Leveraging remote sensing for transparency and accountability in Amazonian commodity supply chains

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Primer

Leveraging remote sensing for transparency and accountability in Amazonian commodity supply chains

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SUMMARY

Stopping deforestation linked to agricultural commodity supply chains is crucial for Amazonian biodiversity protection and climate change mitigation. Remote sensing technologies are essential for monitoring deforestation, providing precise data on land-use changes. However, effective deforestation control requires more than monitoring alone. In this Primer, we explain how remote sensing can be applied to effectively monitor deforestation activities. We further elaborate on what is needed to improve transparency and traceability within commodity supply chains so that we can identify and hold accountable those contributing to forest loss, preventing their products from entering the market. While cross-sector initiatives are transforming approaches to this challenge, greater integration is needed to connect these elements and ensure that forest-risk commodities cease driving deforestation in the Amazon.

INTRODUCTION

The Amazon rainforest, one of the most biodiverse ecosystems on Earth, plays a crucial role in global climate regulation and provides a habitat for a vast array of species. These rainforests store significant amounts of carbon as biomass, while moisture evaporating from the Amazon contributes significantly to the regional water cycle, supporting natural and anthropogenic land systems. The Amazon's exceptional environment provides other crucial ecosystem services, such as delivering rainfall that supports agricultural production, suppressing the risk of fire, and controlling vectors that spread diseases like malaria. Furthermore, it holds immense cultural importance, as it is an ancestral home to numerous Indigenous and local communities whose traditional knowledge and practices are deeply intertwined with the forest's well-being. However, increasing deforestation and forest degradation have raised concerns about the future of the Amazon and its associated ecosystem services. For example, parts of the Amazon have become net carbon sources, releasing more CO_2 into the atmosphere than they sequester, thereby accelerating climate change.

This critical biome is under unprecedented pressure from unsustainable land-management practices, particularly those linked to the expansion of agricultural areas. While agricultural expansion, driven by increasing demand for soy, corn, and beef, is the primary driver of deforestation in the Amazon basin, illegal logging, mining operations, drug trafficking, and infrastructure development further fragment and degrade the forest, creating pathways for encroachment. Adding to these pressures is the rising incidence of wildfires deliberately ignited to clear land for agriculture and/or resource extraction. These fires not only accelerate forest loss and release significant amounts of greenhouse gases, but they also pose a serious risk to human health and well-being, displacing communities and threatening livelihoods.

The interconnected nature of these threats underscores the urgent need for active monitoring of these land systems to identify and address the drivers of deforestation. Remote sensing is one such tool that allows us to monitor and identify the drivers of deforestation and degradation with greater detail at regional scales. In this Primer, we first introduce the history of agricultural expansion in the Amazon and the associated driving forces of deforestation. We then elaborate on how remote sensing can be utilized to better monitor and manage deforestation by advancing the transparency of commodity supply chains. Finally, we reflect upon barriers to efficiently deploying remote sensing techniques along commodity supply chains. We emphasize that the usage of remote sensing technology is crucial to inform more effective and transparent identification of actors operating within the supply chains associated with deforestation commodities and, ultimately, halt the destruction of the Amazon.

THE HISTORY OF AGRICULTURAL EXPANSION IN THE AMAZON

The expansion of agricultural land use in the Amazon has a complex history, deeply intertwined with social and economic forces.

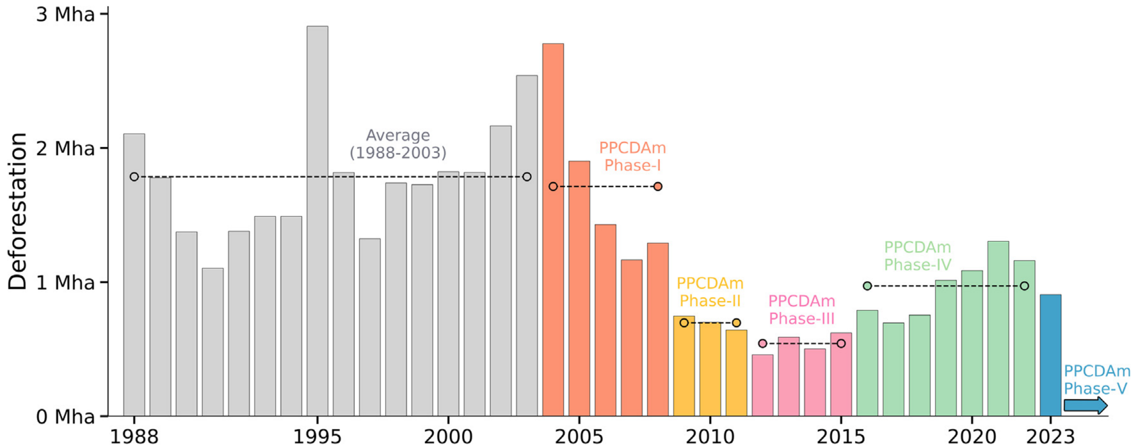

Figure 1. Annual deforestation rates in hectares
Data source: PRODES/INPE.

Initially, during the early stages of frontier settlement, land was abundant, while labor and capital were scarce. These farmers typically practiced shifting cultivation, also known as slash-and-burn agriculture, a system where small plots of forest are cleared and burned to release nutrients for crops. After a few years of cultivation, the soil fertility declines, and the plot is abandoned, allowing a secondary forest to regrow. This cycle, while having some environmental impact, generally allowed for forest regeneration and maintained a diverse mosaic of forest patches at different stages of succession. As more people migrated to the Amazon, the result of a series of public policies in the 1960s that incentivized the occupation of the region (e.g., the construction of the Transamazon road and mass land regularization), land became scarcer for some, and the labor market emerged.

The shift in the balance of resources altered the power dynamics, weakening the position of small-scale farmers and strengthening that of large landowners who controlled increasing amounts of land and capital. At this point, the type of cattle ranching adopted by large landowners created by lenient land regularization programs significantly altered the landscape. Large swaths of forest, including secondary forests recovering from previous agricultural use, were converted to pasture, leading to more extensive and permanent deforestation. While small-scale farmers also sometimes transitioned to cattle ranching as their families and resources grew, their operations remained smaller and more diversified, often retaining some annual crops and even incorporating perennials, thus creating a more heterogeneous land-use pattern. The scenario of fast and intense occupation and forest destruction started to call international attention, as in the early 1980s, more than 14 million hectares of forest had already been lost.

Agricultural expansion pressure intensified in subsequent years, shifting to the expansion of mechanized monocultures such as soy, driven especially by international demand. This placed Amazonian governments in the increasingly difficult position of reversing deforestation trends while grappling with the legacies of fast and intense occupation that resulted in land disputes and violence, in particular against local communities and Indigenous peoples. A change in this pattern would only start to be observed after 2004, when significant slowdown in Brazilian deforestation rates began to be observed due to a confluence of factors, including public policies like the Action Plan for Deforestation Prevention and Control in the Legal Amazon (PPCDAm) and private commitments such as the Soy Moratorium, which together contributed to a nearly 80% reduction in deforestation (Figure 1).

While significant progress was made in reducing deforestation from 2004 to 2012, recent trends show a resurgence in deforestation beginning in 2013. Simultaneously, increasing global demand for agricultural commodities like beef and soy incentivizes the further expansion of agriculture into forested areas. Furthermore, infrastructure projects such as roads and dams, while potentially boosting economic development, can also facilitate deforestation by opening up previously inaccessible areas to agricultural activities and extractive industries. These combined pressures have, once again, contributed to the recent increase in deforestation rates, undermining the progress made in previous years and threatening the long-term sustainability of the Amazon.

AGRICULTURAL SUPPLY CHAINS DRIVING DEFORESTATION

Deforestation in the Amazon is significantly influenced by both global and domestic demands for agricultural commodities, particularly beef and soy (Figure 2). Given the important role that agricultural markets play in driving deforestation in the Amazon, supply chain initiatives such as zero-deforestation commitments have emerged as potential policy solutions. The Amazon soy moratorium serves as a key example of such an initiative. Initially established in 2006, the moratorium was an agreement among major soybean traders not to purchase soybeans grown on recently deforested lands in the Brazilian Amazon biome. The soy moratorium has played an important role in reducing deforestation in this region, preventing around 18,000 ± 9,000 km^2 of deforestation during its first decade (2006–2016). Building on this success, a variety of other supply chain initiatives have been adopted, including efforts to expand their scope to other commodities (e.g., cattle agreements such

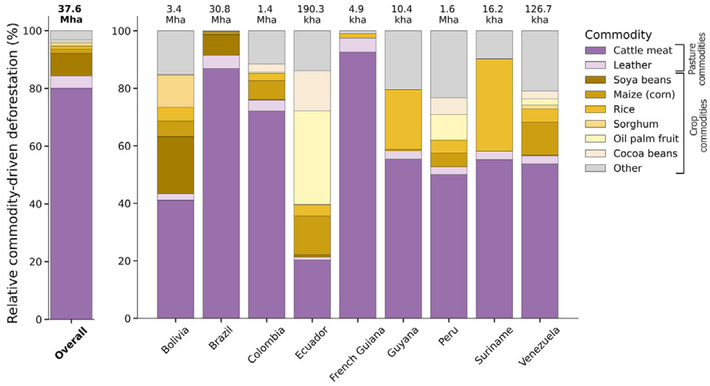

Figure 2. Agricultural commodity-driven deforestation, shown as a percentage of total deforestation across the Amazon (i.e., overall) and separately for each Amazonian country between 2001 and 2022

Estimates for French Guiana cover the period from 2001 to 2006 due to the lack of agricultural statistics data post-2006. Deforestation estimates are based on the Deforestation Driver and Carbon Emission (DeDuCE) model, version 1.0.1.

as G4), more directly influence domestic supply chains (e.g., Boi na Linha and the Cerrado Protocol), or transition from voluntary corporate initiatives toward regulatory obligations (e.g., European Union Deforestation Regulation [EUDR]).

Despite their promise, multiple gaps in implementation have undermined the impact of supply chain interventions seeking to reduce deforestation in the Amazon. First, the voluntary nature of many supply chain interventions may lead to selective adoption, whereby actors with cleaner supply chains enter into agreements, while dirtier producers do not. Such sorting can give individual buyers the ability to honestly claim an absence of deforestation within their supply chains while doing little to address the underlying drivers of deforestation within a commodity production system. Second, early supply chain interventions often targeted deforestation in specific geographies or commodity supply chains. Such targeting encouraged indirect land-use change and leakage, whereby deforestation reductions in some locations could drive commodity expansion, and associated deforestation in other locations. Finally, to simplify implementation, many supply chain interventions have focused monitoring on direct suppliers. However, such incomplete implementation ignores deforestation undertaken by indirect suppliers, creating incentives for longer supply chains that can evade monitoring. While the importance of each of these processes has varied across different supply chain initiatives, together they represent an important challenge preventing reductions in commodity-driven deforestation.

THE POWER OF REMOTE SENSING MONITORING TOOLS

Remote sensing has emerged as a transformative tool in monitoring commodity supply chains, offering unprecedented insights into the complex relationship between production and environmental impacts. Traditional methods of supply chain monitoring often rely on self-reported data, which can be unreliable and lack transparency. However, knowing precise sourcing patterns, such as clearly defined supply sheds, allows remote sensing via satellite imagery to provide independent, objective verification of on-the-ground practices and detect unsustainable activities like deforestation for agricultural expansion (Figure 3). This enhanced transparency empowers consumers, investors, and governments to hold companies accountable for their environmental commitments and promotes greater responsibility throughout the supply chain.

The power of remote sensing lies in its ability to monitor vast areas efficiently and cost effectively. Satellite imagery can cover extensive regions, including remote and inaccessible areas, providing a comprehensive view of land-use changes and environmental impacts associated with commodity production. This broad perspective is crucial for understanding the full scope of supply chain sustainability and identifying potential risks and hotspots of deforestation and forest degradation. Added to that, remote sensing data can be collected repeatedly over time, enabling the monitoring of trends and assessment of the effectiveness of interventions aimed at reducing environmental impact.

High-spatial- and -temporal-resolution satellite imagery, combined with advanced data processing and analysis techniques, enables detailed monitoring of specific areas within commodity supply sheds. This granular level of detail allows for the identification of individual farms, plantations, or mines and the assessment of their specific environmental performance. By integrating remote sensing data with supply chain information, such as the location of farms and processing facilities, it becomes possible to trace the origin of commodities and monitor deforestation and other environmental impacts within specific supply chains. This detailed monitoring enables companies to identify and address sustainability risks within their own operations and supply chains and promotes greater accountability and transparency.

Publicly available remote sensing data play a vital role in empowering stakeholders beyond the private sector. Governments can use remote sensing data to monitor compliance with environmental regulations, target enforcement actions, and assess the effectiveness of land-use policies. Civil society organizations and researchers can use these data to independently monitor deforestation and other environmental impacts, holding companies and governments accountable and advocating for greater environmental protection. The democratization of information fosters a more inclusive and transparent approach to supply chain sustainability and promotes more effective forest governance.

Numerous remote-sensing-based deforestation monitoring systems track forest loss across the Amazon. Governmental systems like Brazil's PRODES (National Institute for Space Research - INPE) and civil society initiatives like Global Forest Watch (University of Maryland/World Resources Institute) provide spatially explicit data to inform deforestation location and trends. More recently, MapBiomas Amazonia, a multi-sectoral partnership encompassing non-governmental organizations (NGOs), universities, and tech companies, offered a particularly

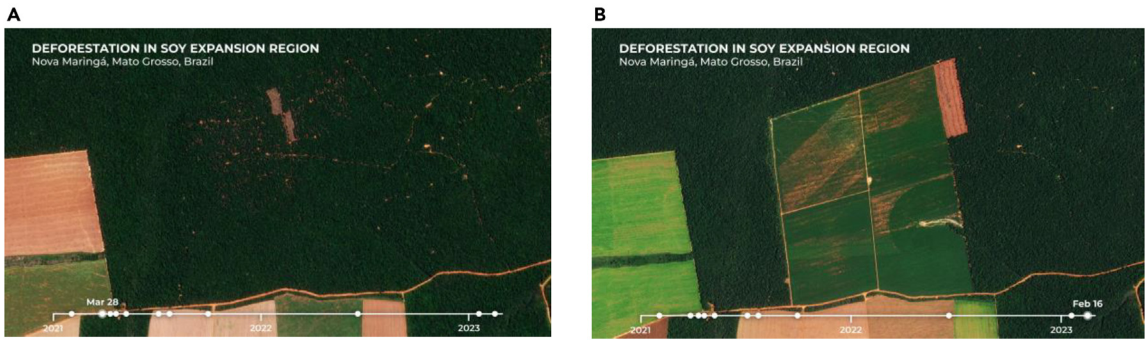

Figure 3. PlanetScope data showing the transition from forest to cropland
In only 2 years, this area (A) has been degraded, deforested, prepared, and turned into (B) agriculture. Nova Maringá was mapped in the soy moratorium annual report as one of the largest deforested areas that has been converted into soybean fields.

powerful platform for monitoring land-use and cover change across the entire Amazon biome. This collaborative effort, bringing together all Amazonian countries with local partners to create tailored national systems, facilitates knowledge sharing, promotes best practices, and strengthens regional monitoring capacity. MapBiomas leverages advanced cloud computing and machine learning to process vast quantities of satellite imagery, generating high-resolution annual land cover maps. Complementing these efforts, near-real-time deforestation alert systems like GLAD (University of Maryland) and SAD (Imazon) enable rapid responses and targeted enforcement actions.

These advancements in publicly accessible remote sensing data are revolutionizing deforestation monitoring and creating new opportunities for supply chain transparency. In Brazil, the Rural Environmental Registry (CAR), a cadastral system that requires landowners to register their property boundaries, can be linked with remote sensing data to monitor deforestation at the property level. This integration enables the precise monitoring of deforestation within specific company supply sheds, allowing companies to track the origin of commodities and ensure that their sourcing practices are not contributing to deforestation. By combining near-real-time deforestation alerts with CAR data, companies can rapidly identify and respond to deforestation events within their supply chains, minimizing their environmental impact and promoting greater accountability. This granular level of monitoring, combined with transparent and accessible data, is essential for building effective monitoring systems and fostering sustainable commodity supply chains in the Amazon.

SUPPLY CHAIN TRANSPARENCY FOR DEFORESTATION MONITORING

To improve the accountability and effectiveness of supply chain initiatives, enhanced visibility, traceability, and transparency are crucial. This requires detailed information on the origin of commodities and the actors involved at each stage of the supply chain. As mentioned before, for remote sensing information to be effective, companies and consumer markets must know from where the products are coming from, information that remains highly inaccessible for many supply chains around the world. Initiatives like Trase, which maps trade flows from the place of production to the country of consumption, offer important sector-wide insights for identifying deforestation risks associated with specific actors and markets. By combining trade data, agricultural production statistics, and deforestation and crop maps, Trase creates a comprehensive picture of commodity supply chains, facilitating more targeted interventions. This granular level of detail allows companies, consumers, and governments to understand their exposure to deforestation risk and make more informed decisions about sourcing and consumption.

It is important to highlight that the solution developed and distributed by Trase is a sectoral representation, not an individual depiction of each company's operations. Because Trase applies the same operational assumptions across an entire sector within a given country, accuracy can be reduced for specific companies and their supply sheds. More accurate and transparent estimations, leading to a better understanding of impact propagation along trade flows, require a more ambitious commitment to transparency from companies. For example, companies could disclose their supply sheds, even if aggregated at the jurisdictional level (municipalities or departments), in their sustainability reports, not only allowing better risk estimates but also improving the risk allocation to those not committing to the same level of transparency.

By integrating remote sensing data with supply chain information, it becomes possible to monitor deforestation within specific company supply sheds, enhancing transparency and enabling companies to take responsibility for the environmental impacts of their sourcing practices. Publicly available remote sensing data empower governments, civil society organizations, and researchers to independently monitor deforestation and hold actors accountable, fostering greater transparency and promoting more effective forest governance.

CHALLENGES TO IMPROVING SUPPLY CHAIN MONITORING IN THE AMAZON

The increasing availability of sophisticated deforestation monitoring systems, models, and cadastral datasets offers valuable opportunities for improving governance in agricultural supply chains and reducing deforestation linked to commodity production. However, realizing this potential requires addressing several key challenges, particularly the need for more comprehensive commitments from companies that go beyond simply monitoring their direct operations. While data and tools for

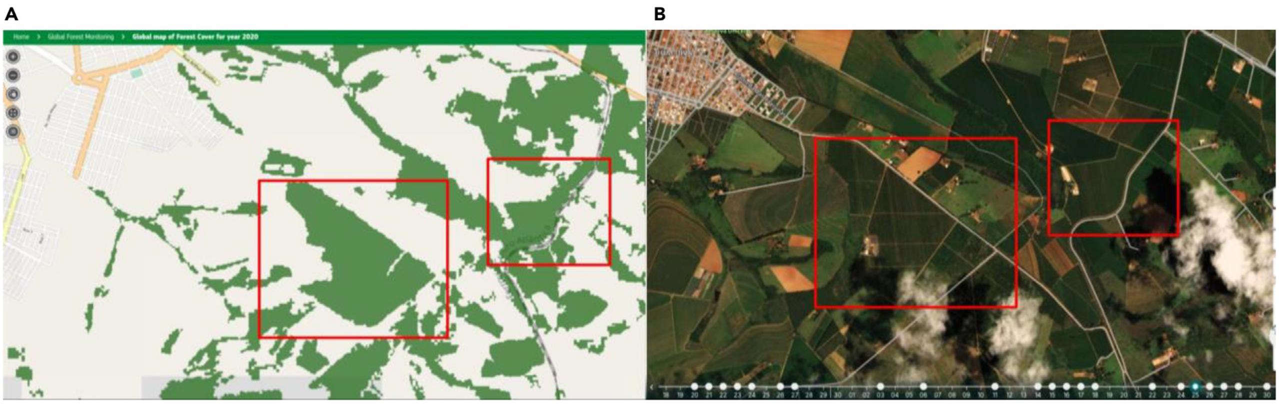

Figure 4. The usage of high-resolution data to refine land cover classification
(A) The forest (in green) and non-forest map from JRC located in one of the largest coffee-producing municipalities (Patrocinio - Minas Gerais) in Brazil.
(B) A PlanetScope image from Decmeber 25, 2020, showing that the areas inside the red squares were already coffee plantations.

effective monitoring are increasingly accessible, the inherent complexities of land-use dynamics and intertwined supply chains hinder their efficient deployment.

Managing risks along complex and opaque supply chains

Emerging regulations, such as the EUDR, reflect a growing recognition of the increase in maturity around conciliating traceability data and remote-sensing-based products to detect deforestation; however, at the same time, they introduce ambitious requirements for compliance from supply chains that are still opaque, complex, and fragmented. The EUDR not only requires granular data on sourcing locations but also compels companies to thoroughly assess and mitigate deforestation risks throughout their entire supply chain, from the production area to the final product that will be placed in the European market. Meeting these requirements demands a significant improvement in corporate approaches to supply chain monitoring and a greater commitment to comprehensive risk assessment along the supply chain. This will require innovative approaches to data collection and analysis, enhanced collaboration between public and private sectors, and a greater willingness from companies to invest in robust monitoring systems and engage in responsible sourcing practices.

Accurate mapping of tree-crop commodities

One of the most pressing technical challenges shared across various sectors, from small-scale producers to large commodity exporters, is the accurate mapping of tree-crop commodities without mistakenly classifying them as natural forest cover. The complexity arises from the overlap in spectral and structural characteristics between tree crops and forested areas when using remote sensing data.

For example, a forest and non-forest map developed by the Joint Research Centre (JRC) provides a useful baseline. However, as a global product, it inherently contains limitations. In the context of the EUDR, the JRC global forest cover map can be employed as a non-mandatory and non-legally-binding source of information. Despite areas being marked as forest, when high-resolution imagery is analyzed, we often discover mistakes. Figure 4 shows a specific case of a coffee plantation that was already established by the EUDR cutoff date in December 2020 but was misclassified as forest. This example underscores the risk of relying on few or single datasets, which can lead to misinterpretation. Due to errors in the mapping of commodities, another challenge arises: false positive alerts of deforestation and degradation, where an alert system flags deforestation or disturbance. For example, coffee pruning may be mistaken for tree cover loss.

Detecting deforestation risk at the asset level

Another significant challenge in detecting deforestation propagation along the supply chain is linked to both identifying the location of assets, such as mills, silos, and slaughterhouses and linking individual assets to trade flows. While facilities can be detected by the usage of remote sensing techniques, this challenge extends beyond mapping their location to also understanding how they are connected to individual trade flows, preventing, through well-managed procurement practices, farms with deforestation from joining the facility. A good example of how governments, sectors of civil society, and companies come together to solve this challenge is the Supply Chain Data Partnership, established with the aim of generating and providing reliable and verified facility location databases. This initiative has the potential to support certification efforts and traceability systems by verifying the geographic origin of assets, enabling buyers and investors to ensure transparency and monitor the asset's environmental compliance.

Cross-sectoral collaboration

These challenges underscore the critical need for cross-sectoral collaboration to address commodity-driven deforestation. Partnerships involving public, private, and civil society actors are essential to bridge technological gaps and develop systems that can revolutionize our capacity to monitor and act to prevent deforestation from reaching international and domestic markets. Initiatives like the Forest Data Partnership are playing a key role by fostering multi-sectoral collaboration, engaging stakeholders to facilitate knowledge sharing, creating discussion for functional consensus, and enabling the production of open and credible data, actively supporting the development of more sustainable commodity supply chains in the Amazon and other forestry environments.

The window of opportunity to act is closing fast. We must move beyond incremental changes and embrace bold, transformative solutions that address the systemic drivers of deforestation. Connecting cutting-edge technologies, such as remote sensing, with robust private and public governance mechanisms offers a powerful pathway to enhance the sustainability of supply chains and avert this irreversible damage.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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