterministic estimates to probabilistic modelling, improving the transparency and statistical robustness of AGB predictions.

Instead of producing single-value outputs, the system generates a full distribution of possible AGB values for each pixel, enabling the explicit derivation and reporting of confidence intervals.

Area aggregation: The project further demonstrated that, although uncertainty at the pixel level can be substantial, aggregating results across larger spatial extents significantly reduces overall error. This scaling effect makes it possible to distinguish meaningful landscape-level structural trends from sensor noise and local variability.

### 1.6 Synthetic Data Feasibility Study

As part of the CarbComply methodology development, the project conducted a feasibility study on the use of fully synthetic multispectral imagery to support model training and enhance data availability. Specifically, synthetic image tiles designed to emulate high-resolution Pleiades-like satellite data were generated and used to train U-Net convolutional neural networks for biomass estimation tasks.

The study evaluated both the potential and limitations of this approach. While the models demonstrated an ability to generalize to real-world imagery, they consistently underestimated AGB values when applied operationally. This bias was primarily attributed to a mismatch in data distributions, as the synthetic training dataset had a substantially lower biomass range (mean approximately 95 Mg/ha) compared to real-world conditions, which exceeded 300 Mg/ha on average.

### 1.7 Achieved Results and TRL Status

Metric

Austria (Direct Model)

Bulgaria (GEDI Adjusted)

Coefficient of Determination ( $r^2$ )

0.4851

0.3642

Relative RMSE

51.63

22.81

Resolution

30m (Era 1); 10m (Era 2)

30m (Era 1); 10m (Era 2)

## 2. Spatially Explicit Soil Organic Carbon Mapping

The CarbComply project successfully advanced satellite-based Soil Organic Carbon (SOC) modelling from traditional point-based observations toward a spatially explicit monitoring framework, reaching TRL 5 to 6. This represents a significant step forward in enabling scalable, repeatable, and policy-relevant soil carbon monitoring using Earth Observation data.

A key outcome of this work was the production of high-resolution SOC maps at 10 m spatial resolution for agricultural areas in Austria and Bulgaria. These datasets were specifically designed to support reporting requirements under the EU Soil Strategy 2030 and the proposed EU Soil Monitoring Law.

The following sections provide a detailed technical overview of the SOC component of the project.

### 2.1 Input Data and Reference Baselines

The SOC modelling framework was built on a combination of in-situ measurements and multi sensor EO data to ensure both spatial coverage and scientific robustness. By integrating harmonized reference datasets with high-resolution satellite imagery, the project established a consistent baseline for spatially explicit Soil Organic Carbon estimation.

**Target variable:** The modelling approach relied on the LUCAS Soil 2018 database, which provides harmonized, EU-wide topsoil measurements. Only observations located within cropland areas were included, resulting in 142 samples for Austria and 276 samples for Bulgaria.

**Predictor variables:** The core spatial predictors were derived from Sentinel-2 multispectral imagery, selected for its 10 m spatial resolution and high temporal revisit frequency, which are well suited for detailed agricultural monitoring.

Ancillary data: Additional explanatory variables included spectral indices such as the Normalized Difference Vegetation Index (NDVI) and Brightness Index (BI), as well as topographic parameters such as elevation. Elevation proved to be a particularly important predictor, especially in the more complex mountainous terrain of Austria.

## 2.2 Bare Soil Composite Workflow

To enable robust retrieval of soil properties from optical Earth Observation data, the project developed a refined Bare Soil Composite (BSC) workflow designed to isolate soil-specific surface reflectance signals and reduce interference from vegetation and seasonal variability.

Temporal aggregation: The workflow combined cloud-free Sentinel-2 observations collected between March and October for the years 2017 to 2019. This seasonal window was selected to maximize the probability of capturing bare soil conditions across agricultural fields.

Vegetation filtering: An automated pixel-based masking approach was applied using the PV+IR2 index to remove vegetation-contaminated pixels, excluding observations with index values greater than 0.65.

Final product: The resulting Bare Soil Composite provides a 10 m resolution, temporally stable, and spatially consistent reflectance dataset, which serves as the foundation for nationwide Soil Organic Carbon estimation.

## 2.3 Modeling Methodology and Performance

SOC modelling framework evaluated multiple machine learning approaches to identify the most robust and transferable solution for spatial prediction across heterogeneous agricultural landscapes. The analysis focused on balancing predictive performance, model stability, and interpretability under limited and noisy training conditions.

The project tested several machine learning algorithms, including Random Forest, XGBoost, and a range of regularized linear models.

Ridge regression: Ridge regression achieved the most reliable overall performance. Its strength lay in effectively managing multicollinearity among spectral predictors while maintaining stable coefficient estimates despite relatively limited training data.

Preprocessing steps: The modelling pipeline included Box-Cox transformations of the target variable to improve normality, along with a weighting scheme designed to improve sensitivity to extreme SOC values and better represent high-carbon soils.

Validation metrics:

Bulgaria:  $R^2 = 0.213$ ; Mean Absolute Error (MAE) = 3.14 g C/kg

Austria:  $R^2 = 0.223$ ; Mean Absolute Error (MAE) = 4.15 g C/kg

Key findings: Model performance was primarily constrained by the inherently complex and multi-factorial nature of SOC dynamics, as well as the limited availability of spatially explicit management data. Despite these limitations, the models successfully captured broad spatial patterns and regional gradients in SOC distribution.

## 2.4 Hyperspectral Feasibility Study

As part of the SOC modelling work, the CarbComply project conducted a feasibility assessment to evaluate the potential added value of hyperspectral Earth Observation data for Soil Organic Carbon estimation. The study focused on determining whether hyperspectral imagery could improve predictive performance compared to established multispectral approaches.

Comparison framework: Models based on Sentinel-2 data were compared against hyperspectral models derived from the Kuva Space Hyperfield-1 sensor, using a subset of 43 ground reference samples.

Outcome: The results showed that Sentinel-2-based models significantly outperformed the hyperspectral approach, achieving an  $R^2$  of 0.458 compared to 0.143 for the hyperspectral dataset and  $R^2$  of 0.433 for the combined model (hyperspectral+multispectral input features).

Technical explanation: This performance difference was primarily attributed to the limited spectral coverage of the hyperspectral sensor, which did not extend into the Shortwave Infrared (SWIR) region that is critical for soil property estimation. In addition, the limited number of hyperspectral acquisitions prevented the construction of multi temporal bare soil composites, further constraining model performance.

## 3. Validated Deforestation Detection Algorithm

The CarbComply project successfully developed and validated a proprietary deep learning based algorithm for deforestation detection, adapting a model originally designed for tropical environments to the specific forest conditions of Central and Northern Europe. This work represents a key advancement in translating EO analytics into operational tools for regulatory compliance.

The resulting algorithm plays a central role in generating the conclusive and verifiable evidence required to support compliance with the EU Deforestation Regulation (EUDR).

### 3.1 Algorithm Architecture

The deforestation detection algorithm is based on the Attention U-Net architecture, a specialized deep learning framework designed for pixel-level image segmentation. This architecture was selected for its ability to capture both fine spatial detail and high-level contextual information, which is essential for accurately detecting forest change in complex landscapes.

Attention gates (AG): Attention mechanisms enable the model to selectively focus on the most relevant features while

suppressing less informative signals. This is particularly important for identifying subtle forest disturbances and rare change events in highly imbalanced datasets.

Encoder and decoder structure: The network follows a standard U-Net design, with a contracting path (encoder) that learns hierarchical representations of forest structure, and an expanding path (decoder) that reconstructs detailed segmentation masks at the same spatial resolution as the input data.

Skip connections: Skip connections link corresponding layers in the encoder and decoder, preserving fine-grained spatial information throughout the network. This ensures accurate delineation of forest boundaries, including clear-cuts and other disturbance patterns.

### 3.2 Input Design and Feature Engineering

The deforestation detection model is designed to process multispectral EO data from Sentinel-2 at a spatial resolution of 10 meters. The input design and feature engineering strategy were developed to maximize sensitivity to forest change signals while minimizing confusion from seasonal variability and atmospheric effects.

Multi-temporal approach: The model evaluates paired satellite observations representing pre- and post-change conditions, enabling explicit detection of temporal differences associated with forest loss events.

Feature stacking: Input data are structured as a multi-channel tensor comprising 10 spectral bands (B02 to B12) from both time steps, ensuring that the model can jointly learn spatial and spectral change patterns.

Derived indices: The framework incorporates NDVI change signals to enhance the detection of vegetation loss. This improves the model's ability to distinguish true deforestation events from natural seasonal variation.

### 3.3 Training and Data Preparation

To support robust model development, the CarbComply project established a rigorous data collection and preparation pipeline, producing a geographically diverse training dataset spanning Germany, Finland, Austria, and Sweden. This ensured exposure to a wide range of forest types and disturbance regimes, improving model generalisability across Central and Northern European conditions.

Dataset size: The model was trained from scratch using more than 10,000 high-quality image patches, each with a spatial resolution of 256 by 256 pixels.

Classification scheme: The algorithm was designed to differentiate between three distinct forest change categories: clear-cut logging, general forest disturbance, and transitions from disturbance to clear-cut.

Sampling strategy: Training samples were selected using hotspot analysis of historical forest loss density, ensuring that the dataset captured a broad and representative range of real-world disturbance patterns in Central and Northern Europe.

### 3.4 Validation Strategy and Performance

To ensure robustness and operational readiness, the CarbComply deforestation detection model was evaluated using a structured three-level validation framework. This approach assessed performance across held-out data, unseen geographic regions, and real-world ground-based observations, providing a comprehensive measure of model reliability.

Level 1 (standard assessment): Using a hold-out test set of 1,036 image patches, the model achieved an overall accuracy of 0.99, with a precision of 0.86, a recall of 0.84, and an F1-score of 0.84.

Level 2 (independent testing): When applied to entirely new geographic regions, the model demonstrated strong transferability, achieving an F1-score of 0.88 in Finland and 0.83 in Germany.

Level 3 (ground-based evaluation): Validation against 51 wood collection points provided by the Pfeifer Group in Bavaria resulted in a precision of 0.83 and a recall of 0.91, confirming strong alignment with real-world operational data.

## 4. Integrated ICT System and API Backbone

The CarbComply project successfully translated advanced EO methodologies into a scalable, cloud-native Integrated ICT System and API backbone, reaching TRL 6 to 7. This system establishes a robust evidentiary infrastructure that enables both public and private stakeholders to address emerging European Union regulatory requirements, including the EUDR and the EU Soil Strategy.

### 4.1 Cloud-Native System Architecture

The CarbComply Integrated ICT System is built on a distributed, containerized architecture using Docker and deployed on Ubuntu-based virtual machines. This setup was designed to ensure scalability, modularity, and efficient processing of large geospatial datasets in a cloud-native environment.

Infrastructure: Core data storage and processing are integrated through the CREODIAS S3 infrastructure, enabling high-performance management of large-scale Earth Observation datasets.

Storage-API-database architecture: The system is built around a structured architecture in which the API acts as an abstraction layer between users and the underlying data infrastructure. It mediates access to both the PostgreSQL database, which stores metadata and indexing information, and S3 object storage, which contains the actual file assets such as GeoTIFF datasets.

Security and monitoring: Authentication and role-based access control (RBAC) are managed through Keycloak. System performance and health monitoring are implemented using Prometheus and Grafana, ensuring continuous observability and operational stability.

### 4.2 Backend API Backbone

The RESTful API serves as the primary technical interface for the CarbComply system and is designed to support seamless integration into external workflows and enterprise systems. It provides a stable and standardized access layer for all core system functionalities and EO-derived outputs.

**Technology stack:** The API is developed in Go and built using the Huma framework, enabling robust data validation, structured serialization, and automatically generated documentation in line with modern API standards.

**Functionality:** The system supports dynamic CRUD (Create, Read, Update, Delete) operations, along with structured data transformations and logging. This ensures consistent handling of key outputs, including deforestation alerts, AGB estimates, and SOC metrics.

**Interoperability:** The API is designed for direct integration with existing Enterprise Resource Planning (ERP) systems, such as SAP, Timbertec, or Osapiens. This enables automated workflows, including streamlined “negligible-risk” assessments in compliance contexts.

### 4.3 Geospatial Database and Spatial Processing

The CarbComply system incorporates a geospatial data management layer built on PostgreSQL extended with PostGIS to support advanced spatial processing requirements. This architecture enables efficient handling, querying, and analysis of large-scale geospatial datasets within a unified database environment.

**Spatial operations:** Spatial computations are executed directly within the database, including spatial filtering, intersection analysis, and geometry processing. This approach reduces data transfer between system components and improves performance for geographically constrained Area of Interest (Aoi) queries. Final output generation, including GeoTIFF creation and stitching, is performed during endpoint execution using GDAL-based processing in Go.

**Standardised formats:** The system supports interoperable data export formats, including GeoJSON, GeoTIFF, CSV, and JSON, ensuring compatibility with external GIS platforms, enterprise systems, and regulatory reporting frameworks.

### 4.4 Prototype Dashboard (Reference Implementation)

As part of the CarbComply system, a web-based dashboard was designed as a reference implementation for visualising EO-derived indicators and illustrating how analytical outputs could be translated into user-facing tools for compliance and decision support.

**Geometry management:** Users would be able to define Aois by entering coordinates, selecting land parcel identifiers (specifically implemented for Austria), drawing polygons directly within the interface, or uploading standard geospatial files such as Shapefiles and GeoJSON.

**Compliance visualisation:** The interface would include a traffic-light indicator system (green/red) providing an immediate

assessment of parcel-level compliance status in relation to the EUDR cut-off date.

Environmental analysis tools: Dedicated modules would allow users to explore AGB change trends over time (1995–2025) and interact with spatial SOC baseline maps.

Automated reporting: The system would generate standardised, audit-ready PDF and CSV evidence packages, including explicit uncertainty metrics such as RMSE and bias, designed to support inspections by Competent Authorities.

#### 4.5 Regulatory and Institutional Integration

The CarbComply ICT backbone has been designed with a strong focus on long-term scalability, interoperability, and regulatory resilience. The architecture ensures that the system can evolve in line with emerging European Union regulatory requirements and future Earth Observation missions, while maintaining compliance with established data governance standards.

TRACES NT alignment: The system roadmap prioritises API interoperability with the EUDR Information System (TRACES NT) to enable the automated submission of Due Diligence Statements (DDS).

Institutional data flow: The architecture follows FAIR data principles and complies with INSPIRE standards, ensuring seamless integration with national environmental registries and the Copernicus Land Monitoring Service (CLMS).

Mission readiness: The system is designed to readily incorporate data from upcoming Earth Observation missions such as ESA BIOMASS (P-band SAR) and Copernicus CHIME (hyperspectral) without requiring structural redesign.

### 5. Legal-Technical Risk Assessment Framework

The CarbComply project successfully established a Legal-Technical Risk Assessment Framework designed to bridge the gap between EO science and the operational enforcement of the EUDR. This framework, delivered primarily through Key Exploitable Results (KER) 2 and 3, enables the translation of biophysical satellite-derived indicators into conclusive and verifiable legal evidence suitable for compliance and audit purposes.

#### 5.1 Statutory Mapping and Technical Alignment

A central achievement of the framework is the systematic translation of raw geospatial data into classifications aligned with regulatory definitions under the EUDR. This ensures that Earth Observation outputs are directly interpretable within a legal compliance context and can be reliably used for enforcement and reporting purposes.

Definition mapping: Technical workflows were aligned with Article 2 of the EUDR, including the formal definition of “forest” as land exceeding 0.5 hectares, with trees higher than 5 meters and a canopy cover greater than 10 percent.

Class differentiation: The system distinguishes between primary forests, naturally regenerating forests, and agricultural plantations, ensuring that only legally relevant land-use changes are classified as deforestation or forest degradation.

Cut-off verification: All algorithms are referenced against the 31 December 2020 cut off date, enabling precise verification of compliance in line with regulatory requirements.

## 5.2 The "Compliance Scale" and Risk Assessment

The CarbComply project introduced the concept of a "Compliance Scale" as a methodological bridge to support structured corporate due diligence under evolving regulatory requirements. This framework provides a graduated approach to evidence assessment, linking the level of required verification to the assessed level of risk.

Evidence proportionality: The framework establishes that evidentiary requirements increase in line with the level of perceived risk, for example when sourcing from higher risk countries compared to lower-risk regions.

Independent ground truth: Within this framework, EO data is positioned as an independent and tamper-resistant source of evidence. It can be used both to substantiate "negligible-risk" claims and to challenge or refute inaccurate allegations of deforestation, particularly in cases where documentary evidence such as supplier declarations is insufficient.

## 5.3 Liability and Strategic Support

The CarbComply framework is designed to directly address the "first operator" liability model, under which the entity placing a product on the EU market for the first time bears full legal responsibility for compliance. To support this requirement, the system provides an independent, high-resolution (10 m) source of truth based on Earth Observation data, enabling more robust and defensible compliance assessments.

This improved quality and traceability of evidence gives operators a stronger basis for risk management decisions and can help safeguard up to 4 percent of annual turnover from potential non-compliance penalties.

### **Projektkoordinator**

- GeoVille Informationssysteme und Datenverarbeitung GmbH

### **Projektpartner**

- Remote Sensing Solutions GmbH
- UMWELTDATA Gesellschaft m.b.H.