Space Business Challenge

Team 4 – Rubber

Rotterdam School of Management

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Meet the team making this project possible

Milan van den Heuvel

Eva Haupt

Jiya Ahuja

Eva Formica

Fabio Grassmugg

Executive Summary

Context & Objective

EUDR requires companies to demonstrate deforestation-free supply chains through traceability and geolocation-based due diligence.

Question: What technologies can help companies comply with EUDR?

Technology Solution

Earth Observation (EO) + Blockchain

- Combine EO with **Hyperledger Fabric** integrated in ERP systems
- EU companies access local dealers' IDs and Asian dealers database with location data
- EO detects deforested regions; dealers within **70km radius** flagged as high-risk

Risk-Based Compliance Model

Competitive Advantage

Current market solutions rely on polygon mapping requiring customers to first map areas.

Our approach: Holistic picture-first analysis that identifies deforested areas— no technological gap exists for deforestation identification.

Critical Implementation Gaps

No technical gap in deforestation detection, but two fundamental barriers make EO a poor business case:

1. **Lack of incentivization** in the upstream supply chain
2. **Lack of legal coordination** at international and national levels alongside missing enforcement mechanisms in Asia

Strategic Recommendation

To strengthen the business case, collaborations between public sector, private sectors, and civil society must redesign EUDR implementation strategy.

- Offer incentives for both downstream and upstream supply chain participants

Market Context

- EU represents **significant but non-dominant** share of demand
- Rubber markets exhibit **diversion capacity**
- Land-use change responds to **global price signals**
- **Leakage risk is non-trivial** in trade-based environmental policy

Key Takeaway

Successful EUDR compliance requires not just technological capability, but systemic redesign addressing upstream incentives and cross-border enforcement to prevent market leakage.

Problem Framing

Under the European Union Deforestation Regulation (EUDR), the placing of commodities and products on the EU market is prohibited if they are associated with deforestation or forest degradation after the established cut-off date. The regulation requires companies to exercise due diligence and ensure that their supply chains are free from deforestation. The objective is to enable companies to independently assess whether their suppliers have engaged in deforestation for the production of imported commodities. In this context, the following research question arises:

How can Earth Observation (EO) technologies support companies in identifying deforestation within their supply chains, and what existing gaps hinder the timely implementation of such technologies?

Two levels of the problem

Compliance

How can companies in the EU trace back the origin of their rubber-based products in accordance to the EUDR compliance obligations ?

Impact

At its core, EUDR aims to decrease deforesstation but how impactful can the EUDR really be ?

Methodology Adopted

1. Map rubber supply-chain structure
Identified key stages and locate where issues occur

2. Identify EO detection capabilities
Assess EO capabilities, and critical areas where it lacks

3. Identify points of identity loss
Analyse where material mixing break farm-level attribution and its implications

4. Compare regulatory expectations with technical reality
Interpret EUDR requirements on origin and deforestation-free status and whether EO outputs satisfy these requirements

5. Explore realistic EO-based contributions
Define boundaries of EO-supported compliance

OVERVIEW

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Rubber Industry Overview

Understanding the industry dynamics and relevant EUDR Criteria

RUBBER INDUSTRY OVERVIEW

Market at a Glance

2024 Market Size

$48.77B

Current valuation

2030 Projection

$65.65B

Forecasted value

CAGR 2025-2030

5.1%

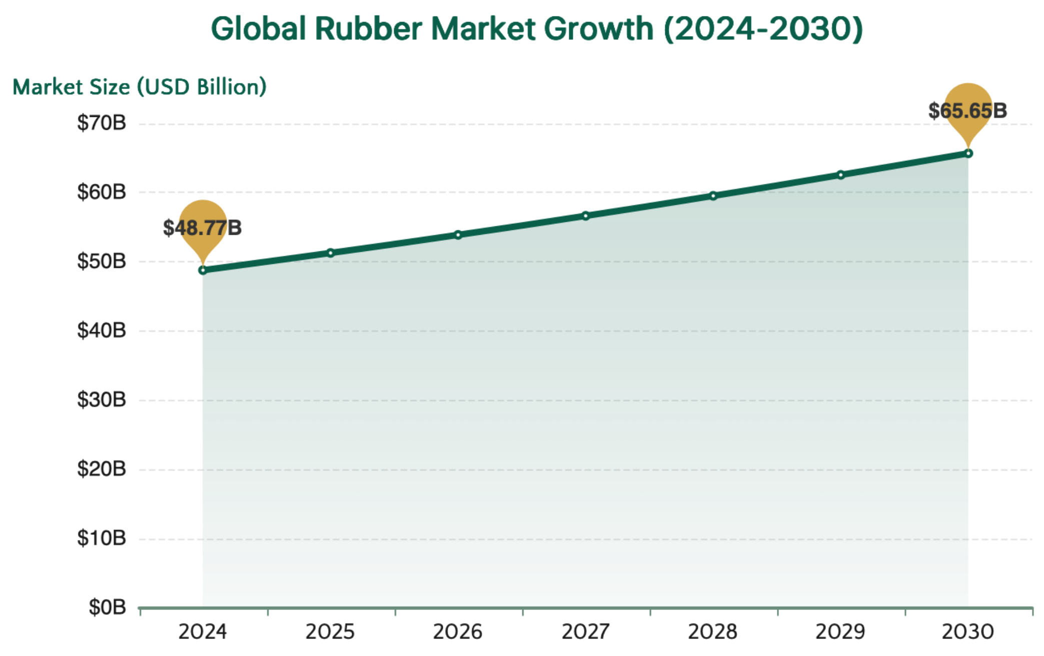
Annual growth rate

Superior Material Properties

- **Abrasion Resistance:** Essential for tire durability and long-term performance in automotive applications
- **Heat Resistance:** Critical for high-performance applications in industrial and automotive sectors
- **Vibration Dampening:** Key characteristic for automotive seals and industrial machinery

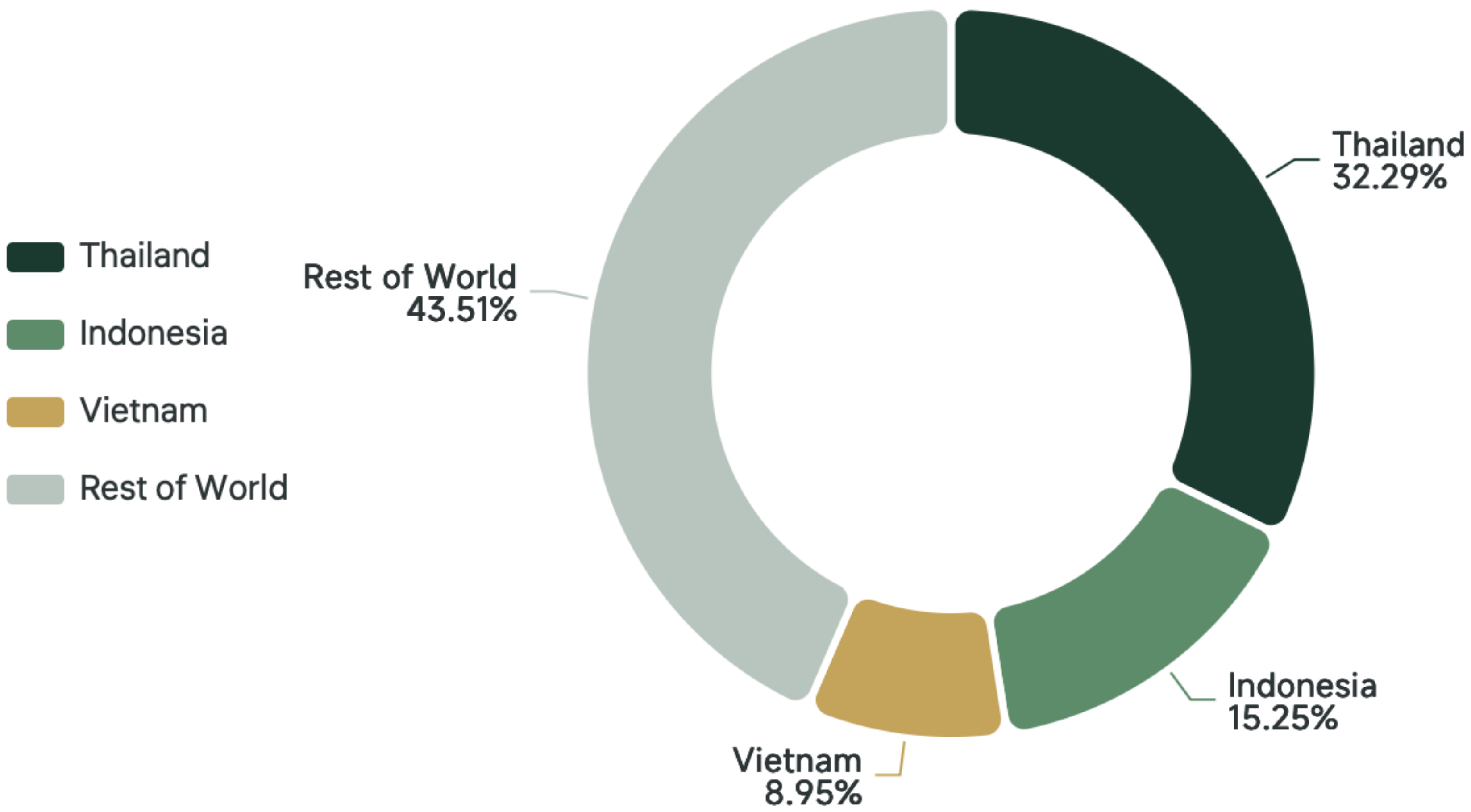
Growth Drivers

- Rising automotive production and EV adoption
- Global infrastructure development and construction boom
- Industrial automation and smart manufacturing growth
- Aviation sector expansion increasing tire demand
- Consumer fitness awareness driving rubber flooring demand



Strategic Insight: The global rubber market demonstrates robust fundamentals driven by irreplaceable material properties and diversified end-use demand across critical industrial sectors, positioning it for sustained growth through 2030.

Regional Market Landscape



Market Leader

Asia Pacific

56.50%

Combined world production share

Top Producer

Thailand

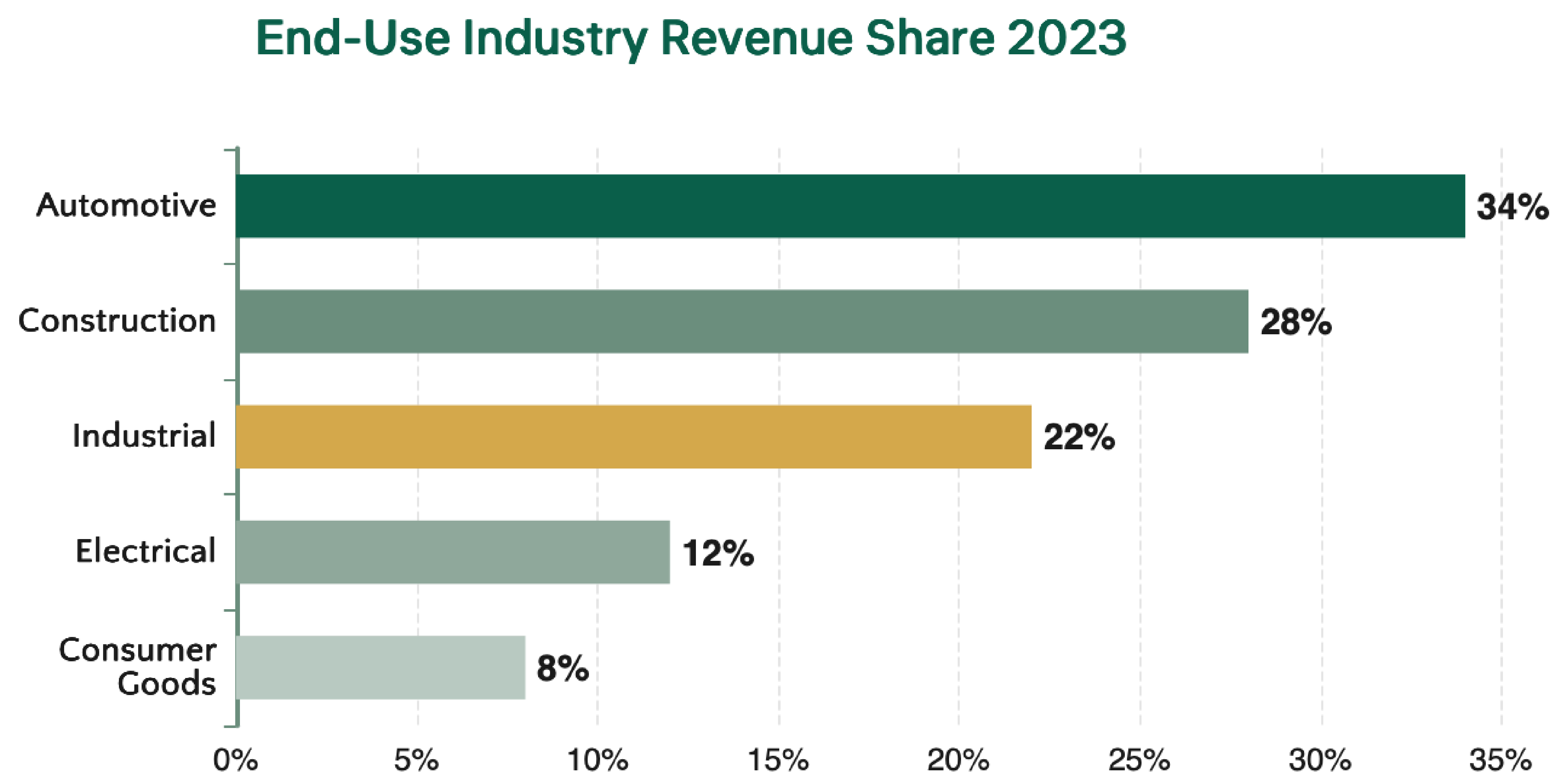
32.29%

Production Quantity: 4,789,042

Key Insight

Southeast Asian countries dominate global production, with Thailand leading at over 32% share. The three main producers collectively control more than half of worldwide output.

End-Use Industry Analysis



Market Leader
Automotive
34%+
Revenue share

Second
Construction
28%
Revenue share

Third
Industrial
22%
Revenue share

Automotive

Rubber's distinctive characteristics make it ideal for automotive applications:

- High tensile strength
- Vibration dampening
- Tear & abrasion resistance

Construction

Key properties driving construction demand:

- Durability & weather resistance
- Energy efficiency
- Expansion joints & sealants

Industrial

Growth driven by automation and smart manufacturing:

- Manufacturing equipment
- Mining machinery
- Energy sector applications

Rubber Type Segmentation

Market Leader

Synthetic Rubber

57%+

Key Advantages

- **Low Cost:** More economical production compared to natural rubber
- **Lightweight:** Enhanced performance in automotive and aerospace
- **Customizable:** Tailored properties for specific applications

Fastest Growing

Natural Rubber

43%

Superior Properties

- **High Tensile Strength:** Superior elasticity and durability
- **Vibration Dampening:** Excellent shock absorption
- **Eco-Friendly:** Renewable and biodegradable

Synthetic Rubber Applications

- Automotive (tires, hoses)
- Textiles & footwear
- Defense equipment
- Construction materials
- Pharmaceuticals
- Adhesives & sealants

Natural Rubber Applications

- Vehicle tires
- Surgical gloves
- Clothing & footwear
- Medical equipment
- Industrial components
- Toys & mattresses

Market Insight: While synthetic rubber dominates with cost advantages, natural rubber is experiencing significant growth driven by automotive production, construction activity, footwear demand, and aircraft production — with its superior mechanical properties making it preferred for critical applications.

Market Drivers & Sustainability Trends

Sustainability Shift

Environmental Awareness

Growing consumer awareness toward environmental conservation and rubber manufacturers' approach toward sustainability have created high demand for reclaimed rubber across multiple end-use sectors.

Reclaimed Rubber Applications

- Footwear industry
- Automotive sector
- Flooring applications
- Consumer goods

Core Market Drivers

Irreplaceable Properties

Rubber's robust qualities including tear resistance and durability make it indispensable for tire manufacturing and critical industrial applications where material failure is not an option.

Industry Growth Catalysts

- → Rising demand for natural rubber goods
- → Developing global automobile industry
- → Expanding construction sector worldwide

Eco-Friendly Demand

Environmental consciousness driving reclaimed rubber adoption

Material Superiority

Unmatched mechanical properties ensuring market relevance

Global Expansion

Automotive and construction industry growth worldwide

Strategic Implication: The convergence of sustainability trends and irreplaceable material properties creates a dual-growth engine. Manufacturers investing in reclaimed rubber technologies while maintaining quality standards are positioned to capture value from both environmental consciousness and core industrial demand.

EU Deforestation Regulation

What is EUDR?

EUDR was primarily implemented to minimize the EU's contribution to deforestation worldwide, reducing global forest loss and degradation and thereby also greenhouse gas emissions and global biodiversity loss.

Key Terms

It distinguishes between **operators** and **traders**. Any natural and legal person who in commercial activity places relevant products on market, exports relevant products or excludes downstream operators is considered as an **operator** whereas any person in the supply chain (other than the operator) who makes available relevant products on the market or is in course of commercial activity whether for payment or for free is considered a **trader**.

Deforestation Criteria

The regulation specifies that forest converted to agricultural use after the **critical cut-off date, 31st Dec 2020**, is considered deforested and cannot be used for producing relevant commodities. **Agricultural use** includes plantations, set-aside areas and livestock rearing while land is considered as **forest** if it spans more than 0.5 hectares with trees higher than 5 metres, canopy cover of more than 10% and trees able to reach thresholds in situ.

Enforcement Timeline

- **December 2026**
  Enforcement begins for operators and traders that are **not SMEs**
- **June 2027**
  Enforcement begins for **small and micro enterprises**

* SME = Small and Medium-sized Enterprises

EU Deforestation Regulation

Scope: Commodities and Products Covered

EUDR is relevant to following **seven commodities**:

- Cattle
- Cocoa
- Coffee
- Palm Oil
- Rubber
- Soya
- Wood & Wood Products

The regulation extends beyond raw commodities to encompass all products containing these commodities, products fed with them and products made using them.

It applies to all products either first made available on the EU (imports), any supply for distribution, consumption or use or any products exported from the EU.

(Lab, 2024)

Non-compliance Consequences

Financial Fines
Substantial monetary penalties proportionate to the severity and extent of non-compliance, designed to deter violations

Product Confiscation
Seizure and removal of non-compliant products from the EU market, preventing their distribution or sale

Revenue Seizure
Confiscation of revenues generated from non-compliant products, removing financial benefit from violations

Market Access Loss
Temporary or permanent exclusion from the EU market, representing the most severe consequence for repeated violations

EU Due Diligence Process

It introduces a mandatory due diligence system, stating that companies must prove that all their products are deforestation free, produced in accordance with local laws and covered by a Due Diligence Statement submitted to EU authorities. Without this, products cannot be sold in the EU. Under the EUDR, operators must follow four steps:

Step 1

Information collection: According to article 9, they need to collect and document supply chain and origin data including commodity and product description, quantity, country of production, supplier information, geolocation coordinates of all plots of land where the commodity was produced and the date or time range of production.

Step 2

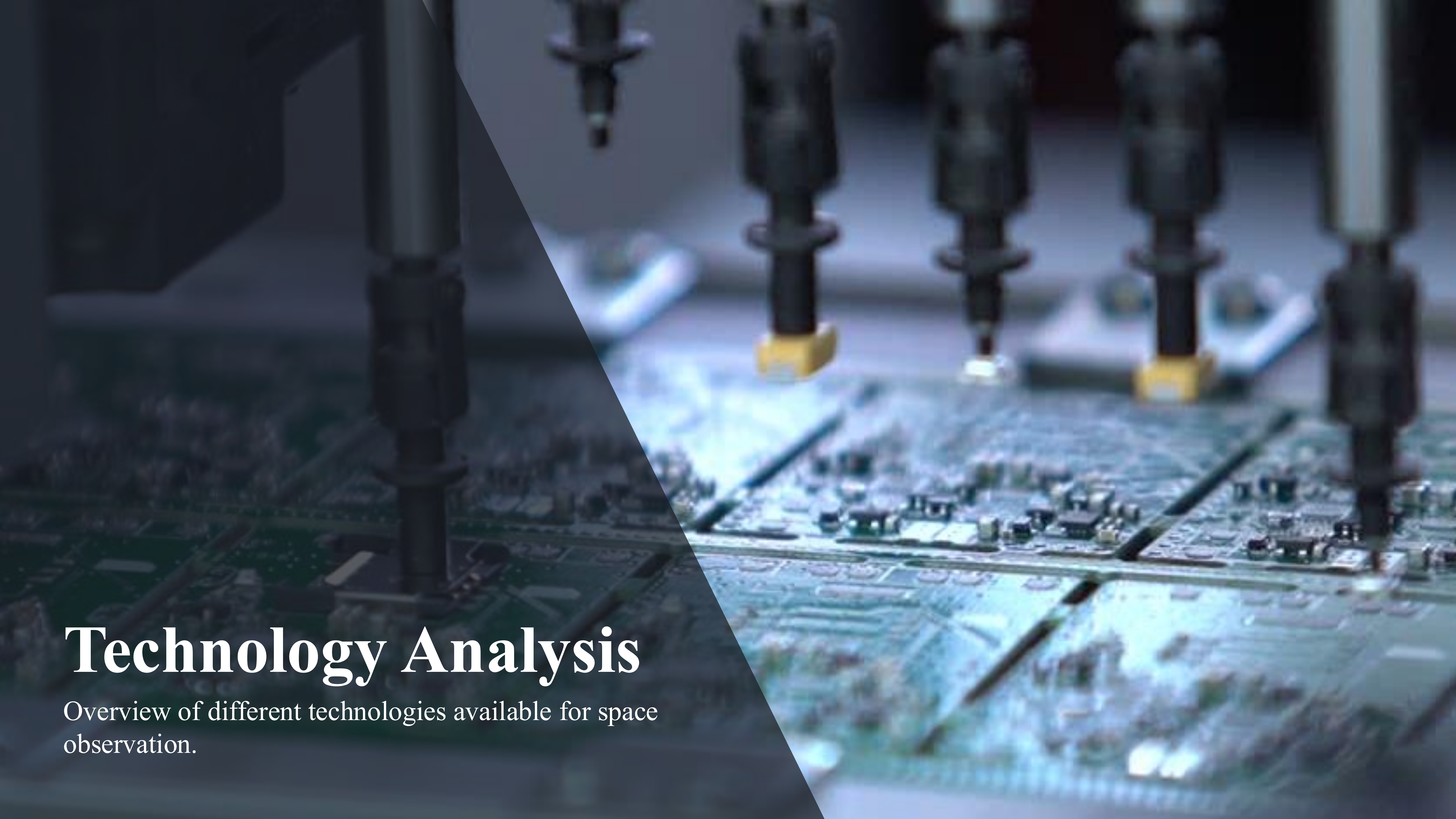
Risk Assessment: Secondly, they need to determine whether the product was produced on land that was subject to deforestation after the critical cut-off date and/or violates local laws and conclude whether the risk is negligible or non-negligible, according to article 10. The level of scrutiny required for this step depends on how the country of production is classified by the EU's benchmarking system – as high risk, standard risk or low risk.

Step 3

Risk Mitigation: If the previous step decided on the risk to be non-negligible, companies have to obtain additional documentation, conduct independent audits or change suppliers since the product cannot be placed on the EU market before risk is determined as negligible (Article 11).

Step 4

Due Diligence Statement (DDS) Submission: Finally, companies need to submit a DDS through the EU's information systems to the competent authority, in which they declare compliance and accept legal responsibility.



Technology Analysis

Overview of different technologies available for space observation.

TECHNOLOGY ANALYSIS

Visual Remote Sensing Technologies

1 Optical Satellite Imagery

Multispectral Satellites

Operating Principle

Captures imagery in visible and near-visible portions of the electromagnetic spectrum by recording sunlight reflected from the Earth's surface and atmosphere.

Key Limitations

Cannot operate effectively at night and are limited by cloud cover, which can obstruct the view of the surface.

Operational Advantages

Generally require less energy and are more cost-effective to operate than radar technology because they rely on the sun as their primary source of illumination.

Primary Applications

Elevation mapping, infrastructure planning, long-term monitoring of urban development, vegetation management, agriculture, tracking deforestation, coastal monitoring, and environmental assessment.

Key Missions: Landsat 9 and Sentinel-2 deliver consistent, high-resolution data for global observation and analysis.

2 Thermal Infrared Sensor

TIRS

Operating Principle

Collects image data in multiple thermal-infrared spectral bands to measure the energy emitted from the Earth's surface. These sensors detect long wavelengths of light and apply principles of quantum physics to accurately derive land and water surface temperatures.

Key Capabilities

Can measure surface temperature regardless of solar illumination, enabling 24/7 monitoring capabilities.

Primary Applications

Monitoring surface temperature, volcanic activity, and active wildfires, as well as measuring water temperatures in oceans, lakes, and rivers. These observations are critical for understanding natural hazards, climate processes, and environmental change.

Key Mission: Landsat 8 delivers calibrated, repeatable measurements for long-term Earth surface temperature monitoring.

3 Hyperspectral Imaging

High Spectral Resolution

Operating Principle

Obtains very high spectral resolution imagery by dividing reflected or emitted light into many narrow, contiguous spectral bands across the electromagnetic spectrum. Unlike multispectral systems, hyperspectral sensors collect detailed spectral information for each pixel, enabling precise identification of surface materials.

Data Structure

A hyperspectral image consists of a stack of images, with each layer representing a single spectral band. Together, these layers form a three-dimensional "spectral cube," with two spatial dimensions and one spectral dimension, allowing analysts to examine both the location and the unique spectral signature of surface features.

Primary Applications

Mapping mineral composition and soils, identifying vegetation species and assessing plant health, monitoring crop stress, evaluating water quality, studying shallow coastal environments and coral reef habitats.

Key Missions: ISS (EMIT), PRISMA, and PACE support advanced environmental monitoring and resource management applications.

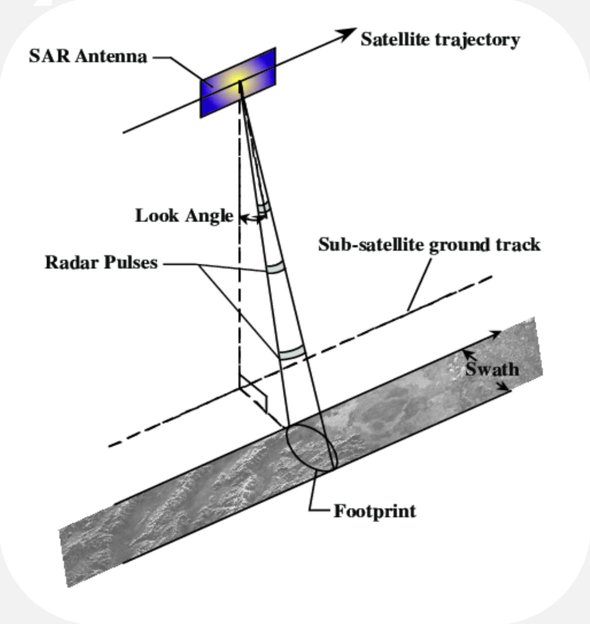
Non-Visual Remote Sensing Technologies

1 Synthetic Aperture Radar

Operating Principle: Active microwave remote sensing systems operate by transmitting a pulse of energy toward the Earth's surface and recording the portion of that energy that is reflected back to the sensor after interaction with surface features.

Key Advantages: Because these systems provide their own source of energy, they can operate day or night and are largely unaffected by cloud cover, making them highly reliable in all weather conditions.

Applications: Monitoring Antarctic icebergs, tracking oil spills as they move into sensitive marsh environments, mapping remote wetlands such as those in Alaska, measuring soil moisture, determining flood extent, monitoring ice motion, and assessing surface roughness.



(Knobloch, 2025)

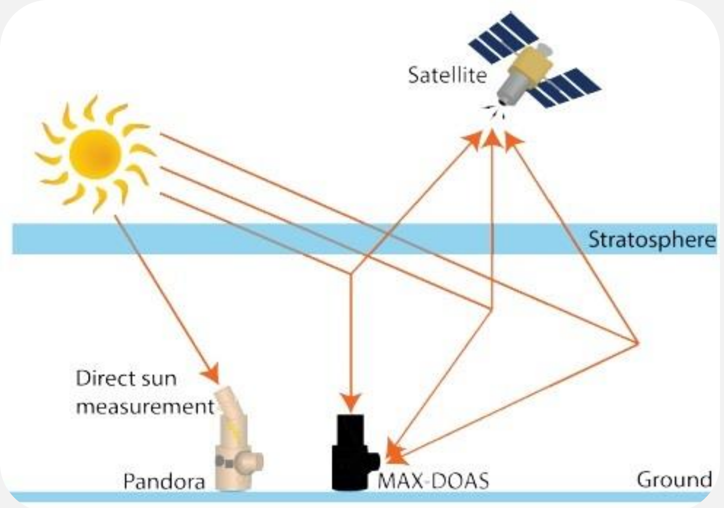
Key Missions: Sentinel-1 and RADARSAT deliver consistent, high-resolution microwave observations for environmental monitoring and hazard response.

2 Atmospheric Spectrometers

Operating Principle: Atmospheric spectrometry measures trace gases in the atmosphere by analyzing how different gases absorb specific wavelengths of light. Incoming sunlight is split into its component wavelengths, revealing distinct absorption lines in the spectrum.

Identification Method: Each gas has a unique spectral signature, allowing scientists to identify and quantify gases based on the position and strength of these absorption features. By examining these patterns, it is possible to determine the concentration and distribution of atmospheric constituents with high precision.

Applications: Measuring methane, ozone, and carbon monoxide, monitoring overall air quality, tracking the health of the ozone layer, and identifying aviation safety hazards such as volcanic ash and atmospheric pollutants.



(Sun, 2018)

(ESA, 2017)

Key Missions: GOME-2 and Sentinel-5P deliver continuous global observations for environmental monitoring and climate research.

Non-Visual Remote Sensing Technologies

3 Gravity Field Missions

Operating Principle: Satellite gravimetry observes mass change on Earth by measuring tiny variations in the planet's time-variable gravity field. This is accomplished using two satellites flying in the same orbit in an in-line formation, typically separated by about 100 kilometers.

Measurement Method: As the pair passes over regions with different mass distributions—such as large ice sheets or groundwater reservoirs - each satellite experiences slightly different gravitational acceleration. By precisely measuring changes in the distance between the two satellites, scientists can detect subtle shifts in Earth's gravity field and infer changes in surface and subsurface mass.

Applications: Monitoring ice sheet mass changes in Greenland and Antarctica, tracking terrestrial water storage, assessing groundwater depletion and drought conditions, contributing to understanding sea level rise and large-scale ocean circulation patterns by measuring mass redistribution within the Earth system.

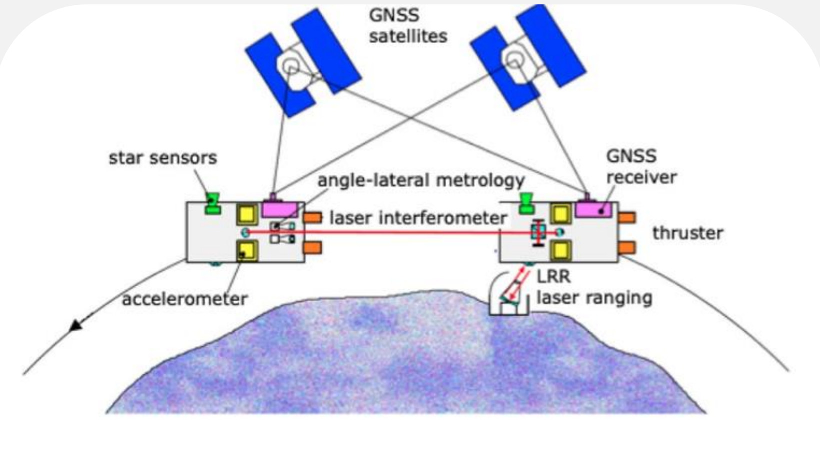
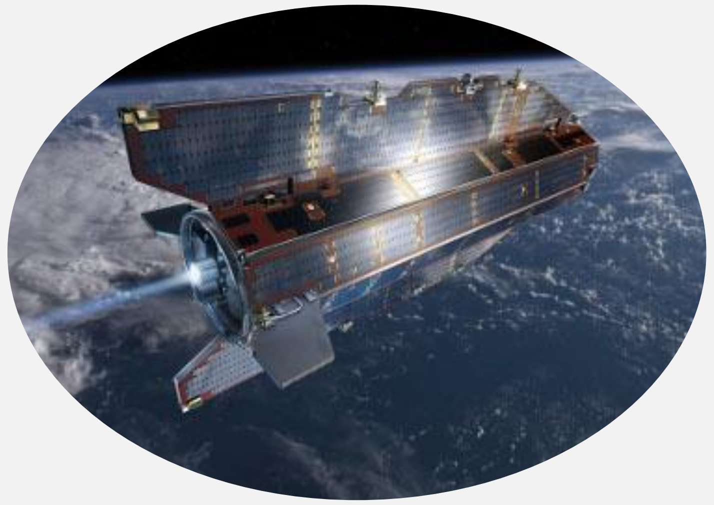


Fig. 1 Measurement principle of NGGM. Figure reproduced from Silvestrin et al. (2015)



(ESA)

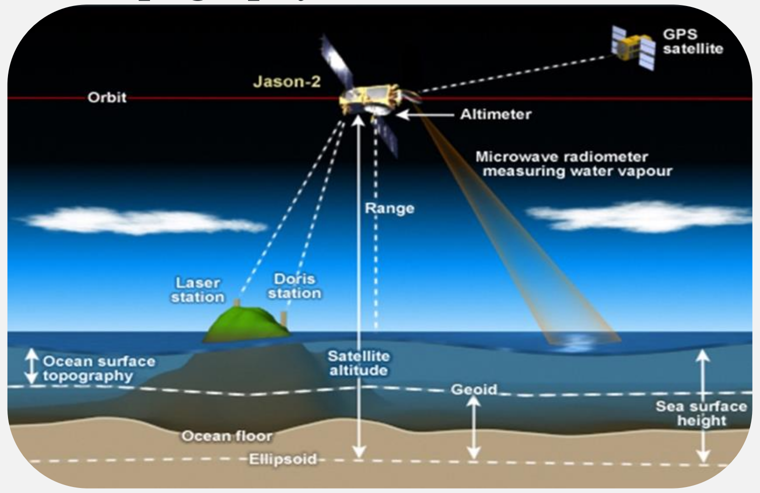
Significance: GRACE and GRACE-FO missions

4 Radar Altimetry

Operating Principle: An active remote sensing technique that measures the time delay of radar pulses reflected from the ocean surface to determine distance. By precisely calculating the time it takes for a radar signal to travel from the satellite to the surface and back, scientists can compute the distance between the satellite and the sea surface.

Measurement Process: After accurately determining the satellite's orbital position and applying necessary atmospheric corrections, the exact sea surface height can be derived. This method enables highly precise measurements of ocean topography and surface elevation over time.

Applications: Monitoring time-varying sea surface height essential for understanding ocean circulation and climate processes, measuring sea ice thickness, large iceberg height above sea level, river and lake levels, and land and ice sheet topography. Indirectly, variations in sea surface height can reveal information about seafloor topography.



(Blumenfeld, 2021)

(Copernicus, 2026)

Key Missions: ERS-1, ERS-2, and TOPEX/Poseidon have provided long-term datasets critical for oceanographic and climate research.

Competitor Analysis

Looking at competitors to understand the proposed solution.

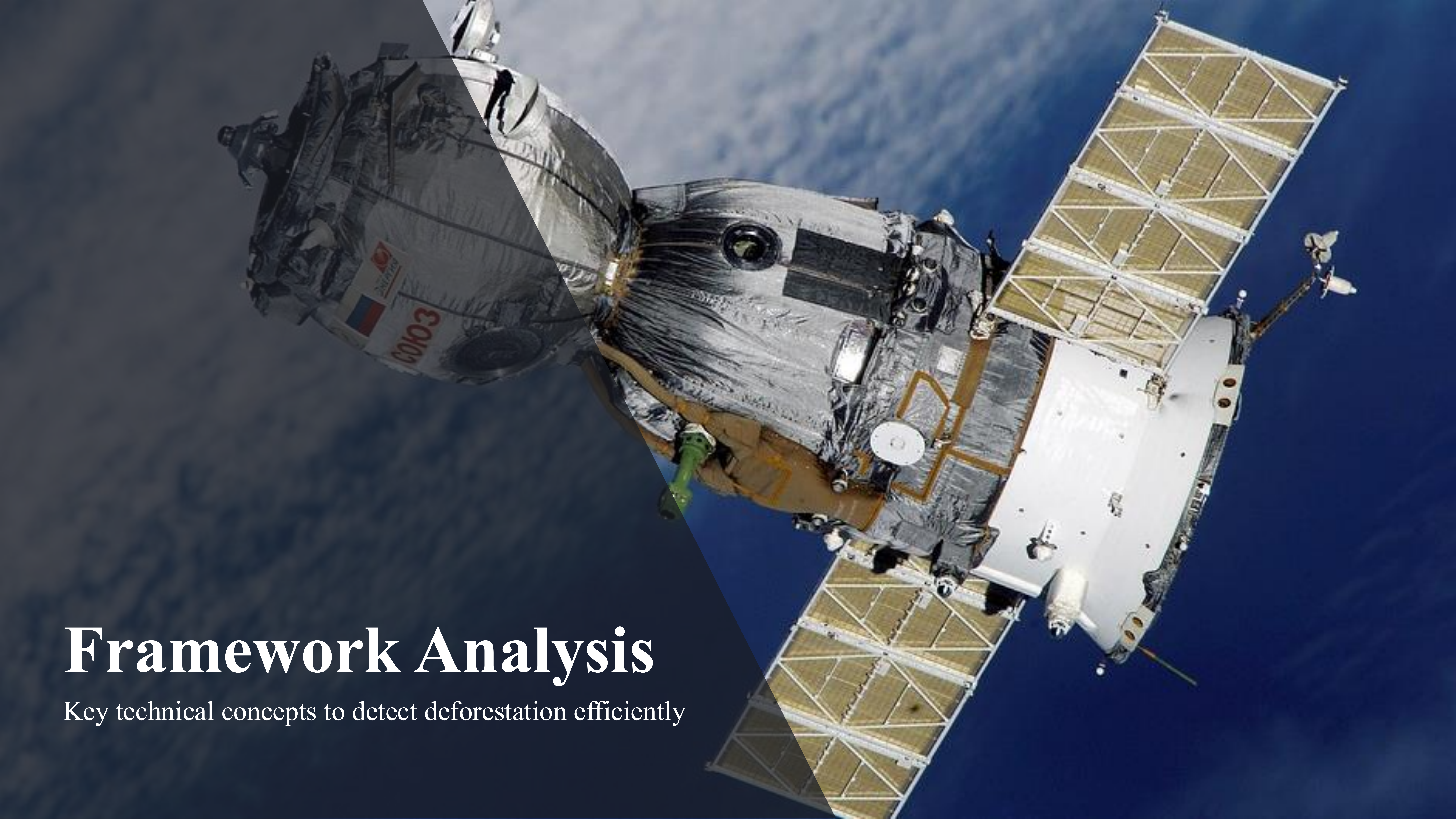
COMPETITOPR ANALYSIS

Alternative EUDR Compliance Solutions

Evaluation Criteria	LiveEO Berlin-based	Master Sustainability Today Multi-regulation Platform	EUDRx EUDR-Specific
Core Technology	**Multi-temporal, 5m-resolution** satellite imagery combined with machine learning	Satellite-based solution with **undisclosed technical specifications**	**Landsat, Sentinel 1 & 2, PALSAR** satellite data with machine learning
Key Products	**TradeAware:** End-to-end EUDR solution with deforestation assessment **Treeline:** Vegetation management platform **SurfaceScout:** AI-powered pipeline monitoring	**All-in-one ESG platform:** 9+ modules including EUDR, CSRD, CBAM, SFDR, CSDDD Centralized supply chain data integration	**EUDR compliance platform:** Consignment-specific deforestation analysis **Data storage:** Up to 5 years retention Sector-specific customization (coffee-focused)
Key Strengths	• **Fully accurate deforestation assessment** with high-res satellite imagery • Inbuilt legality checks • Seamless system integration capabilities • Multi-product portfolio beyond EUDR	• **Comprehensive regulatory coverage:** Single platform for multiple EU regulations • Automated regulatory processes • Streamlined due diligence workflows • Supplier assessment & reporting automation	• **Rapid, thorough insights:** Automated consignment-specific analysis • Structured analysis process guidance • Long-term data storage (5 years) • Sector-specific customization
Critical Gaps	• Limited risk mitigation action capabilities • No full due-diligence operating system	• Lacks in-depth EUDR-specific compliance	• No end-to-end traceability

Strategic Insight

All three solutions work with polygon mapping. They start by looking at the area that the relevant commodities where produced (as provided by the companies) and then verify if these have been subject to deforestation. This is how our solution is different, as introduced in the next slides.



Framework Analysis

Key technical concepts to detect deforestation efficiently

General Framework

This flowchart represents a paradigm shift from area-specific monitoring to universal forest observation, combining computational efficiency with regulatory compliance capabilities across all commodity types.

100% Coverage

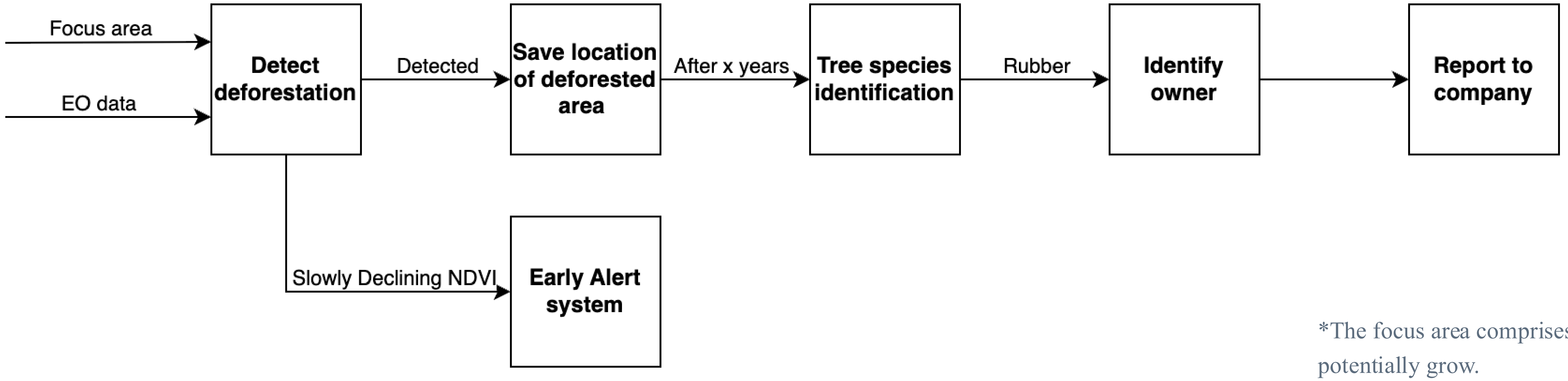
The system monitors all forest areas worldwide that are suitable for rubber cultivation, rather than limiting surveillance to predefined high-risk regions, thereby reducing the risk of undetected deforestation.

Modular Design

Adaptable to all commodity types through the interchangeable third pillar, providing universal EUDR compliance monitoring.

Efficient Processing

Tiered analysis approach conserves computational resources while maintaining detection accuracy and reliability.



*The focus area comprises regions where rubber trees can potentially grow.

FRAMEWORK ANALYSIS

Input Data and Initial Detection

Starting Point: EO Data and Focus Area

The system begins by receiving Earth Observation (EO) data in the form of satellite pictures along with the specific geographic area designated for observation. This dual input provides both the visual data necessary for analysis and the regions suitable for rubber cultivation.

By measuring forest density and assessing forest health conditions, the system establishes baseline metrics that enable the detection of deforestation activities. This analytical capability is contingent upon comparing current data against historical records, with the European Union Deforestation Regulation (EUDR) establishing 2020 as the critical cutoff date for compliance purposes.

Detection Logic and Decision Points

When the system detects a significant decrease in forest density, indicating potential deforestation activity, it automatically advances to the next processing step where the identified location is saved for subsequent analysis.

Conversely, if forest density remains stable but the health condition shows deterioration, the system activates its early alert mechanism. This subsystem monitors declining health conditions over multiple years, recognizing that sustained degradation can serve as an early indicator that a particular area may become a target for future deforestation activities.

System Workflow

1. **EO Data Input**
   Satellite imagery + focus area
2. **Detect deforestation**
   By using the NDVI Index measuring the forest density
3. **Safe location of deforested area**
   Use location for tree species identification
4. **Identify tree species**
   By using image recognition software

EUDR Compliance

The year 2020 serves as the regulatory cutoff date, meaning all historical comparisons must reference conditions from this baseline year forward to ensure compliance with European Union Deforestation Regulation requirements.

FRAMEWORK ANALYSIS

System Architecture: Why this System?

Computational Efficiency

The calculation of forest density is a relatively straightforward computational process that does not demand excessive processing power. This efficiency is critical for enabling large-scale monitoring across extensive geographic areas without requiring prohibitively expensive infrastructure investments.

The same analytical technique used for density measurement is also applied to determine forest health conditions, creating synergies that maximize the utility of each computational operation performed by the system.

Early Alert Capability

This architectural approach enables the deployment of an early alert system that can identify areas showing signs of stress or degradation before actual deforestation occurs. This predictive capability provides valuable lead time for intervention and preventive action.

By monitoring health trends over multiple years, the system can flag locations that warrant closer attention, allowing resources to be allocated strategically to areas with the highest risk profiles.

Resource Optimization

The system conserves computational resources by deferring the use of picture identification software to only those cases where density analysis alone cannot provide sufficient evidence of deforestation activity.

If forest structure remains stable over multiple years, the more computationally intensive image recognition algorithms are never activated for those areas, resulting in significant processing savings across the global monitoring scope.

System Architecture Logic Flow

Step 1
Density calculation

→

Step 2
Recognize deforestation

→

Step 3
Identify the sort of tree

Core Design Principle

Picture identification algorithms are reserved for deployment only when forest density measurements do not provide adequate detail to determine whether deforestation was specifically conducted for rubber tree planting. This tiered approach ensures optimal resource allocation while maintaining detection accuracy.

FRAMEWORK ANALYSIS

Competitive Advantages of the System

Global Scalability

The system's architecture enables monitoring of virtually the entire world's forested areas. Because forest density measurement is computationally efficient, the system can process data for gigantic geographic regions without encountering performance bottlenecks or requiring excessive infrastructure scaling.

This global reach represents a fundamental departure from traditional approaches that focus only on predefined high-risk areas, providing comprehensive coverage that leaves no forest unobserved.

Modular Commodity Detection

Step 3 of the system, which identifies specific tree species, is fully modular in design. By simply adding or exchanging software components in this third pillar, the system can detect all different kinds of commodities beyond rubber.

This modularity means the same underlying infrastructure can be applied to monitor palm oil, soy, cattle ranching, or any other commodity linked to deforestation, making the system universally adaptable to evolving regulatory requirements.

Closed System Architecture

1 Universal Detection

The system can observe earth and detects deforestation universally, regardless of the commodity type that will eventually be planted.

2 Density Principle

Independent of the commodity, forest density always decreases when deforestation is applied, making this a universal detection metric.

3 Commodity Assignment

Only the third pillar determines which commodity was planted, enabling the same infrastructure to serve all compliance needs.

Key Differentiator from Competitors

Competitors typically focus only on predefined areas, but as we know, defining these areas is the most complicated aspect of supply chain verification. This system looks at 100% of the world's forests, ensuring rigorous detection of deforestation regardless of where it occurs. This comprehensive approach eliminates the risk of missing deforestation activities in areas that were not pre-identified as high-risk.

NDVI Index: Definition & Calculation: Pillar 1

NDVI Definition and Purpose

NDVI (Normalized Difference Vegetation Index) serves as the core metric in our model for determining forest density and feeding the early alert system with data about forest health conditions. This index leverages the unique spectral properties of vegetation to quantify vegetation presence and vitality.

The NDVI formula utilizes light reflected from the Earth's surface by measuring red and near-infrared (NIR) wavelengths. Healthy plants absorb more red light and reflect more near-infrared radiation, producing higher NDVI values. Conversely, unhealthy or stressed vegetation reflects more red light and less NIR, resulting in lower index values(Adam, 2025).

NDVI Formula

$$NDVI = (NIR - RED) / (NIR + RED)$$

NIR
Near-infrared wavelength reflectance

RED
Red wavelength reflectance

NDVI Value Interpretation

NDVI values range from -1 to +1, with each range indicating distinct surface characteristics. A value close to +1 indicates vibrant, dense vegetation such as healthy forest. Values around 0 suggest areas with little or no plant life, such as urban areas or rocky terrain. Values close to -1 indicate water bodies, snow cover, or cloud coverage.

This quantitative framework enables observable tracking of plant behavior and landscape changes over time, making it suitable for distinguishing between forested areas (values close to 1) and deforested land (values around 0).

NDVI Value Ranges

+0.6 to +1	Dense vegetation	Healthy forest
+0.2 to +0.6	Sparse vegetation	Shrubs, grassland
-0.1 to +0.2	Non-vegetated	Urban, rock, bare soil
-1 to -0.1	Water/Clouds	Water bodies, snow, clouds

NDVI Application: Three Detection Scenarios

1 Stable NDVI

Scenario: The NDVI index in a specific area remains the same as in previous years.

Conclusion: The forest is untouched and has not experienced deforestation activity.

Action: No further analysis is needed for this specific area. The system stops here and moves on to analyze new areas.

System Status: No Action Required

2 Slowly Decreasing NDVI

Scenario: The NDVI index decreases slowly in the same area over several years.

Conclusion: This hints at an increasingly unhealthy forest showing signs of stress or degradation.

Action: Insights are forwarded to local governments or organizations focused on maintaining forest health. However, it is not possible to conclude that deforestation was happening, and no further analysis will be conducted.

System Status: Early Alert Triggered

3 Significant NDVI Decrease

Scenario: The new NDVI index is significantly lower than in previous years and close to zero.

Conclusion: Deforestation was happening in this area, as evidenced by the dramatic drop in vegetation index values.

Action: Further analysis must be conducted. The location is saved, and the system will revisit this area after the predefined waiting period.

System Status: Proceed to Next Step

Level-1 vs Level-2 Data (Adam, 2025)

Level-1 represents NDVI calculated with non-atmospherically corrected data, while **Level-2** describes atmospherically corrected satellite data.

Level-2 minimizes atmospheric distortions such as noise from atmospheric interference. Although the NDVI formula remains identical, Level-2 data are essential for accurate and meaningful vegetation monitoring.

Addressing NDVI Critics

Although more precise measures of forest density exist (such as EVI), they are not necessary for this use case because they require additional satellite data and higher processing power(Collins Mwiti, 2025).

Using one of the most standardized indexes provides the advantage that most satellites have the necessary hardware on board, and data access is relatively straightforward. NDVI accuracy is sufficient for distinguishing between forest and deforested land and can provide rough suggestions of forest health.

NDVI Index: End-to-End Framework for Density Estimation

The underlying research paper presents a comprehensive end-to-end framework for forest density estimation using satellite imagery, describing the full process from raw data acquisition to final predictive output. This systematic approach transforms raw satellite data into actionable forest density insights suitable for deforestation monitoring and environmental management.

1 Data Collection

The workflow begins with the collection of satellite images from sources such as Landsat and other remote sensing platforms.

Sources: Landsat, remote sensing satellites

2 Preprocessing

Preprocessing steps include resizing, normalization, and cloud masking to standardize raw data and reduce atmospheric or illumination distortions.

Steps: Resize, normalize, cloud mask

3 Segmentation

Segmentation techniques isolate forested regions from non-vegetated areas using color thresholding in HSV color space combined with morphological operations.

Method: HSV thresholding + morphology

4 Feature Extraction

Feature extraction incorporates spectral features such as NDVI, color histograms, and texture measures (GLCM-based features) to quantitatively describe vegetation.

Features: NDVI, histograms, GLCM texture

5 Density Labeling

Forest density labels are computed by calculating the proportion of vegetation area relative to the total image area, providing quantitative density measurements.

Calculation: Vegetation area / Total area

6 Model Training

A Support Vector Regressor (SVR) model is trained on extracted features to predict forest density, with performance evaluated using MSE, MAE, R^2, F1-score, and IoU metrics.

Model: SVR | Metrics: MSE, MAE, R^2, F1, IoU

Framework Outcome

The resulting framework demonstrates how raw satellite data can be systematically transformed into actionable forest density insights suitable for deforestation monitoring and environmental management. By comparing data from previous years with current observations, areas where deforestation has occurred become visible through a dramatic decrease in the NDVI index.

SAVE LOCATION OF DEFORESTED AREA

Location Saving Methodology and Timing Rationale

Save location of deforested area

Why Locations Are Saved Rather Than Immediately Analyzed

In cases where deforestation was detected in the previous step, the system saves the identified area rather than conducting immediate analysis. This approach is necessitated by biological reality: examining the deforested area immediately will not yield meaningful insights because newly planted trees require time to grow and develop sufficient canopy cover to be distinguishable from bare soil.

Rubber trees specifically need 4-6 years to reach maturity and can be tapped when they are 6-8 years old. After approximately 3-4 years, rubber trees have developed enough canopy cover to be distinguished from bare soil or young, immature ground cover, making them detectable through satellite imagery analysis.

Continued Monitoring of Saved Locations

During the waiting period, these saved areas continue to be observed because it is possible that additional land in the vicinity may become deforested. The system precisely marks areas where the NDVI index shows decreasing density.

By repeating this process over time, the system can track by how much the deforested area increases in the coming years, providing valuable data about the expansion patterns of agricultural conversion activities.

System Process for Saved Locations

Mark Location
Precise NDVI-identified area

Waiting Period
~3 years for canopy growth

Track Expansion
Monitor area growth

Rubber Tree Growth Timeline

4-6 Years — **Growth to Maturity**
Time needed for rubber trees to reach full growth

6-8 Years — **Tapping Age**
When trees can be tapped for latex production

3-4 Years — **Canopy Visibility**
Sufficient cover for satellite detection

This biological timeline determines when picture identification software can effectively detect rubber plantations from satellite imagery.

Biological Necessity

This step is necessary because trees need time to grow before they can be detected by technology. The waiting period is not a system limitation but a biological requirement.

EARLY ALTERT AND TREE SPECIES IDENTIFICATION

Alert Mechanism and Verification Process

Early Alert system

Tree species identification

Early Alert System Functionality

The early alert system serves as a predictive monitoring tool that tracks forest health degradation patterns over extended time periods. By identifying areas where vegetation health is progressively declining, the system provides advance warning that these locations may become candidates for future deforestation activities.

This proactive approach enables stakeholders to intervene before actual deforestation occurs, supporting conservation efforts and allowing for preventive measures to be implemented in at-risk areas.

Multi-Year Verification Protocol

After the previously defined waiting period, the system revisits previously identified locations where deforestation was detected. New Earth Observation pictures are captured and analyzed to determine whether a rubber plantation has been established on the deforested land.

The verification process employs pattern recognition to identify the sequence: original forest → cleared plain field → rubber plantation. When this pattern is confirmed, the system concludes that deforestation was specifically conducted to establish rubber cultivation.

Complete Verification and Reporting Chain

Waiting Period
Biological constraint

EO Image Capture
New satellite pictures

Plantation Detection
Tree species identification

Final Reporting
Report deforestation

Owner Identification and Company Notification

Upon confirmation of the deforestation-to-plantation pattern, the system proceeds to identify the legal owner of the affected field. A comprehensive report is then generated and transmitted to the relevant company, providing documented evidence of EUDR non-compliance for supply chain verification purposes.

Picture Identification Software: Rubber Tree Detection

Tree species identification

Final System Pillar: Commodity Detection

After deforestation has been detected, the location has been saved, and the waiting period of several years has elapsed, the next step in the system is to detect the specific plants that have been established on the deforested ground.

This phase focuses specifically on the detection of rubber trees using advanced picture identification software. The system analyzes Earth Observation imagery to identify distinctive patterns and characteristics that indicate the presence of rubber plantations.

Modular Architecture Advantage

The picture identification component is designed with full modularity in mind. By simply changing or adding software parts to this third pillar, the system can detect other sorts of trees and commodities beyond rubber.

This architectural flexibility provides the significant advantage that the same underlying system infrastructure can be used to detect EUDR compliance for all types of commodities, not just rubber, making it a universal solution for deforestation-linked commodity monitoring.

Holistic System Architecture View

Pillar 1

Density Detection

Universal deforestation identification regardless of commodity type

Pillar 2

Waiting period

Wait the previously specified time-period until moving forward

Pillar 3

Identify tree species

Modular detection: rubber, palm oil, soy, cattle, etc.

Adaptability to Any Commodity

The modular design means agricultural commodities like palm oil and soy to cattle ranching can be monitored using the same infrastructure. Only the picture identification algorithms in the third pillar need modification.

EUDR Compliance Scope

The European Union Deforestation Regulation covers multiple commodities. This system's modular architecture ensures compliance monitoring can extend to all regulated products without requiring entirely new monitoring infrastructure.

Satellite Imagery Sources

Sentinel-2 (Optical) (Wang et al., 2023b)

Resolution

10–20 meters

Key Capabilities

- Vegetation indices for phenology analysis
- Red-edge bands for rubber separability
- Multi-spectral classification

Peer-Reviewed Applications

Rubber mapping at scale has been demonstrated using Sentinel-2 phenology signatures, achieving high accuracy in distinguishing rubber plantations from other land cover types.

Sentinel-1 (Radar)

Resolution

~10 meters (IW mode)

Key Capabilities

- Works through clouds (all-weather)
- Adds canopy structure information
- Day/night operation capability

Fusion Benefits

Combining S1+S2 significantly improves mapping accuracy in cloud-prone tropical regions compared to optical-only approaches. SAR data fills gaps during monsoon seasons.

Critical Insight

The synergistic use of both sensors addresses the fundamental challenge of tropical rubber monitoring: **Sentinel-2 provides the spectral-phenological signature** that distinguishes rubber, while **Sentinel-1 ensures continuous temporal coverage** regardless of cloud conditions. This fusion approach is essential for robust EUDR compliance verification.

(Science Direct, 2023)

Methodology Step 1: Building Clean Time Series

For Each Deforested Area

1 Sentinel-2 Data Acquisition

Pull all Sentinel-2 observations over **multiple years** (e.g., 2–4 years after clearing and onward) to capture the full phenological cycle.

Temporal depth is critical for rubber identification

2 Cloud-Masking and Compositing(Wang et al., 2023)

Apply cloud-masking algorithms and build **multi-date composites** (monthly or quarterly medians) to avoid reliance on single scenes affected by atmospheric conditions.

Large Southeast Asia rubber maps used multiyear composites to handle persistent cloud cover

3 Sentinel-1 Time Series

Pull Sentinel-1 time series with **VV/VH backscatter** measurements, computing temporal medians to characterize structural development.

Why Time Series?

Rubber is often not uniquely identifiable from a single date, but becomes distinguishable through its:

Seasonal Pattern
Distinct leaf-shedding and regrowth cycles

Persistence Over Years
Consistent plantation structure and management

Temporal Signature
Unique NDVI trajectory compared to natural forest

Key Considerations

- **Temporal resolution:** Balance between data volume and phenological capture
- **Cloud contamination:** Aggressive masking required in tropical regions
- **Composite windows:** Monthly/quarterly balances noise reduction with seasonal fidelity

DATA ANALYTICS

Methodology Step 1: Engineering Rubber Sensitive Features

Tree species identification

a Phenology Features

Strongest signal in many regions

Rubber plantations exhibit distinctive **leaf fall + regrowth signatures** during specific time windows (region-dependent), enabling separation from evergreen forests.

Typical Features Computed:

- NDVI/EVI minimum, maximum, amplitude
- Timing of minimum NDVI (leaf-off)
- Green-up slope (refoliation rate)
- Percentile composites during defoliation windows

b Spectral + Red-Edge

Sentinel-2 specific

Sentinel-2's **red-edge bands** (B5, B6, B7) discriminate rubber via canopy density and moisture changes not visible in standard bands.

Key Spectral Indices:

- Red-edge position and amplitude
- Chlorophyll-sensitive ratios
- Canopy moisture indicators
- SWIR-based water stress measures

Sentinel-2 red-edge approach: OA ~92.5% for mature rubber (Laos)

c Radar Structure

Sentinel-1 critical addition

Radar adds **canopy structure information** and critically reduces the "no data because of clouds" problem that plagues optical-only approaches.

SAR Features:

- VV/VH backscatter temporal profiles
- Polarization ratio dynamics
- Canopy structural development
- Biomass-related scattering

S1+S2 fusion improved accuracy in monsoon/cloud-prone settings

Feature Engineering Principle

The combination of **phenological timing** (when changes happen), **spectral characteristics** (what the canopy looks like), and **structural properties** (how the canopy scatters radar) creates a multi-dimensional signature that distinguishes rubber from confounding land cover types. No single feature is sufficient; convergence across all three categories provides robust discrimination.

(Science Direct, 2023)

DATA ANALYTICS

Detecting When Rubber Becomes Identifiable

Tree species identification

Maximizing accuracy

Rather than mapping rubber once, the system looks at the identified areas several times, to ensure the highest level of accuracy in identify rubber plantations.

Step 1: Compute Probabilities

Calculate annual or quarterly **P(rubber)** probabilities using the engineered feature set and trained classifier.

Step 2: Establishment Criteria

Declare **"rubber established"** when P(rubber) exceeds a conservative threshold for **2 consecutive seasons**, reducing one-off noise and false positives.

Accuracy Progression: Young to Mature Rubber

Peer-reviewed studies using multi-source time series (Sentinel-1 + Sentinel-2) demonstrate clear accuracy improvement as rubber matures:

Key Reality: Young Rubber Challenge

Young rubber is difficult to detect at 10–30m resolution until the canopy develops and closes. Early-stage plantations spectrally resemble grassland or mixed regrowth.

Practical Implications for EUDR

- **Minimum 2-year wait:** Required for any meaningful detection capability
- **3-4 years optimal:** Balance between compliance timeline and accuracy
- **Conservative thresholds:** Reduce false positives in early years

(Science Direct, 2023)

Evidence and Confidence Criteria

The Certainty Challenge

Species cannot truly be identified with absolute certainty from medium-resolution satellites alone. What is achievable is building a high-confidence classification based on multiple independent, converging signatures.

Four Strong, Repeatable "Rubber Signs" from Space:

1 Distinct Phenology (Wang et al., 2023b

Leaf fall + regrowth timing is a primary discriminator separating rubber from evergreen forests.

⚠ Limitation: In equatorial climates, defoliation can be partial or variable

2 Red-Edge Response

Sentinel-2 red-edge indices highlight canopy/moisture dynamics unique to rubber.

✓ Reported OA ~92.5% for mature rubber mapping

3 Spatial Pattern

Regular plantation blocks, consistent edges, and uniform canopy development across plots.

4 Multi-Sensor Agreement

Optical phenology indicates "rubber-like" AND radar structure confirms plantation canopy development.

Auditor-Level Confidence Requirements

"Sure" requires **converging evidence**, not a single model output. EUDR auditors expect:

- **Model Map + Uncertainty Layer**
  P(rubber) probabilities for each pixel
- **Independent Validation**
  Field data or very-high-resolution imagery interpretation
- **Documented Methodology**
  Peer-reviewed approach with reported error rates
- **Conservative Thresholds**
  Minimize false positives in compliance decisions

Large published rubber mapping studies report both accuracy metrics and detailed analysis of where and why errors occur. This is essential for transparent EUDR compliance documentation.

(Science Direct, 2023)

DATA ANALYTICS

Expected Accuracy Ranges

Mature Rubber (Easiest Case) (Ye et al., 2018)

Overall accuracy **0.89–0.95+** is commonly achievable with good phenology data and machine learning classifiers.

Southeast Asia (Overall)	**0.95 ± 0.02**
Mainland SE Asia Distinct dry-season phenology	**>0.99**
Insular/Equatorial Less distinct seasonality	**~0.85**
Laos (Red-edge indices)	**~92.5%**
Cambodia	**~89%**

Immature/Young Rubber (Science Direct, 2023)

Expect **noticeably lower performance early on**, improving as canopy closes and spectral-radar signature strengthens.

Accuracy Progression (Multi-source: S1+S2)

Year 2 after planting	**78%**
Year 3 after planting	**87%**
Year 4 after planting	**93%**

Key Accuracy Drivers

- **Climate/Seasonality:** Predictable dry-season leaf-off increases accuracy; near-equator variability increases omission errors
- **Confusers:** Other tree crops (oil palm, coconut) and secondary regrowth
- **Label quality:** Poor ground truth makes reported accuracy meaningless
- **Cloud frequency:** Radar fusion mitigates optical data gaps

DATA SHEET

Sentinel-1 (SAR Radar) Technical Specifications

Tree species identification

Mission Overview (ESA)

Mission **Sentinel-1**	Agency **European Space Agency**
Program **Copernicus Programme**	Sensor Type **C-band SAR**
Resolution **~10 m (IW mode)**	Revisit Time **~6 days (2 sats)**

★ Key Advantage

Works day/night and through clouds—critical capability for tropical regions with persistent cloud cover during monsoon seasons.

How Sentinel-1 Works

Sentinel-1 is a **radar satellite** that sends microwave pulses to Earth and measures the backscatter (energy that returns).

What Affects Backscatter:

- Surface roughness
- Vegetation structure
- Moisture content
- Canopy density

Polarizations

VV

Vertical-Vertical

Transmit V, Receive V

VH

Vertical-Horizontal

Transmit V, Receive H

VV/VH Ratio

Often helps distinguish vegetation types and canopy structure characteristics.

Why Sentinel-1 is Useful for Rubber Detection

1. **Cloud Penetration**
   Tropical rubber regions are cloud-heavy. Optical imagery often has gaps. Radar solves this.
2. **Canopy Structure Sensitivity**
   As rubber trees grow, biomass increases, canopy closes, and structural complexity rises → backscatter changes.
3. **Young vs. Mature Differentiation**
   Radar becomes more reliable once canopy develops. Early seedlings are harder to detect.
4. **Time-Series Consistency**
   Rubber plantations show gradual structural development after planting, trackable with SAR.

Limitation(Torres et al., 2012)

- Confusion possible with other tree crops and secondary forest
- Works best combined with optical data

📖 S1+S2 fusion improves classification accuracy in cloudy regions

DATA SHEET

Sentinel-2 (Multispectral Optical) Technical Specifications

Tree species identification

Mission Overview (The European Space Agency, 2023)

Mission	Agency
Sentinel-2	**European Space Agency**

Program	Sensor Type
Copernicus Programme	**Multispectral Optical**

Resolution	Revisit Time
10 m / 20 m	**~5 days (2 sats)**

Resolution Details:

10 m:	**Visible + NIR**
20 m:	**Red-edge + SWIR**

How Sentinel-2 Works (The European Space Agency, 2023)

Sentinel-2 measures **reflected sunlight in 13 spectral bands**, enabling detailed vegetation characterization.

Important Bands for Rubber Detection:

- **B4 (Red):** Chlorophyll absorption
- **B8 (NIR):** Vegetation vigor, NDVI
- **B5-B7 (Red-edge):** Chlorophyll content
- **B11-B12 (SWIR):** Moisture content

Why Sentinel-2 is Powerful for Rubber Detection

1 Phenology (Strongest Signal)

Rubber trees often show a **seasonal drop in greenness (leaf shedding)** followed by a rapid green-up phase, creating a distinct NDVI time-series pattern.

Large-scale mapping achieved ~95% OA in mainland SE Asia; lower (~85%) in equatorial regions with less distinct seasonality.

2 Red-Edge Sensitivity

Red-edge bands capture **subtle chlorophyll changes** during rubber's defoliation-refoliation cycle.

Studies using Sentinel-2 red-edge indices report **~92% overall accuracy** for mature rubber mapping.

3 Spectral Separation from Forest

Rubber plantations are often **more homogeneous** with different seasonal dynamics and canopy moisture behavior than natural forest.

Limitations

- Cannot see through clouds
- Young rubber (first 1–2 years) difficult to separate from grassland and mixed regrowth
- Spectral confusion possible with other plantations (oil palm, coconut)

TECHNICAL OVERVIEW

Combined Sensor Approach and Practical Takeaways

Tree species identification

Why Combining Sentinel-1 + Sentinel-2 is Best

Feature	Sentinel-1	Sentinel-2
Cloud Resistance	✓	✗
Vegetation Structure	✓	Limited
Chlorophyll / Phenology	✗	✓
Species Discrimination	Weak	Moderate
Early Growth Detection	Moderate	Weak

Together they provide: (1) Structural signal from SAR, (2) Seasonal greenness pattern from optical, and (3) Improved accuracy and temporal stability. Peer-reviewed fusion approaches consistently outperform single-sensor methods in tropical tree-crop mapping.

Practical Takeaways for Rubber Monitoring

Use Sentinel-2
For phenology detection and vegetation type classification

Use Sentinel-1
For continuous monitoring and structural validation

Combine Both
In a time-series classifier with multi-source features

Expect High Accuracy
≈90–95% for mature rubber in favorable regions

Lower Accuracy Early
First 2 years after planting are most challenging

Regional Variation
Reduced performance in equatorial areas without clear leaf-off season

System Architecture Summary

1 **Deforestation Detection**
Initial identification and location saving

↓

2 **Waiting Period**
Approximately 3 years for canopy development

↓

3 **Time-Series Analysis**
S1+S2 multi-year feature extraction

↓

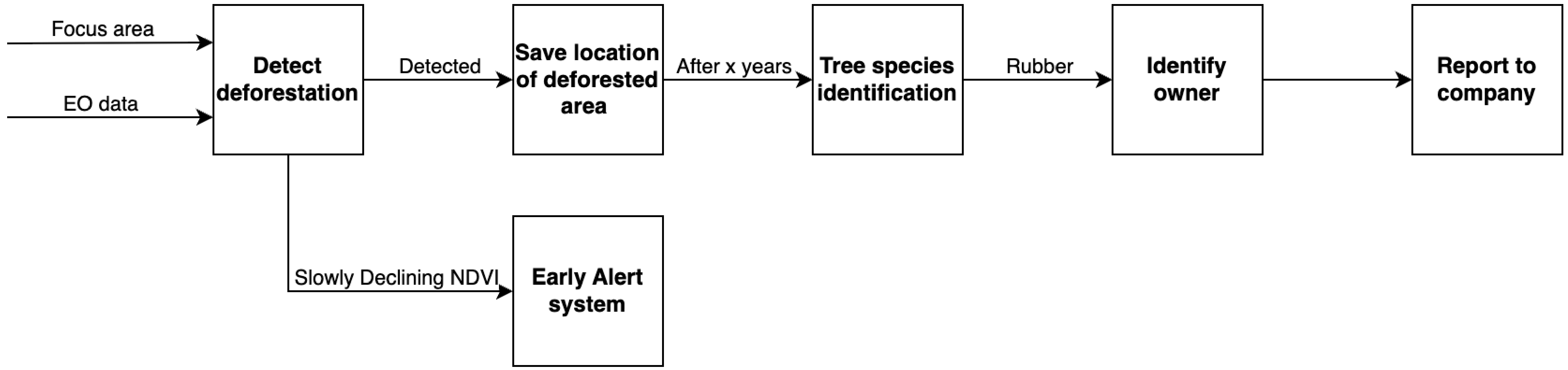
4 **EUDR Compliance Verification**
Rubber establishment confirmation ready for reporting

Extensibility

By modifying feature engineering and classifier training, this system can be adapted for **any tree species.** This enables comprehensive EUDR compliance monitoring across all regulated commodities (palm oil, cocoa, coffee, timber, etc.).

What happens after deforestation was used to set up a new rubber plantation?

After the detection of deforestation and the positive identification of a rubber plant, this information needs to be forwarded to the company buying products from this specific farmer. As previously outlined, there is no technological gap which is hindering the process of identifying deforestation. Next, the procedure of identifying the ownership of the deforested field is outlined.



*The focus area comprises regions where rubber trees can potentially grow.

Traceability Solution

Potential Pathway: Use of a Blockchain system to connect EO with compliance data.

Traceability through a HyperLedger Fabric

Key Understanding;

Earth Observation alone will be of no use if EU companies have no way to link the rubber they have to the region where it originates from. This shows that for EO to have a business case in the context of the EUDR, a traceability system need to be combined with satellite imagery. Multiple cases across various industries show the increasing relevance of adoption of a blockchain integrated system as a solution for tracing goods. In the case of rubber, blockchain would appear as a sound solution to implement alongside EO. More precisely, a private blockchain would be more adapted for companies and thus the use of a Hyperledger Fabric Architecture appears to be the most aligned fit in the context of the EUDR.

What is HyperLedger Fabric?

A permissioned blockchain solution that is intended for commercial use. Only approved members are allowed to access the blockchain and enter transactions into the network. The technology enables organizations to securely share data using smart contracts, which helps to create immutable records without the need for a public blockchain.

Modular Tool

The different components of Hyperledger Fabric (consensus mechanism, membership services, smart contracts, data storage, …) can be used as plug-and-play modules. This allow firms to implement blockchain in their system without raising the need to create an entire new network.

Data Security

Fabric's permissioned architecture uses Membership Service Providers (MSPs) to authenticate known participants and allows the creation of private channels or private data collections. This enables EU companies to share compliance-relevant data with regulators while restricting access to sensitive information.

High-Processing capabilities

Unlike most public blockchains, Fabric differentiate transaction execution, ordering, and validation, which improves throughput and reduces delays. This makes it suitable for high-volume supply chains like rubber, where many small transactions must be processed efficiently without compromising data integrity.

(Chen et al., 2023)

Traceability Challenge: Rubber Smallholder Reality

A challenge of the rubber supply chain is the high number of smallholders who are not always registered with legal identification and who make the supply chain highly fragmented, making individual traceability (required by EUDR) a real challenge. While polygon-mapping could be a potential solution to create a database with the geo-localization of farmers' plots, it appears to be a very tedious solution considering that, often, independent smallholders operate with plots smaller than 2 hectares. Moreover, since the current polygon-mapping technics require for the process to be approached individually with every farmer, its realistic implementation in the next few years remains highly uncertain if not impossible in the context of EUDR.

The Smallholder Dominance

85%
of global natural rubber

6M
smallholder farmers worldwide

The Polygon Mapping Challenge

- **Manual Process:** Requires physical farm visits to walk plot boundaries
- **Timeline:** Years before comprehensive database is viable
- **Digital Divide:** Many smallholders lack smartphones, connectivity, digital literacy

The Pragmatic Reality

The EU recognizes this operational constraint and stay aware that fragmented international supply chains can make it difficult to trace back products to the exact farmers. Due to this, the EU has validated compliance models which are only able to traceback products to steps following smallholders such as dealers and operators.

→

Based on this information, the following content will be focused on tracing back rubber to local dealers, which is the next logical step after farmers in the rubber supply chain.

Integrating Blockchain in the Rubber Supply Chain

The content below described how Hyperledger Fabric is used to trace back rubber to dealers based on the information that dealers trading rubber in the ASEAN are legally required to possess an identification code in order to operate.

Smallholders →	Dealers →	Factories →	EU Companies
	Since dealers are legally required to have an identification number, these IDs will need to be collected on a centralized database which also indicates the location of dealers' operations.	Factories register dealers' ID in a smart contract using a blockchain layer in their ERP system.	Each rubber-based product is linked to a list of dealers whose origin can be traced back and retrieve from the blockchain layer to the firm's ERP system.

Technological Requirements for factories and EU companies:

Factories

The key technology requirement is the integration of ERP systems that have the ability to track the arrival of batches, processing, and transformations of batches (splitting or mixing). Each factory needs to be registered on the blockchain with a distinct digital identity provided by Fabric's Certificate Authority (based on the Hyperledger Fabric). Upon completion of processing, the ERP system initiates an API call to a middleware layer, which checks the identity of the factory, hashes the relevant data of the ERP system for confidentiality, and makes a call to a smart contract. The smart contract checks if the input batches are present and associated with the newly created output batch

EU companies

For EU firms, the structure is similar but emphasizes compliance and auditability. Their ERP system needs to record import confirmations, contracts, and regulatory documents, and send API events to append these to the blockchain. Since all previous dealer and factory events are already connected on the blockchain, the EU firms can trace each batch back to its source, even if the batches were mixed together, without needing to access the sensitive ERP information. This is consistent with academic research that has found that permissioned blockchains are most appropriate for supply chain management that demands transparency and controlled access to data.

Linking EO with the HyperLedger system to Assess Compliance

The final step is for EU companies to be able to link dealers' IDs with the conclusions gathered by the EO tools in order to assess the compliance status of their products.

Overview of EU firms' system:

Product Batch ID
RB-2026-TH-8842

Linked Dealer IDs
TH-12345 (Primary)
TH-12346 (Secondary)

Compliance Status
● **COMPLIANT**

Blockchain Record
0x7a8b9c...d2e3f4a5b6c7

EO
Detects regions where deforestation for rubber has occurred.

Dealers Database
Dealers located in a radius of 70km from the regions where deforestation occurred are flagged as high-risk.

EU firms' ERP
If one of the dealers' ID matches a high-risk dealer from the database, a notification of non-compliance is sent.

Gap Analysis

Understanding the challenges faced in the implementation of EUDR

Technical Gaps Analysis: Which Solutions Exist?

Earth Observation (EO)

As detailed in section 2, using a solution combining EO with the NVDI index could allow to detect deforestation. Instances of use of satellite tools to detect deforestation already exist and are continuously improved. The case below depicts a current use of EO for this same purpose :

Global Forest Watch (GFW)

GFW uses satellite Earth observation data, including imagery from NASA's Landsat program, to provide near-real-time alerts of tree cover loss. In Brazil, these alerts complement monitoring by local climate initiatives, enabling local authorities to detect illegal deforestation more quickly. In Indonesia, GFW's alerts are shared with NGOs and local communities' initiatives in tracking forest clearing and fires. In Africa, it has been estimated that these alerts have allowed to decrease deforestation by 18%.

(Bhattacharya et al., 2025)

Blockchain Traceability System

Next to EO, blockchain is a strong tool which could allow EU companies to trace back the origin of their rubber-based products to the region where the rubber was collected. While this is a system that is not fully adopted yet due to its high cost and need of systemic collaboration, there are still a few cases illustrating successful proof-of-concept of blockchain for traceability purposes:

Colombian Coffee

Use of Hyperledger Fabric to trace Colombian coffee supply chains, featuring a four-layered architecture with smart contracts that validate and immutably record critical traceability data like timestamps and custody changes. (Bettín-Díaz et al., 2022)

Verstegen Spices

Successful project led by Fairfood with Verstegen spices that uses public blockchain and QR codes to trace nutmeg from Indonesian farmers to Dutch consumers, enabling shoppers to verify farmer identities and fair prices. (van Hilten et al., 2020)

Technical Gaps Analysis: Solutions Exist, Implementation Lacks

Earth Observation (EO) + **Blockchain Traceability System**

Critical Insight

In the end, on a technological point of view, it would be fully possible to detect deforestation linked to rubber plantations and trace back every rubber-based product entering the European Union to the region where its rubber was collected. This would allow EU actors of the supply chain to be able to either certify that their rubber comes from compliant regions or realize that it does not and thus help companies to act upon this conclusion.

This demonstrates that the gap is not on the technical side. Yet, while solutions exist, it can clearly be observed that they are not being implemented, signifying that other gaps are hindering companies to currently implement and adopt them.

The gap is not technical

Legal Gaps: 2 Perspectives

First Gap : EU-ASEAN collaboration gap

As of 2020, the European Union (EU) and the Association of South-East Asian Nations (ASEAN) have signed a Strategic Partnership focusing on political dialogue, trade and investment, regional security, sustainable development and connectivity, with ongoing work towards stronger economic relations and future potential region-to-region trade agreement. (Bhattacharya et al., 2025)

This nascent relationship causes that most agreements are still on discussions, and little has yet been done regarding sustainable development agreements. As a matter of fact, the first discussion between the EU and the ASEAN on environmental and climate change was hosted only in September 2025 with no clear agreements or initiatives signed but rather prospects of future shared project. With the EUDR being implemented only a few months after this conference, it could have been thought that this would be one of the main subjects as the largest portion of rubber received in Europe is collected in South-East Asia, however, this did not appear to be the case.

The two main reasons explaining the slow evolution of this partnership and the lack of coordinated agreements are the divergent decision-making processes and the different priorities between the EU and the ASEAN:

Decision-Making Processes

EU:

- Can adopt binding policies across all member states.
- Enables coordinated and uniform action on sustainability issues.

ASEAN:

- Follows a consensus-based "ASEAN Way."
- Decisions are non-binding and require agreement from all members.
- Slower coordination on regional SDG initiatives.

Priorities

EU:

- Emphasizes strict environmental standards and climate actions (eg: EUDR).
- Focuses on green growth and sustainable development as core objectives

ASEAN:

- Prioritizes rapid economic development, industrialization, and poverty reduction.
- Environmental policies may be secondary to national growth goals.
- Variation in priorities across member states creates gaps in joint SDG implementation.

Legal Gaps: 2 Perspectives

Second Gap : Non-Effective compliance at regional and national levels

ASEAN Regional Initiatives

The ASEAN has established several regional framework addressing forest conservation and sustainable land use. An overview of its main initiatives is shared below and while these are the ones the ASEAN focuses the more on, it is relevant to mention that only the Haze Agreement is legally binding. However, as no enforcement rule exists as of today, non-compliance to this regulation is not sanctioned.

ASEAN Cooperation on Forests

Includes programs on forest monitoring, biodiversity protection, and capacity-building, often supported by external partners, aiming to balance forest conservation with economic development and regional environmental security.

Haze Agreement

Treaty among ASEAN member states to prevent, monitor, and mitigate land and forest fires that cause transboundary haze pollution. It establishes framework for monitoring , early warning systems, technical cooperation, and mutual assistance. The agreement also created an ASEAN Coordinating Centre for Transboundary Haze Pollution Control to facilitate coordination.

Biodiversity Network

This initiative focuses on building collaboration among ASEAN countries in education, research, and environmental conservation. It was established through seminars and discussions involving universities, governments ministries, and private sector partners to address biodiversity crises, land degradation and deforestation challenges.

Forest Utllization Policy

Promotes sustainable forest management, enhancing trade facilitation for forest products and strengthening social forestry programs that contribute to rural development and poverty alleviation. ASEAN has also developed guidelines for forest certification and chain-of-custody for timber products.

Legal Gaps: 2 Perspectives

Second Gap : Non-Effective compliance at regional and national levels

National-Level Policy Frameworks

At a national level, member countries of the ASEAN also enact and implement initiatives aiming to protect forests and reduce deforestation in their territories. Some examples of policies are shared below :

Indonesia

Moratorium on New Forest Clearing

This policy suspends new permits for cleaning primary forests and peatlands. Covering millions of hectares, it aims to reduce deforestation and carbon emissions, though enforcement remains inconsistent and it is based on a presidential instruction rather than a stronger legal act.

Malaysia

National Forestry Policy

This policy guides sustainable forest management, balancing conservation with required production. Forestry falls under state jurisdiction, so implementation varies across Malaysia's 13 states, with the policy serving as a coordinating framework more than a centrally enforced mandate.

Thailand

Community Forest Act

This law grants communities' legal rights to manage and use designated forest areas. Communities can register their forests with the government and engage in sustainable activities like foraging and ecotourism, with over 11,000 community forests now officially recognized.

Legal Gaps: 2 Perspectives

Second Gap : Non-Effective compliance at regional and national levels

ASEAN Regional Initiatives x National-Level Policy Framework

As shown, both the ASEAN and member countries are actively taking initiatives to limit deforestation. However, the impact behind these policies and frameworks remains little to non-existent in some contexts. While some countries barely even see their national regulations being implemented, it seems hard to envision in these same countries the implementation of policies decided at a regional level through the ASEAN. The problem mainly lies at the national level where enforcement of rules appears to be the issue. Indeed, according to the World Bank rule of law score, the rule of law index for South-East Asia is –0.24 points (2024).

Implementation Failures

Weak rule of law is one of the factors causing the slow implementation of policies, but this is not the only cause leading to a poor enforcement of policies :

1 Poor Coordination

ASEAN's forest agreements set regional goals and frameworks, but they rely entirely on member states for implementation. Differences in national legislation, enforcement capacity, and priorities create gaps, so regional policies often fail to translate into consistent, effective action on the ground.

2 Insufficient funding

Many forest protection programs across South and Southeast Asia operate with insufficient financial resources. Limited budgets constrain monitoring, staffing, training, and deployment of technology, reducing the overall effectiveness of both national initiatives and regional cooperation efforts.

3 Political Interference

Enforcement of forest laws is frequently undermined by political interests and competing development priorities. Government decisions favoring economic growth, industrial expansion, or land concessions can override conservation goals, allowing deforestation and illegal logging to continue despite existing legal protections.

Legal Gaps: 2 Perspectives

First Gap : EU-ASEAN collaboration gap

Second Gap : Non-Effective compliance at regional and national levels

Legal Gap Conclusion

The EUDR is a law which requires a collaborative approach between most stakeholders of the supply chain in order to be realistically effective. A majority of these stakeholders are located in South-East Asia where legal enforcement and rule of law are poorly implemented. The EU fails to consider that this makes the traceability of rubber more complex to implement in the upstream part of the chain, resulting in compliance challenges for European companies. Moreover, the European Union mentions their intentions to reduce deforestation through this new law, however, the way the EUDR was designed shows little consideration for the current initiatives attempted in the regions where deforestation takes place, resulting in a law which seems to have been developed in a vacuum, disconnected from the on-going challenges and realities and with a limited collaborative approach at an international level.

The Fundamental Question

"How can the European Union expect to drive environmental change in Southeast Asia without a concrete collaboration plan with ASEAN, especially given that even existing regional and national laws already face significant implementation challenges?"

Incentivization Gap: Misaligned Stakeholder Motivations

An Unbalanced Punitive Compliance Model

The EU employs a behavioral system based on punishment: non-compliance results in financial penalties. This approach is fundamentally reactive, acting only after deforestation has already occurred. Legally, these consequences can only be applied to operators established in the European Union meaning that factories, dealers and smallholders located outside of the European Union are not subject to any consequences if they use rubber originating from deforested areas. However, this causes a discrepancy between the downward side of the supply chain which must avoid to supply non-compliant rubber and the upward side which has no economic incentive to comply to the EUDR. As the EU's initiatives to solve the issue in the upstream part of the chain are limited, the responsibility to enforce down the EUDR also comes down as a burden on European companies which must convince their suppliers to align with their traceability system in order for them to be compliant.

EU Operator Incentives

Besides the mandatory aspect of this law, the EU shared benefits that Europeans operators and traders can benefit from following their alignment with the regulation :

Market Access

Compliance is essentially a "license to operate" for the €7 billion European rubber market, as non-compliant products will be legally barred from entry, protecting essential revenue streams.

ESG Reporting

The due diligence data collected for EUDR directly feeds into corporate sustainability reporting, while signaling ESG performance to attract sustainability-focused investors.

Risk Mitigation & Transparency

Implementing traceability systems allows companies to move from reactive compliance to proactive risk management, securing supply chains by identifying vulnerabilities and building resilient partnerships with transparent suppliers.

Brand Reputation

In a market where consumers are willing to pay a premium for sustainability, verifiable deforestation-free credentials serve as a powerful differentiator that builds trust with both consumers and investors.

GAP ANALYSIS

Incentivization Gap: Misaligned Stakeholder Motivations

The Asian Actor Dilemma

What are Asian actors' incentives to incur extra costs to align with EUDR when they have no legal obligations to do so, and considering that EU importers do not possess the highest bargaining power with only 13.49% (retrieved from the economic model section) of global natural rubber market share ?

Missing Upstream Incentives

- ✕ No legal obligation for smallholders
- ✕ Additional compliance costs without compensation
- ✕ Limited EU market leverage
- ✕ Alternative markets available enable leakage (China, India)

Geopolitical Tensions

In 2023, the Indonesian President, Jokowi, criticized EUDR and described it as discriminatory and non-considerate regulation which could have a harmful impact on the life of thousand of smallholders. (Fisher et al., 2024) He described the problem to be about the lack of financial and technical help from the EU which could have incentivized and helped farmers, the root of the problem, to stop deforestation and become more cooperative for compliance.

This reinforces the legal gap by making Asian policymakers question the goals and efficiency of the regulation, further reducing willingness to engage in collaborative compliance frameworks.

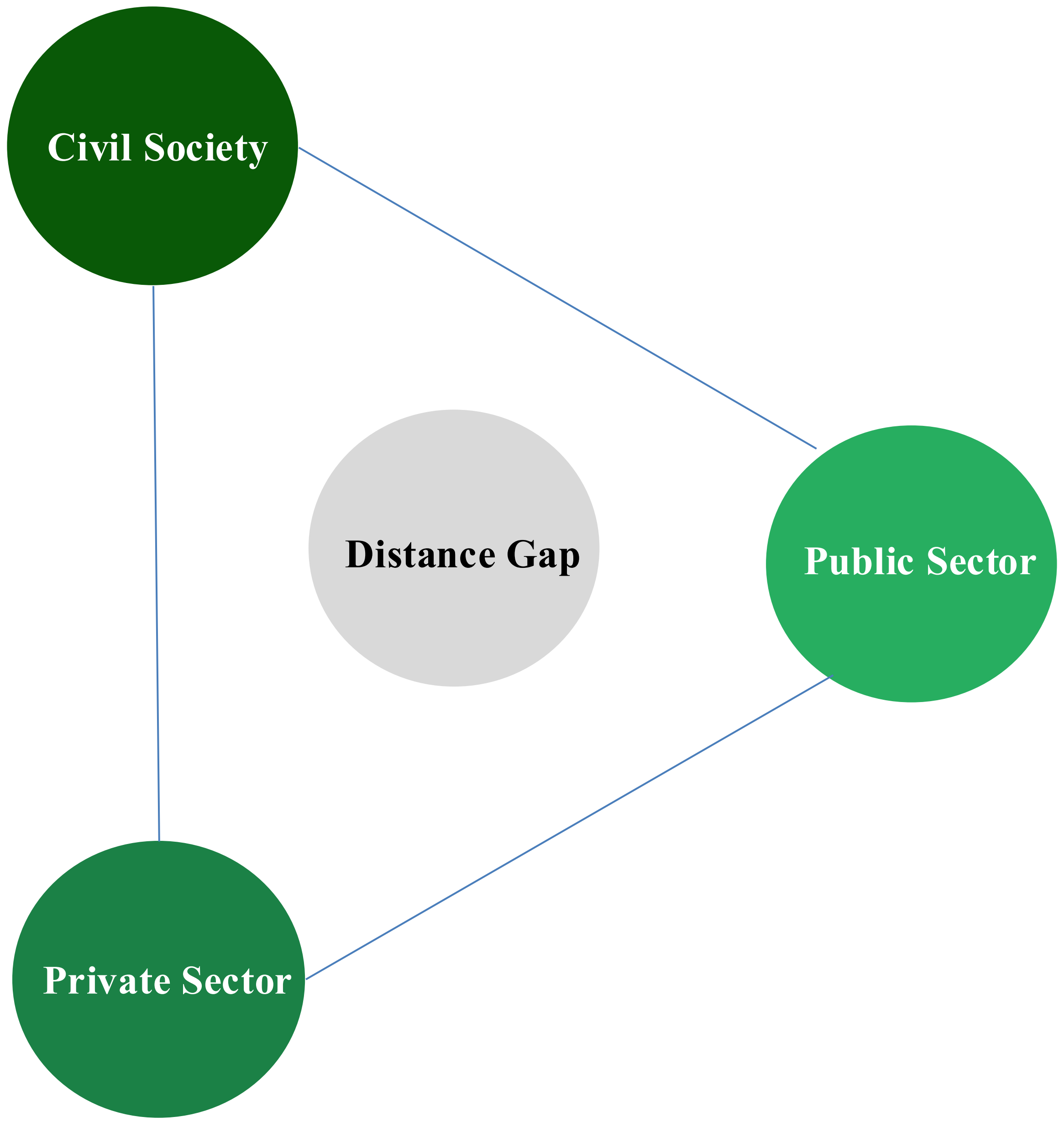
Incentivization Gap Conclusion

The second gap lies in the incentivization of the adoption of traceability tools in the upstream side of the supply chain. It notably highlights the lack of tools and incentives from the EU considering the conditions and technical means of some actors, which leads to uncooperative behaviors from upstream actors. Many smallholders in Southeast Asia still struggle with basic requirements like geolocation mapping and land documentation, yet the EU has provided very little funding to help them prepare. Without financial or technical assistance, many farmers, dealers and sometimes factories cannot afford the tools needed to comply, leaving European companies to bear the full burden of enforcing the law down the chain. The market threat that EUDR poses could also lead to increased leakage, where deforestation-risk products are simply diverted to less regulated markets like China or India instead of being addressed. This would just move the problem outside the European Union instead of solving it, undermining the regulation's core environmental objective.

Governance

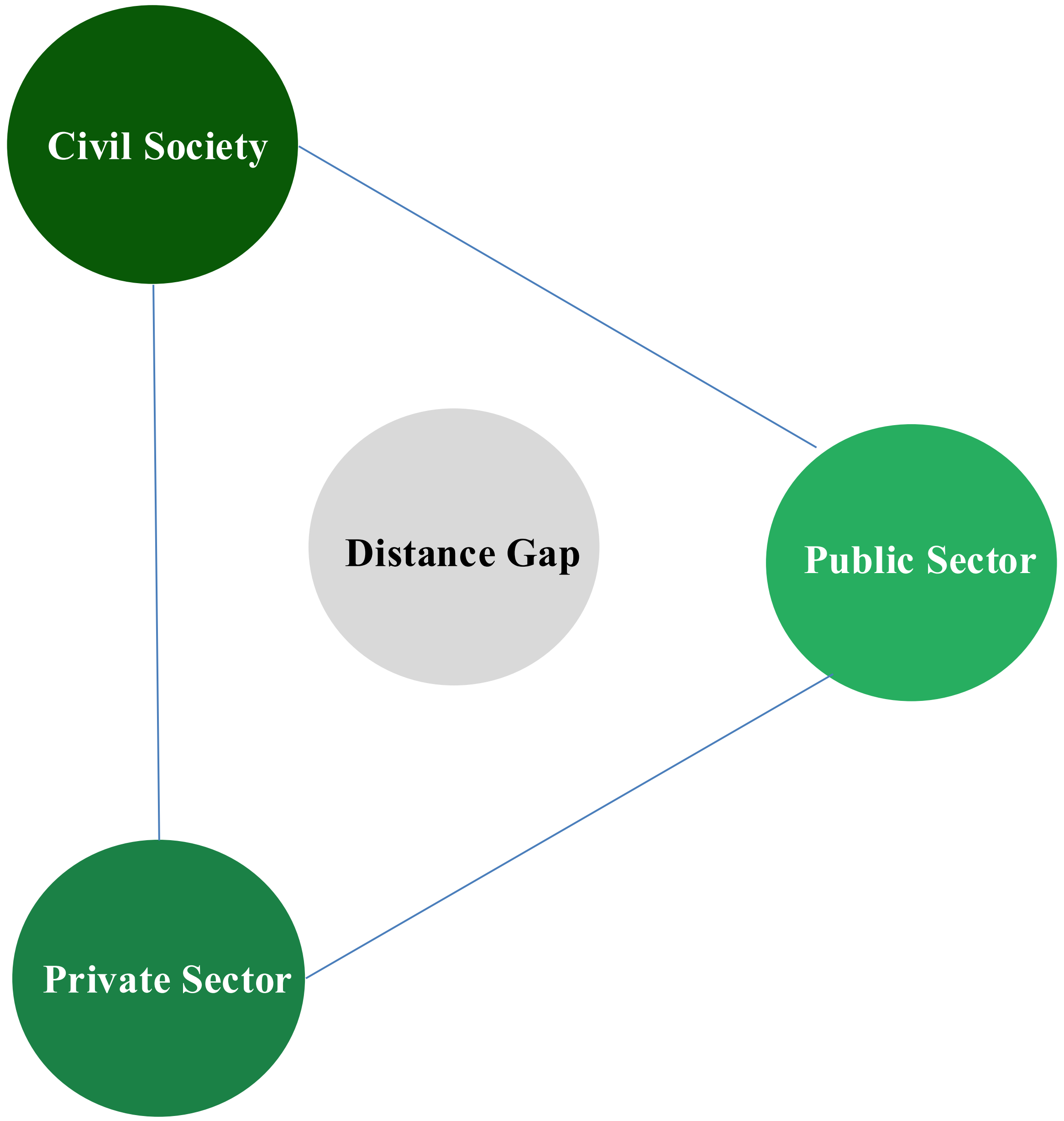
A multi-stakeholders approach to guide change

Multi-Stakeholder Governance Framework: Closing the Distance Gap



The gaps uncovered in the section before are the results of insufficient and non-coordinated efforts from the public sector, the private sector and the civil society. In order to decrease the mentioned gaps, these three parties must reconsider and redesign their approaches and initiatives. This raises the importance for each party to take actions if an unbalanced situation wishes to be avoided. Section 6 explores different ways and suggestions which should be considered by the three parties in order to make the implementation of the EUDR more feasible as well as realistic.

Multi-Stakeholder Governance Framework: Closing the Distance Gap



Public Sector EU Government & Public Institutions

- Promote R&D in green technologies to increase their affordability.

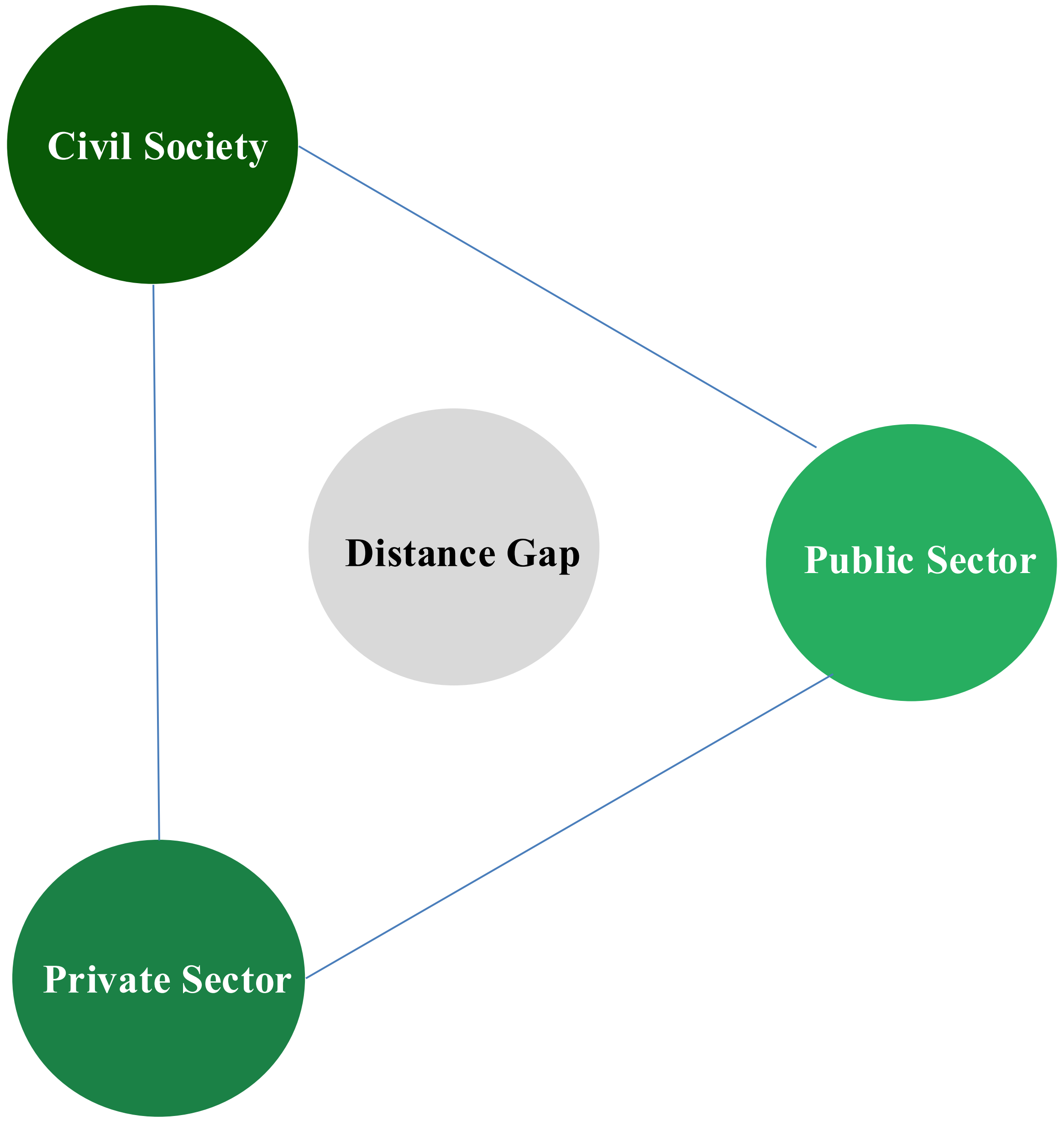
Green technology is technology that directly reduces environmental harm **or** indirectly enables more sustainable production and consumption by improving resource efficiency, transparency, and environmental accountability.

- Strengthen international collaborations (especially with ASEAN) to enable better informed policy making processes as well as cohesive adoption of regulations adapted to different parties' situation and means.

-Incentivization of adoption of green technologies through subsidies, grant funding and concessional credit.

-Legally enable grouped compliance model that allows cooperatives to submit collective geolocation and traceability data, reducing per-farmer costs. Provide clear legal guidance confirming how group certification and cooperative structures can formally meet EUDR traceability and due diligence requirements.

Multi-Stakeholder Governance Framework: Closing the Distance Gap



Public Sector Asian Government & Public Institutions

- Strengthening government expenditures in sustainability monitoring to help farmers comply. (NI-SCOPS)

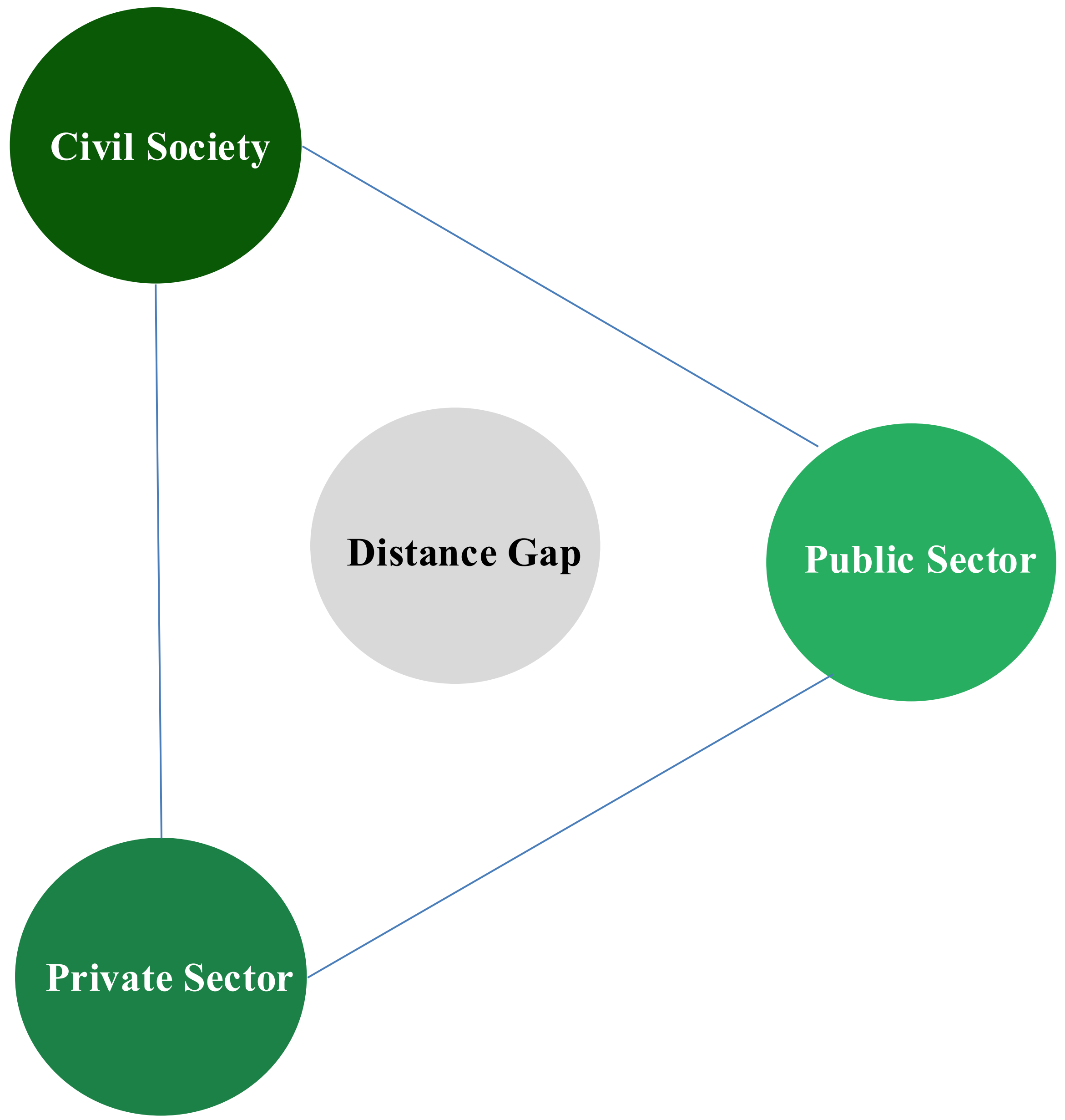
- Develop new mechanisms to reinforce rule of law.

- Develop a country wide digital database to support traceability, in line with EUDR requirements to avoid double verification and compliance costs. (Hithaishi CB, 2023)

- Embed farmer support within rural development strategies, prioritizing vulnerable groups like Indigenous Peoples and women. (WWF, 2025)

- Provide tax incentives or subsidies for actors of the upstream part of the rubber supply chain investing in GPS mapping and digital traceability tools.

Multi-Stakeholder Governance Framework: Closing the Distance Gap



Civil Society NGOs & Non-Profit Actors

- Promote and operationalize initiatives such as REDD+ ('Reducing emissions from deforestation and forest degradation in developing countries. The '+' stands for additional forest-related activities that protect the climate) (UNFCCC, n.d.)

- Push for rights and representation of smallholders and their needs. Work with local communities, conduct primary research, and be the voice for smallholders.

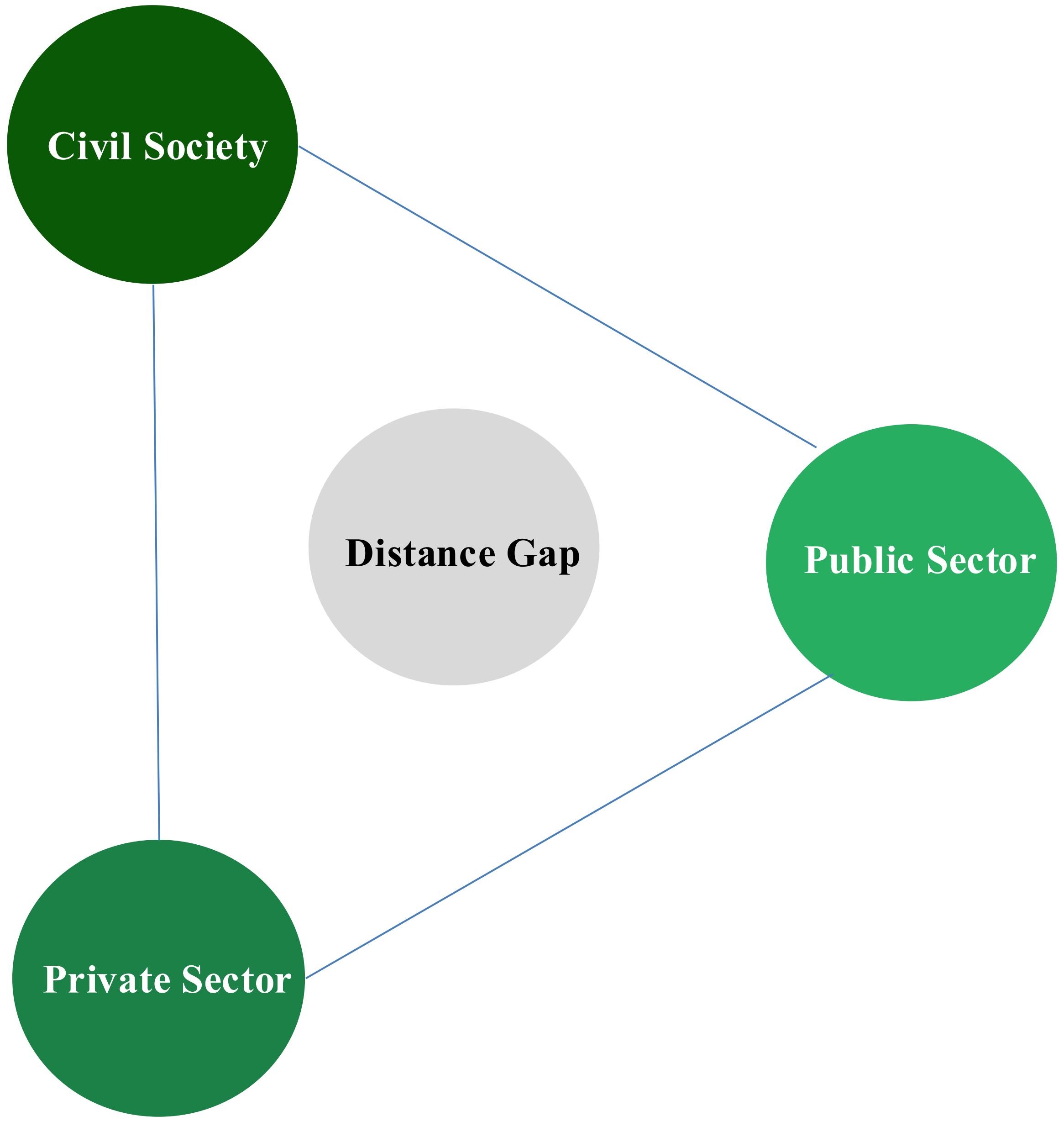
- Develop open-source compliance toolkits in local languages explaining:
•Required documentation
•Geolocation submission
•Risk mitigation expectations

- Help farmers impacted by the "cut and exit" risk strategy of private actors to an "engage and improve" approach more centered on proactiveness instead of reaction.

- Act as intermediaries in data collection to reduce mistrust between farmers and corporations.

GAPS ANALYSIS

Multi-Stakeholder Governance Framework: Closing the Distance Gap



Private Sector Market Actors in Rubber Supply Chain

-Lobby together to re-adapt EUDR to align with smallholders real contexts. This doesn’t mean loosening deforestation rules or removing geolocation, but changing the structural way in which compliance is needed to be met.

-Establish long-term sourcing agreements, pre-financing, and premium payments tied to sustainability outcomes.

-Support cooperative and producer organization structures to pool resources and improve smallholder bargaining power.

-Co-create technologies required for EUDR with the public sector. This could be done for instance through a collective fund from large market players.

-Offer multi-year purchase contracts to compliant smallholders to reduce uncertainty and prevent side-selling.

From Reactive to Proactive Governance

Key Conclusion: **The current gaps have demonstrated that, as of now, a business case for deforestation detection and traceability tools barely exists. Success would require moving beyond punitive compliance** toward collaborative governance where the public sector provides structural frameworks and international coordination, the private sector shares compliance burdens and co-creates solutions, and civil society ensures inclusive implementation that protects smallholder livelihoods. The next section links this conclusion with an economic model detailing quantitatively the potential impact of EUDR.

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Economic Model

Understanding the economic model embedded in the EUDR Requirement

ECONOMIC MODEL

Exposing the implicit theoretical framework underlying trade-based deforestation regulation

EUDR [1](“Regulation - 2023/1115 - EN - EUR-Lex”) is a trade-based conditional market access instrument designed to reduce deforestation by restricting EU market access to non-compliant commodities.

The embedded economic transmission mechanism is:

$$\Delta EU_{demand} \rightarrow \Delta Export\ Revenue \rightarrow \Delta Producer\ Price \rightarrow \Delta Land\ Conversion$$

Effectiveness therefore depends on price transmission, producer responsiveness, and limited displacement.

Core Structural Assumptions

1 Producer Revenue Sensitivity

Loss of EU demand or increased compliance costs reduce net export revenue and alter marginal land-use decisions.

→ Assumes positive land-use supply elasticity.

2 Compliance and Enforcement Efficacy

Monitoring, traceability, and sanctions are sufficiently robust to make non-compliance costly.

→ Assumes low evasion and uniform enforcement across Member States.

3 Limited Trade Diversion (Leakage Constraint)

Non-compliant exports are not fully reallocated to alternative importing markets.

→ Assumes imperfect substitution across export destinations (Armington,1969)(Hertel, 1997)

4 Effective Global Price Transmission

EU demand shocks influence world prices sufficiently to affect marginal land conversion.

→ Assumes integrated global rubber markets.

Analytical Implication

EUDR’s global deforestation impact is bounded by:

- EU share of global demand
- Elasticity of substitution across markets
- Global demand concentration.
- Land-use supply elasticity

Subsequent slides test whether these structural conditions hold for natural rubber (HS4001).

	Low Substitution	**High Substitution**
High EU Share	Larger impact	Moderate impact
Low EU Share	Moderate impact	Small impact

ECONOMIC MODEL

Global Import Share Analysis

Leverage Proxy Calculation

EU Imports of HS4001 (2023)

€1,592,462,531

Source: 1, Eurostat (2026)

Global Imports of HS4001 (2023)

€11,805,035,042

Source: 2, UN Comtrade (2023)

EU Leverage Proxy (Global)

EU leverage = €1,592,462,531 / €11,805,035,042

13.49%

Market Position Assessment

The EU accounts for **approximately 13.49% of global HS4001 imports**, positioning it as a **significant but non-dominant buyer** in the natural rubber market. This market share has critical implications for regulatory effectiveness:

Strategic Significance

€1.59B annual import value creates meaningful economic exposure for producers

Structural Limitation

86.5% of global demand lies outside EU jurisdiction, enabling market diversion

Impact Bound

Maximum direct demand-side shock ≤ 13.49% of global import demand.

→ Realized global land-use effect depends on substitution elasticity and diversion capacity.

ECONOMIC MODEL

Producer Level EU Leverage: Thailand, Indonesia, Vietnam

Thailand

EU Exports (2023) **$389.8M**

Global Exports (2023) **$3,648.6M**

EU Leverage Proxy

$389,764,091 / $3,648,558,935

10.68%

Vietnam

EU Exports (2023) **$94.2M**

Global Exports (2023) **$847.9M**

EU Leverage Proxy

$94,231,126 / $847,932,809

11.11%

Indonesia

EU Exports (2023) **$295.6M**

Global Exports (2023) **$2,478.6M**

EU Leverage Proxy

$295,573,936 / $2,478,600,213

11.93%

(UN, 2026)

Aggregate Findings

Producer Exposure Range

EU Global Share: 13.5%
Producer Revenue Exposure: 10–12%

Impact bound:

Maximum direct revenue shock to major producers ≤ 12% of export revenue.

Alternative Buyers

China (~25.6%) + unconcentrated demand = high diversion plausibility

ECONOMIC MODEL

Alternative buyers and Diversion Risk

China's Dominant Market Position

China's Global Import Share

25.61%

Nearly double the EU's share

Strategic Implications

- Absorbs non-compliant supply
- Undermines EU price signals
- Enables producer market switching

China's dominant position at **~25.6% of global imports** creates a viable alternative market for producers facing EU compliance costs. This structural reality significantly increases the plausibility of trade diversion and leakage.

Additional Major Import Markets

USA*	India	Rest of World
10.61%	5.12%	45.17%

*USA including Puerto Rico and US Virgin Islands

The Leakage Problem

Empirical Reality

Leakage is **very common** in trade-based environmental regulations. When one market restricts supply, it typically diverts to less regulated markets rather than reducing production.

EUDR's Assumption

EUDR assumes excluded supply **won't** divert to other markets—a strong assumption contradicted by historical evidence and market structure.

Structural Enabler

The **unconcentrated demand structure** (multiple large buyers) makes diversion not just possible but economically rational for producers.

Top 4 Buyers Concentration

Combined Market Share

54.83%

China + India + USA + EU

ECONOMIC MODEL

Compliance Shock: Economic Mechanisms

How EUDR creates negative demand shifts and their transmission to land-use decisions:

EUDR Compliance Requirements

Traceability Systems

Comprehensive supply chain tracking from plantation to product

Geolocation Data

GPS coordinates for all production plots to verify deforestation-free status

Certification Costs

Third-party verification, documentation, and ongoing compliance monitoring

Market Exclusion Risk

Non-compliant products barred from EU market access

Causal Transmission Chain

Step 1 **ΔEU Demand** → Step 2 **ΔExport Revenue** → Step 3 **ΔProducer Price** → Step 4 **ΔLand Conversion**

EUDR creates a **negative demand shift** for non-compliant HS4001 exports to the EU. This shock propagates through the value chain, theoretically altering producer incentives and land-use decisions.

Revenue Exposure Constraints

Maximum Direct Exposure

10–13%

Of export revenue for major producers

Critical Insight

Even under **full non-compliance**, direct revenue loss cannot exceed ~10-13% for Thailand, Indonesia, and Vietnam due to their diversified export markets.

Land-Use Response Requirements

For deforestation to actually decline, the model assumes: **(1)** producers cannot easily divert supply to alternative markets(Armington, 1969)(**(2)** price transmission from EU demand shocks reaches plantation-level decisions (Hertel, 1997),[1,2] , and **(3)** marginal price changes alter land conversion economics(Viner, 1950)

ECONOMIC MODEL

Modelling Framework: Armington Structure & Trade Diversion

Armington Structure

Source

Armington (1969)

IMF Staff Papers

Core Concept

Imperfect substitution across export markets—products are differentiated by origin, creating segmented markets with varying elasticities.

Application to EUDR

Models how easily producers can switch between EU and non-EU markets when facing compliance costs.

GTAP Framework

Source

Hertel (1997)

Cambridge University Press

Core Concept

Global Trade Analysis Project—comprehensive CGE modeling framework linking trade policy to economy-wide and land-use outcomes.

Application to EUDR

Models land-use response mechanisms and how trade shocks transmit to agricultural production decisions.

Customs Union Theory

Source

Viner (1950)

Carnegie Endowment

Core Concept

Trade diversion dynamics—preferential trade arrangements redirect trade flows from efficient to inefficient suppliers based on regulatory barriers.

Application to EUDR

Explains how EUDR may divert trade toward compliant suppliers while non-compliant supply seeks alternative markets.

Integrated Modeling Insight

When **substitution across export destinations is sufficiently elastic** and displaced supply is absorbed by alternative buyers (e.g., China), global price effects may be significantly attenuated. This means EUDR could successfully clean the EU supply chain while having limited impact on global deforestation rates—a phenomenon known as **leakage** or **carbon/deforestation displacement**.

ECONOMIC MODEL

Global Demand Concentration: Herfindahl-Hirschman Index Analysis

HHI Calculation Methodology

Herfindahl-Hirschman Index Formula:

$$HHI = \Sigma(S_i)^2$$

Where $\mathbf{S_i}$ denotes each importing country's share of global HS4001 imports (UN Comtrade, 2023). HHI ranges from 0 (perfectly competitive) to 10,000 (pure monopoly).

Calculated HHI for Global HS4001 Demand

1,048

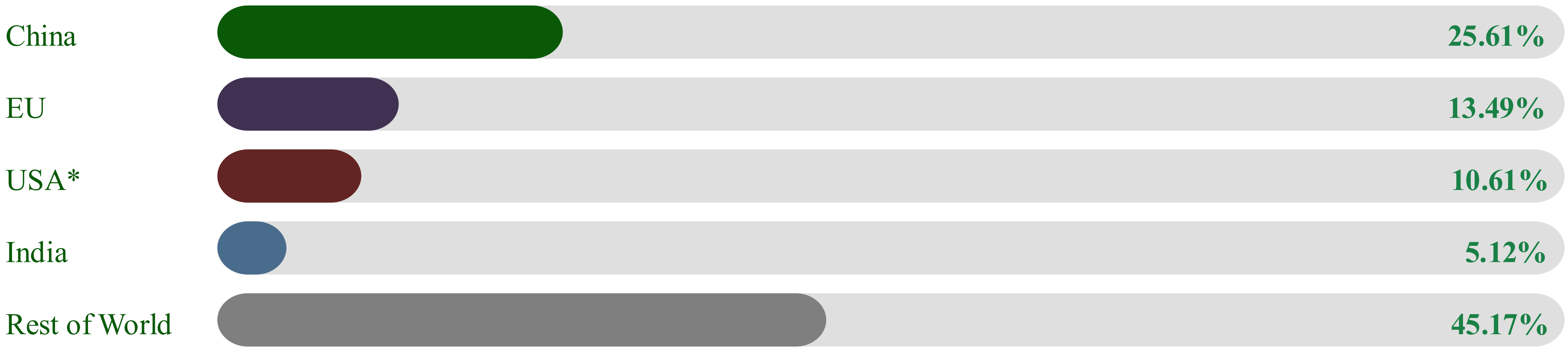
On the 0–10,000 scale

Competition Benchmarks

Unconcentrated	Moderate	Highly Concentrated
HHI < 1,500	**1,500–2,500**	**HHI > 2,500**

Source: U.S. DOJ & FTC Horizontal Merger Guidelines (2010)

Global Import Market Shares (2023)



*USA including Puerto Rico and US Virgin Islands

Structural Interpretation

Unconcentrated Market Structure

The HHI of **1,048** indicates an **unconcentrated demand structure :** no single buyer bloc dominates global demand.

Trade Diversion Plausibility

The presence of **multiple viable alternative buyers** structurally enables trade diversion under partial demand shocks from EUDR.

Policy Implication

Effective deforestation reduction requires **coordinated multilateral action**—unilateral EU measures face structural constraints on global impact.

ECONOMIC MODEL

Empirical Evidence: European Commission Impact Assessment

Ex-ante scenario analysis and critical evaluation of underlying assumptions

Commission's Estimated Impact (Larsen, 2021)

Projected Deforestation Reduction

~29%

in EU-consumption-linked deforestation by 2030

Underlying Assumptions

High Compliance

Assumes producers will adopt compliance systems and meet traceability requirements at scale

Limited Leakage

Assumes minimal diversion of non-compliant supply to alternative markets outside EU

EU-Linked Focus

Measures EU-consumption footprint rather than global land conversion

Price Transmission

Assumes EU demand shocks effectively transmit to producer-level price signals

Critical Evaluation

Ex-Ante vs. Observed

The **~29-30% figure** is an **ex-ante scenario** from the Commission's Impact Assessment, not an observed or validated outcome. It represents modeled projections under idealized conditions.

Assumption Sensitivity

Results are highly sensitive to compliance rates and leakage assumptions. As shown in Sections 4.2-4.4, the **structural characteristics** of the natural rubber market (bounded EU leverage, unconcentrated demand) are sensitive to these parameters.

Scope Limitation

Even if achieved, this represents **EU supply chain cleaning** rather than global deforestation reduction. Total global forest loss may remain unchanged if supply diverts to other markets.

ECONOMIC MODEL

Independent CGE Modeling: Argentina Case Study

Equilibrium analysis with explicit trade reallocation mechanisms

de la Vega (2026) Findings

Deforestation Reduction

2–3%

Reduction in deforested hectares

GDP Impact

~0.1%

Small macroeconomic effect

Key Mechanism

Trade reallocation dampens land-use response—diverted supply finds alternative markets, attenuating price signals.

Operationalized Mechanisms

Armington Substitution

Models' imperfect substitution between EU and non-EU markets, allowing producers to reorient trade flows based on relative compliance costs.

Trade Diversion

Explicitly models how non-compliant supply seeks alternative buyers (e.g., China), reducing the price impact of EU market exclusion.

Price Transmission

Captures how demand shocks transmit (or fail to transmit) through the value chain to plantation-level production decisions.

Comparative Assessment

Consistency with Structural Analysis

The **lower-bound CGE estimate (2-3%)** is consistent with the structural characteristics identified in Sections 4.2–4.4: **bounded EU leverage** (~10-13%) and **unconcentrated global demand** (HHI ~1,048).

Policy Implication

Independent equilibrium modeling that **explicitly allows trade reallocation** produces more modest land-use effects (low single digits), consistent with the view that EU-only market access constraints attenuate global gains through diversion.

Economic Reality: Technology enables compliance, but does not Guarantee impact

What the model shows

- EU accounts for ~13.5% of global HS4001 imports
- Major producers have ~10–12% revenue exposure to EU
- High diversion plausibility (China ~25–27% import share)
- Moderate import concentration (HHI ≈ 1,048)

Implication:
Unilateral EU demand shock is bounded in global price transmission power.

What this means for technology

Technology Can:

- Reduce compliance costs
- Improve traceability credibility
- Detect deforestation events
- Support due diligence reporting

Technology Cannot (Alone):

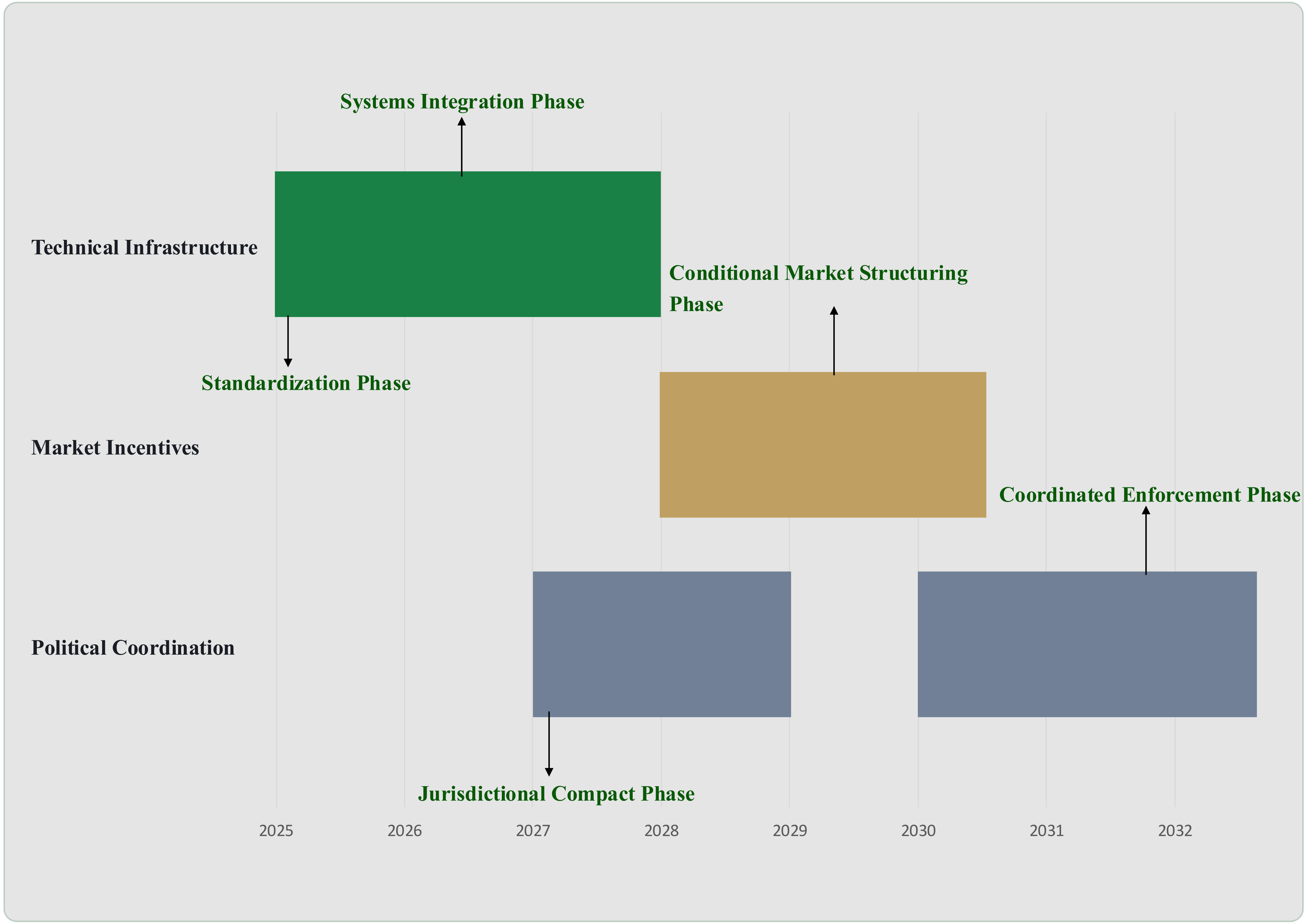
- Prevent trade diversion
- Restructure global demand
- Override substitution elasticities
- Ensure land-use transformation without coordinated enforcement

Therefore, EUDR effectiveness depends not only on monitoring capability, but on systemic integration of technology, incentives, and political coordination.

Roadmap

Implementation roadmap 2025 - 2032

Implementation Framework: 2025-2032 Pathway



Technical Infrastructure

Standardized geospatial reporting and integrated monitoring systems to reduce compliance friction and increase detection credibility.

Market Incentives

Preferential procurement and conditional contracts to amplify effective producer exposure beyond unilateral EU demand.

Political Coordination

Jurisdictional compacts and bilateral enforcement cooperation to constrain substitution and increase effective global leverage.

Strategic Logic

Each phase builds systematic leverage, progressively addressing structural constraints while maintaining credibility through measured claims.

PHASE 1 2025–2026

Standardization Phase

Reduce compliance friction and fragmentation

Structural Constraint Addressed

High Cost

Traceability systems impose prohibitive compliance costs on smallholders

Exclusion Risk

Smallholders face barriers to market access under fragmented standards

Inconsistent Standards

Geolocation protocols vary across member states and supply chains

Key Actions

1. **EU-wide Standardized Geospatial Reporting Protocol**
   Polygon-level minimum requirements harmonized across all member states
2. **Open-Source API Template for Satellite Integration**
   Freely accessible technical infrastructure reducing development costs
3. **Central EU Compliance Registry Format**
   Unified data structure enabling interoperability across platforms

Mechanism

Lower Compliance Cost

↓

Higher Participation

↓

More Credible Enforcement

↓

Stronger Price Signal

Key Risk

Does not solve leakage alone, market diversion remains possible

Impact on Structural Constraint

Reduces compliance fragmentation by establishing unified technical standards. Increases effective producer exposure by lowering barriers to participation, expanding effective participation beyond the current 10–12% exposure baseline.

PHASE 2 2026–2027

Systems Integration Phase

Move from reporting to automatic compliance infrastructure

Structural Constraint Addressed

Static Due Diligence

Current systems rely on periodic documentation rather than continuous monitoring

Documentation-Based Enforcement

Enforcement actions occur after violations, lacking real-time verification capabilities

Key Actions

ERP + Satellite API Integration Requirements

Mandatory connection between enterprise resource planning systems and Earth observation data feeds

Real-Time Risk Flagging Systems

Automated alerts triggered by anomalous land-use changes or supply chain discrepancies

Shared EO Monitoring Dashboards

Customs authorities gain direct access to satellite-derived compliance verification tools

Mechanism

Raises the **expected cost of non-compliance** by shifting from ex-post documentation review to ex-ante risk detection.

- Detection probability increases significantly
- Response time accelerates from months to days
- EUDR's enforcement credibility increases materially

Still unilateral, but significantly stronger

Key Risk

Market diversion to non-EU destinations remains viable for non-compliant producers

Impact on Structural Constraint

Transforms EUDR from a documentation exercise into a credible enforcement mechanism, increasing effective producer exposure by raising detection probability and accelerating enforcement response.

PHASE 3 2027–2028

Jurisdictional Compact Phase

Shift from farm-level policing to regional governance incentives

Structural Constraint Addressed

Millions of Smallholders

Farm-level monitoring is institutionally infeasible at scale across dispersed producers

Fragmented Governance

Lack of coordination between local, regional, and national enforcement bodies

Key Actions

EU Recognizes Subnational Deforestation-Free Jurisdictions
Provinces and districts achieving verified forest conservation receive preferential market access status

Access Preference for Certified Regions
Streamlined compliance pathways and reduced documentation burden for certified jurisdictions

Performance-Based Forest Governance Benchmarks
Transparent metrics measuring jurisdictional progress on deforestation reduction and enforcement capacity

Mechanism

Aligns Incentives at Government Level

Regional governments become stakeholders in compliance outcomes

Reduces Fragmentation

Consolidates monitoring and enforcement at jurisdictional scale

Creates Reputational Competition

Regions compete for preferential market access based on performance

Shifts compliance incentives from individual farms to subnational governance structures.

Key Risk

Jurisdictional certification may mask localized deforestation; requires robust sub-jurisdictional monitoring

Impact on Structural Constraint

Addresses leakage via regional coordination and reduces enforcement fragmentation. Increases effective producer exposure beyond 10–12% by creating jurisdictional-level accountability and reputational incentives for regional governments.

PHASE 4 2028–2030

Conditional Market Structuring Phase

Amplify EU leverage via buyer coordination

Structural Constraint Addressed

13.5% Market Share Insufficient

The EU's share of global natural rubber imports alone is inadequate to drive systemic transformation. Without coordination mechanisms, market power remains fragmented and producers can divert supply to less regulated destinations.

Key Actions

Long-Term Procurement Contracts Conditional on Jurisdictional Compliance
Multi-year supply agreements that lock in compliant supply channels and provide revenue certainty

Preferential Pricing for Compliant Supply
Price premiums and favorable terms for verified deforestation-free rubber

Public Disclosure of Sourcing Regions
Transparency requirements creating reputational pressure and enabling civil society monitoring

Mechanism

Transforms EUDR
From exclusion tool → reward mechanism

Reduces Diversion
Locks supply into compliant channels through contractual commitments

Shifts Market Dynamics
Creates positive incentives for compliance rather than purely punitive measures

Key Risk

Requires significant buyer coordination; free-rider problems may undermine collective action

Impact on Structural Constraint

Amplifies effective leverage beyond the 13.5% market share by coordinating buyer actions and creating contractual lock-in.

PHASE 5 2030+

Coordinated Enforcement Phase

Solve leakage via importer coalition

Structural Constraint Addressed

China (≈27%) + US (~10%)

Major importers outside EU regulatory scope create substantial diversion channels

High Substitutability

Natural rubber is highly fungible across markets, enabling easy supply redirection

Key Actions

Bilateral EU–Producer Enforcement Agreements

Direct government-to-government compacts establishing mutual enforcement obligations and data sharing

Joint Satellite Data Platforms

Shared Earth observation infrastructure enabling coordinated monitoring across importer jurisdictions

Explore Plurilateral Alignment with Major Importers

Negotiate coordinated regulatory frameworks with China, US, and other significant rubber importers

Mechanism

Reduces Substitution Elasticity

Coordinated demand limits alternative market options for non-compliant producers

Transforms Unilateral → Coordinated

Turns isolated regulatory action into synchronized demand shift

Changes Global Equilibrium

This phase addresses the substitution elasticity constraint directly by coordinating demand across major importing jurisdictions.

Key Risk

Geopolitical tensions may impede coordination; requires sustained diplomatic investment

Impact on Structural Constraint

This is the only phase that structurally changes global equilibrium. Reduces substitution elasticity by coordinating demand across major importers, effectively eliminating diversion channels. Potentially transforms unilateral leverage into majority-demand coordination, materially reducing diversion capacity.

Conclusion

What Technologies Can Enable EUDR Compliance?

Detection Layer (Earth Observation)

- Sentinel-1 (radar, cloud-resilient)
- Sentinel-2 (multispectral optical)
- NDVI Index calculation
- ML-based rubber classification

Traceability Layer

- Geolocation capture (polygon-level)
- Blockchain / distributed ledgers (optional)
- ERP–API harmonization
- Digital reporting pipelines

Governance Integration Layer

- Jurisdictional datasets
- Risk-tiering mechanisms
- Procurement-linked enforcement
- Bilateral verification systems

> **Technology is necessary for compliance — but only effective when embedded in aligned incentive structures.**

Integrated stack required:

Monitoring (EO) + Traceability (Data Architecture) + Enforcement Linkage (Governance) → Only the full stack produces credible compliance.

Will EUDR Alone Deliver Major Deforestation Reduction?

Evidence-Based Constraints:

- EU represents a significant but non-dominant share of demand.
- Rubber markets exhibit diversion capacity.
- Land-use change responds to global price signals.
- Leakage risk is non-trivial in trade-based environmental policy.

Balanced Conclusion:

> Given EU's non-dominant market share and high diversion capacity in rubber markets, unilateral trade conditionality has bounded global land-use impact.

However, its impact increases significantly when:

- Compliance technologies reduce monitoring asymmetries
- Major importing blocs coordinate
- Procurement conditionality reinforces price signals

Strategic Takeaway

- EUDR transforms compliance from paper-based verification to data-based verification.
- Earth Observation and digital traceability make deforestation risk measurable.
- Global land-use outcomes depend on coordinated demand-side enforcement beyond the EU.

Appendix

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