Amazon Footprint Report 2025

Technical brief: Drivers of Amazon deforestation in agricultural supply chains

EXECUTIVE SUMMARY

This technical brief provides a region-wide analysis of the commodity-specific agricultural drivers of deforestation across the Amazon region at a sub-national level, and their connections to domestic and international trade-linked consumption. It offers insights to inform more effective and equitable conservation strategies, particularly regarding the potential to influence commodity supply chains that contribute to forest loss. We integrate sub-national agricultural commodity production statistics with satellite data on land use for each country within the Amazon region. We link this information to a downscaled hybridised multi-regional input-output model to allocate production activities to demand drivers, either within domestic markets or – via trade – to regional and international points of consumption. Since agricultural deforestation and its associated climate impacts pose an imminent threat to the Amazon region, enhancing the granular understanding of commodity-specific deforestation and its associated connection to domestic and international markets can empower (sub-)regional, national and international actors and policy makers to identify risk hotspots and trends in deforestation exposure and target place-based interventions to support sustainable land use and forest conservation across the Amazon region.

Key takeaways:

1. The scale of the problem is large.

Crop commodities, beef production, and – to a lesser extent – timber plantations are associated with 8.6 million hectares of deforestation in the Amazon region between 2018 and 2022. This accounts for 36% of the total global deforestation during the same period. Cattle-linked deforestation is the main direct driver, resulting from pasture expansion, and accounts for 78% (6.7 million hectares) of the total commodity-attributed deforestation in this period. Brazil's production systems are linked to the vast majority of the Amazon region footprint, totalling 6.5 million hectares over this period. More than 20% of the recent global deforestation footprints of Portugal, Switzerland, Spain and South Korea originated in the Amazon region. 59% of the world's total cattle deforestation footprint and 33% of the world's soy deforestation footprint originated from the Amazon region.

2. Regional dynamics are important.

Pasture expansion varies across the Amazon landscape and is particularly dominant in eastern and central portions of the Amazon, while also advancing into the interior. Although cattle ranching dominates overall, crop expansion is an important driver in other areas, particularly in Bolivia, Ecuador, and Peru. A combination of cash crops (such as soy, oil palm, cocoa, and coffee) and crops commonly considered staples (such as rice and sorghum) is associated with this expansion. The expansion of pasture is part of a complex process of landuse transition, where it can result from speculative land clearing or serve as a mechanism to claim land tenure. Furthermore, the expansion of soy (and maize) over degraded or underutilised pasture may be displacing pastures further, leading to additional forest loss. These crop-pasture land use dynamics imply that the role of crop commodities in driving Amazon deforestation is inevitably under-estimated by direct land-use change attribution.

3. Both domestic and international demand are important drivers for Amazon deforestation.

The majority of the aggregated deforestation impact appears to be associated with domestic markets, due to the dominance of pasture expansion as a direct land use change after deforestation and with the cattle raised in those lands primarily consumed domestically. However, international demand for soy and maize makes up a greater share of their respective footprints. The pressure for soy expansion, driving the displacement of pasture to new fronts of deforestation, also indicates a more pronounced influence of international markets on the Amazon region. Deforestation footprints for commodities such as maize and oil palm have sharply increased.

4. Continued investment in data provision and transparency is critical.

While the analysis provides unprecedented levels of regional granularity on the local and remote drivers of commodity-linked deforestation, data improvements remain critical to developing even more powerful insights and for ongoing monitoring processes. This includes non-forest biomes in addition to forest systems. Existing gaps in knowledge about where crops are grown and where trade flows originate require enhanced levels of production and supply chain disclosure. Enhanced data is critical to improve risk assessments, guide conservation practices towards areas of current and emerging risk, prevent the displacement of deforestation activity into neighbouring and international landscapes and, more broadly, to promote accountability for impacts by actors operating within and outside the Amazon region.

1. Deforestation in the Amazon

The Amazon region, as defined by RAISG [1], encompasses 843 million hectares covering eight countries and one territory. Tropical rainforests dominate this landscape, with the Amazon accounting for 82.3% of the area, followed by the Cerrado (11.3%), and smaller proportions of Pantanal, Chiquitania, Chaco and other biomes (6.4%). In 2023, the Amazon region's land cover consisted of 82% forest formations, 12.4% flooded forests, and 5.6% savanna formations [2]. This technical brief focuses on examining deforestation – the permanent conversion of forest formations to other land uses – and its links to commodity production, trade, and consumption.

Concerns are growing that the Amazon region may be pushed beyond safe ecological-climatological operating limits, and may even be approaching a critical tipping point, due to the loss and degradation of its natural forests in conjunction with the effects of climate change [3–7]. This is primarily driven by the expansion of agriculture, as well as persistent and unsustainable logging and mining activities, all facilitated by road development [8]. These drivers are increasingly compounded by climate change. Shifting rainfall regimes, rising temperatures and intensifying droughts are interacting with deforestation and amplifying fire occurrence and severity [4,9]. The growing pressures in the Amazon have implications that extend well beyond forest loss. Deforestation and forest degradation release significant amounts of greenhouse gases (and future scenarios project the potential for a further 40 gigatonnes of carbon emissions to arise by 2050 [10]), cause irreversible biodiversity loss, and disrupt freshwater systems [11]. These changes reinforce regional and climate feedbacks, contribute to global warming and changes in rainfall patterns [12], and impact local communities and the economy. Disrupted rainfall cycles already reduce agricultural productivity and revenues (with estimates of potential future losses of billions of dollars for soy (US$5.6 billion by 2050) and cattle (US$180.8 billion by 2050) industries [13]), threaten indigenous territories [14], and undermine water and food security.

More broadly, these cascading climatic and ecological impacts affect the well-being and health of rural and urban people who depend on the Amazon [15].

At the core of these climate and biodiversity crises is commodity-driven deforestation [16]. Halting and reversing forest loss and the conversion of other natural ecosystems is essential to stop biodiversity loss, meet climate commitments, and protect the rights and livelihoods of local farmers, communities, and indigenous peoples. Achieving deforestation- and conversion-free (DCF) supply chains is a critical step. Voluntary efforts such as the Amazon Soy Moratorium (which has had a demonstrable impact on reducing deforestation with low opportunity costs for farmers [17,18]) and essential legal frameworks such as Brazilian environmental law and the EU Deforestation Regulation (EUDR) have demonstrated impact, but they are increasingly threatened with attempts to weaken or dismantle action. Yet, the urgency for decisive, large-scale action to reverse the deforestation pressures across the Amazon region has never been greater.

This technical brief summarises findings of an in-depth study (forthcoming) and accompanying data dashboard (https://www.deforestationfootprint.earth/Amazon) that examine how the production of agricultural and forestry commodities contributes to deforestation in the Amazon region, and how much of it is attributed to domestic, regional, and international consumption. It analyses deforestation associated with commodity production for each Amazonian country, maps the flow of commodities from producer to consumer countries, and highlights key trends linking consumption to deforestation. Compared to previous assessments, this analysis attributes deforestation at an unprecedented level of resolution. By integrating the best available land use information from published remote sensing datasets with national and subnational agricultural production statistics from recognised statistical agencies, it captures commodity-driven deforestation at the subnational level across all Amazonian countries.

1. Deforestation in the Amazon

This enhances the granularity with which deforestation can be linked to commodity production and trade, and contributes to a deeper understanding of intraregional variations within the Amazon region. Ultimately, the goal of this analysis is to provide a clearer understanding of the drivers of commodity-linked deforestation and the pathways through which consumption influences deforestation, thereby strengthening the evidence base for public and private interventions aimed at halting and reversing forest loss.

2. Methodological overview

2.1 Linking deforestation to commodity production across the Amazon

Our deforestation attribution analysis combines geospatial data with land-use statistics associated with cropland, pasture, and forest plantations, following the methodology developed for the Deforestation Drivers and Carbon Emissions (DeDuCE) model [19]. For some commodities and land uses, geospatial data are available, allowing us to confidently attribute deforestation spatially. For example, overlaying dated maps of soy and pasture areas where there was formerly forest allows us to attribute deforestation to soy, cattle meat and leather (we refer to this as direct land-use change; dLUC). However, where deforestation cannot be directly attributed to a particular agricultural or forest plantation commodity through spatial data – which is the case for all crops aside from soy, palm oil, coconut, and (in Brazil) sugarcane – the model instead relies on land-use statistics to infer the drivers of deforestation (we refer to this as statistical land use change; sLUC).

The combination of these methods has two main implications. Firstly, it enables a balanced assessment of the deforestation linked to all recorded agricultural outputs in the region, allowing hotspots and trends in impact to be assessed holistically across landscapes and avoiding a more myopic 'single commodity' focus on the issue. However, it also necessitates a combination of direct and granular attribution of deforestation to crop expansion (via geospatial data) and a more uncertain statistical allocation, which captures the potential for a combination of direct and indirect land use change dynamics.

It should be noted that this attribution does not always capture the eventual land use. For instance, in our analysis, if pasture is identified as the land use three years after forest clearing, it is considered the direct driver of deforestation (i.e., dLUC). However, if this pasture is later converted to soy, our attribution framework still allocates the deforestation to the pasture, even though soy production is ultimately responsible for the subsequent land-use change. Furthermore, in many cases, deforestation driven by pasture expansion can be motivated by land speculation or to justify land ownership, rather than a genuine intention to undertake cattle ranching, and it may take some time for that land to be used productively. This further complicates the attribution of deforestation to the production of forest-risk commodities (see Annex). Additional explanations of these interactions are included in Box 1. In sum, we capture proximate drivers of deforestation, whereas the ultimate drivers may be more complex and indirect.

Box 1: Pasture-related land use transitions in the Amazon region

While pasture expansion is the most significant direct land use after deforestation, it is part of a more complex process of land use transitions. According to Mapbiomas Amazon [20], most pasture expansion originates from forests or, to a lesser extent, natural savannahs and mosaic land uses. Pasture also transitions into other land uses, such as soy and other crops, and some secondary vegetation growth occurs in degraded and abandoned pastures.

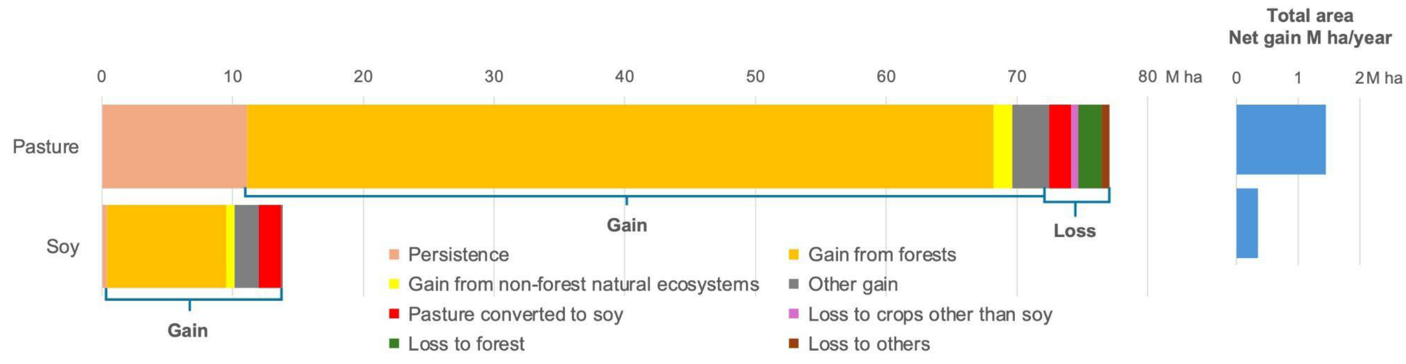
In the Amazon region, there has been a net increase in pasture area over time, as illustrated in Figure 1, which shows trends in three periods. However, the annual average net increase has decreased from 2.6 million hectares/year from 1990 to 2010 to 1.4 million hectares/year from 2010 to 2023. Still, despite this decreasing trend of pasture expansion, more land is converted to pasture – mainly at the expense of forest – than pasture is lost to other land uses. In addition, when considering all pasture lands converted to other land uses (e.g. forest regrowth, mosaic uses, agriculture), the portion of pasture that transitions from pasture to agriculture – mainly soy – has also been growing consistently in recent years, while relatively small in absolute numbers.

Figure 1. Pasture persistence, gain and loss in the Amazon region from 1990 to 2023

Note: **Persistence** refers to the pasture area that remained unchanged at the beginning of the select period. **Gain** refers to the growth of new pasture area at the expense of other land cover and land uses in the select period. **Loss** refers to pasture that transitioned to other land cover and land uses in the select period. Authors elaboration based on land use transition data from Mapbiomas Amazon, Collection 6.0. The analysis adopts the RAISG definition of the Amazon region.

In the Brazilian Legal Amazon, for example, in areas experiencing active agricultural expansion – primarily in southern Mato Grosso, and increasingly southern and eastern Para – soy cultivation frequently replaces degraded or underutilised pasture, often as part of a double-crop regime (e.g. soy-maize). According to Mapbiomas Brazil [21], of the 13.7 million hectares cultivated with soy in the Brazilian Legal Amazon by 2024, 66% (9.1 million hectares) was at the expense of forest formations between 1985 and 2024. The remaining transitions involved other crops and mosaic lands (13%, or 1.8 million hectares), and already established pasture lands (12%, or 1.7 million hectares) (Figure 2). The Soy Moratorium has had a demonstrable impact in reducing the expansion of soy on natural forest lands. However, this also motivated soy farmers to plant on pasture instead, potentially leading to indirect expansion of pasture [22].

Figure 2. Pasture and soy expansion in the Brazilian Legal Amazon from 1985 to 2024



Note: **Persistence** refers to the pasture and soy areas that remained unchanged. **Gain** refers to the area converted to either pasture or soy from other land cover and land uses. **Loss** refers to pasture or soy areas that transitioned to other land cover and land uses. Authors elaboration based on land use transition data from Mapbiomas Brazil, Collection 10.0 (Mapbiomas, 2025)

Furthermore, while pasture is a dominant driver of deforestation, its expansion into the forest also serves an additional purpose. Cattle ranching provides a cheap and effective means to justify land ownership, often as part of a deliberate strategy to establish or reinforce informal land claims. This process of land grabbing is more extensive in undesignated public lands [23]. In addition, land acquisition is also motivated by land speculation, as forest-land prices may reflect expectations of converting forests to agricultural land uses [24].

2.2 Linking deforestation to trade and consumption to provide deforestation footprints

Understanding how commodity trade and consumption drive deforestation requires tracing forest loss along complex agricultural and forestry commodity supply chains – from production in the Amazon region through international trade networks to final consumers. Multiple approaches can be taken to do this, including approaches linked to directly-traded commodities, approaches that adjust trade for re-export activities, or consumption-driven approaches that map production through international trade and processing to final consumption activities[1]. Each approach offers distinct insights (see the accompanying Dashboard for results). In this technical brief, we focus on the consumption-driven results only as these provide the most comprehensive overview of how economic activities downstream influence production – and therefore deforestation – in the Amazon.

To create our consumption-based footprint, we take direct-trade statistics from FAOSTAT [25] and UN Comtrade [26] on bilateral flows between exporting and importing countries as reported by exporting countries for the period 2005 to 2022. Any unreported (including illegal) trade activities will therefore not be captured. These data, in combination with production data, are then adjusted for re-export behaviour to provide estimates of origin-to-final-destination flows, removing trade intermediaries. Finally, these re-export flows are fed into the Input-Output Trade Analysis (IOTA) framework – a hybrid physical-monetary multi-regional input-output (MRIO) model that combines commodity-level data in physical units with sectoral monetary expenditure data derived from the GLORIA MRIO [27] – to map the complete supply chain from producers to consumers for each commodity [28]. Points of consumption identified in the analysis

include domestic consumption (i.e. materials consumed within the same country where they are produced), regional consumption (i.e. production in one Amazonian country consumed in another South American country), and international consumption (i.e. production linked to markets in other parts of the world).

Because data on trade activity originating from the Amazon is only comprehensively available at the national level, we downscale it to subnational production regions using a simple proportional approach, assuming that each subnational region contributes to trade in proportion to its share of the country's total production. For example, if a subnational region produces 20% of a country's soy output, we assign 20% of national soy exports to that region. This method provides a straightforward way to link national trade data to subnational production, but it does not capture heterogeneity in infrastructure, supply chain sourcing, or market access that may cause particular regions to contribute disproportionately to exports. As such, the method should be viewed as an estimate, rather than a full representation of trade dynamics.

The initial consumption results include both Amazon-linked and non-Amazon-linked production and associated deforestation. To isolate Amazon-region-specific results, we apply a scaling factor for each commodity and year that accounts for the proportional difference within each producer country or subregion between non-Amazon and Amazon-specific deforestation.

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[1] Direct trade perspectives account for the exchange of commodities from point A to point B. Re-export adjusted approaches account for, and adjust for, the fact that point A may not be the true supply origin if materials transit through other countries. Consumption-driven approaches account for the onward use of materials, including processing, onward trade, and embedded use in the wider activities of the global economy that are ultimately driven by human consumptive demand.

3. The drivers of deforestation in the Amazon

3.1 Agricultural production impacts

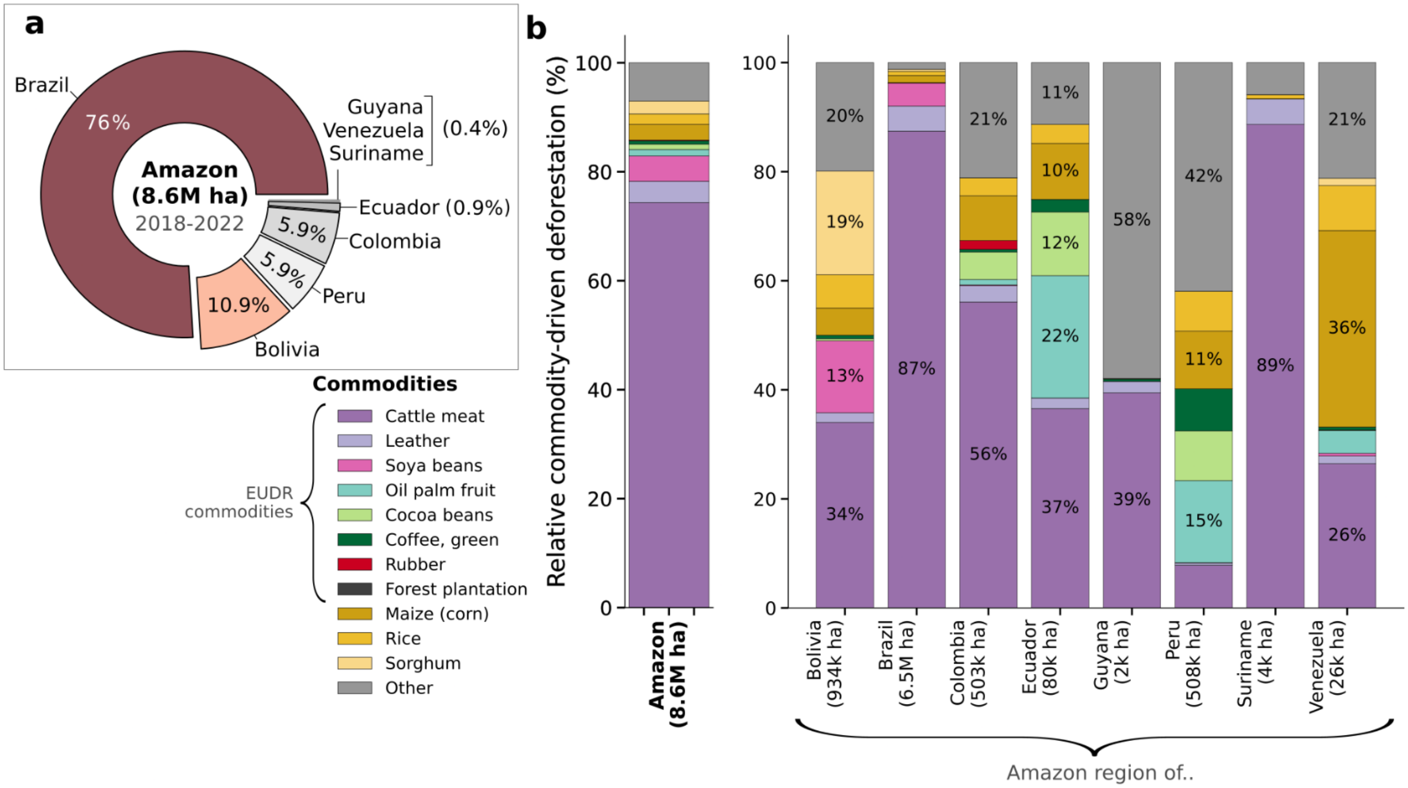
Our analysis finds that crop commodities, cattle production and, to a lesser extent, timber plantations are linked to 8.6 million hectares of deforestation in the Amazon region between 2018 and 2022 (Figure 3). This amount represents an area larger than the size of Austria and is 36% of total global deforestation for the same period.

Cattle, primarily for beef but also for leather, dominates as a direct driver of commodity-linked deforestation, primarily due to pasture expansion (6.7 million hectares, 78%), and is followed by soy cultivation (0.4 million hectares, 4.6%). However, soy and pasture-related land use dynamics operate in a complex interplay that is explained in Box 1. These two major direct drivers are followed by several agricultural crops, which are also linked to export markets, yet their influence on deforestation is more limited, equivalent to 1.5 million hectares (17.4% of total attributed deforestation). Brazil's production systems account for the majority of the regional deforestation footprint (Figure 3a), resulting in 6.5 million hectares (76%) of deforestation over the period, followed by Bolivia (934,000 hectares), Peru (509,000 ha), and Colombia (503,000 ha). Pasture for cattle is the dominant driver of deforestation in the Amazon region of Brazil and Suriname. While its share is relatively smaller in other Amazonian countries, it still plays a significant role in Colombia and, to a lesser extent, in Bolivia, Ecuador, and Guyana (Figure 3b). In Bolivia, Ecuador, Peru and Venezuela, crops traditionally considered 'staples' (e.g., sorghum, rice) are increasingly associated with deforestation activity – given the expansion of these crops in recent years. Additionally, cash crops such as oil palm, cocoa, and coffee have expanded in Ecuador and Peru, accounting for a substantial share of the Amazon deforestation footprint in these countries.

Overall, whilst cattle ranching remains the dominant driver (cropland expansion accounts for only 22% of total deforestation between 2018–2022, compared to 78% from cattle ranching), a critical emerging trend over this period indicates that crop expansion is becoming a more prevalent driver of deforestation across the Amazon region, particularly in Bolivia, Ecuador, Peru, and Venezuela.

Figure 3. Proximate drivers of deforestation across the Amazon region (2018-2022).

Boundaries of the Amazon region, as defined by RAISG, are shown in Figure 4.



Sub-national deforestation patterns (Figure 4) across the Amazon reveal distinct proximate drivers (2017–2021), with pasture dominating in the eastern and central portions of the Amazon – but advancing into the interior of the region – and crop expansion prevailing in the western, southern, and northwestern subregions. These results highlight the need for targeted strategies and interventions to address deforestation, tailored to specific sub-national contexts.

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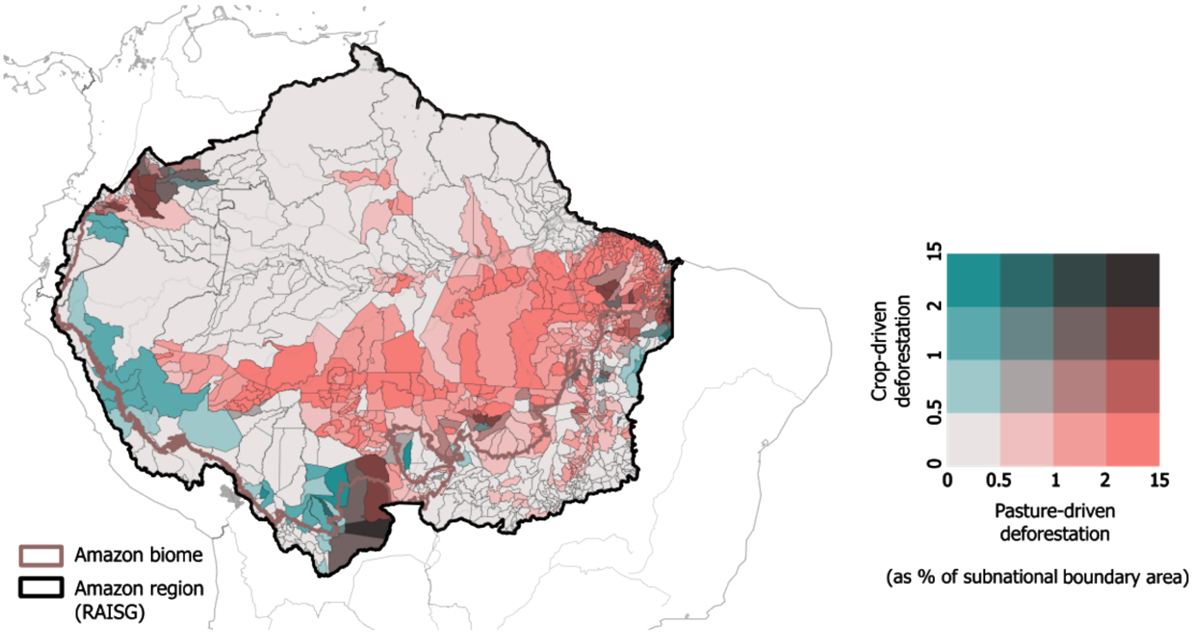
Figure 4. Croplands and pastures as the dominant drivers of deforestation within the Amazon region (2017–2021), represented as a percentage of the sub-national boundary area. Here, total deforestation values refer to deforestation associated with the production of agricultural and forestry commodities. We are unable to undertake this analysis for 2018–2022 due to the lack of subnational agricultural statistics for 2022 across all Amazonian countries, with the exception of Brazil.

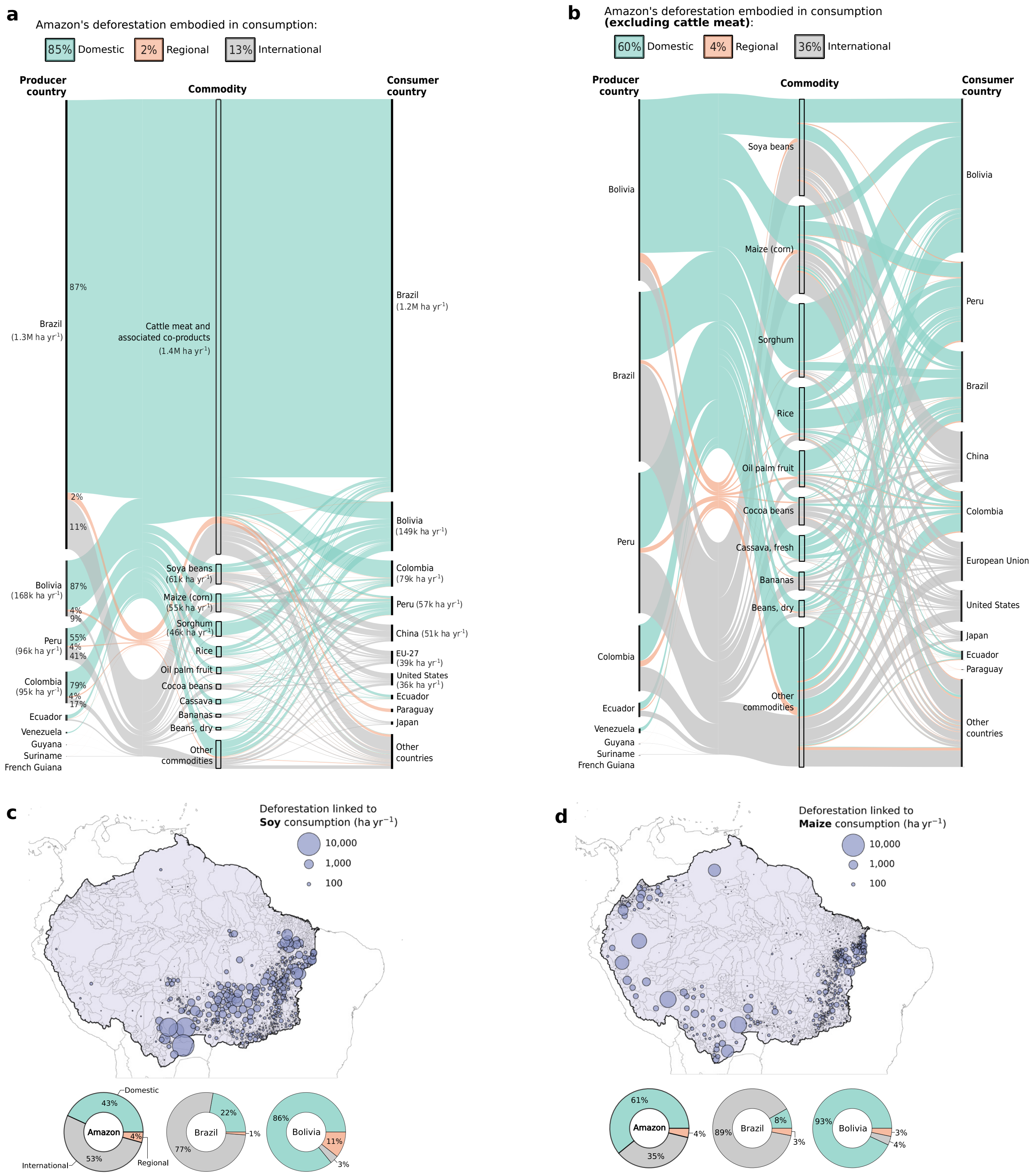


3.2 Markets for deforestation-linked commodities

Monitoring supply chains is essential for understanding the role of national and international trade and consumption in driving deforestation, while also identifying the potential role of markets in solutions. Our analysis shows that, when considering the direct land use after deforestation for the recent period of 2018–2022, much of the deforestation in the Amazon region is linked to domestic markets, although countries like Peru buck this trend with a larger portion of their deforestation footprint associated with international markets (Figure 5). The predominant role of domestic markets is due to the role of pasture in region-wide deforestation activities. In contrast, soy (alongside maize, which may be rotationally cropped alongside soy) is more prominently associated with demand from international markets, for example, for use in animal feed. However, as already mentioned, soy expansion also likely operates as an indirect driver of some deforestation attributed to pasture expansion, which is not directly quantified in the soy footprint.

The distribution of impacts – both in terms of destination and origin – varies by commodity and source country. As illustrated in Figure 5c, international demand accounts for the bulk of the deforestation footprint of Brazilian soy (and of soy from the region overall, which is generally concentrated in the southeastern Amazon region). However, in Bolivia, domestic demand and a substantial component of regional demand collectively make up 97% of the soy footprint. For maize (Figure 5d) – which has a deforestation footprint comparable to soy overall for the 2020–2022 period – the impact is concentrated in western regions of the Amazon with a greater overall proportion destined for domestic consumption, although Brazilian production remains predominantly destined for international markets (to an even higher extent than for soy).

Figure 5: Domestic, regional, and international consumption-linked deforestation footprints for the period 2020–2022, (a) with and (b) without cattle meat. Here, regional aggregation includes all South American countries and the “Rest of America” group. Spatial plots in (c, d) are between 2019–2021 for the same reasons as mentioned in the caption of Figure 4.



Importantly, such patterns of consumption – and the deforestation footprint associated with this consumption – are far from static. Figure 6, which compares the footprint of individual commodities in the first part of our timeseries (2005–2007) to the last part (2020–2022), reveals that changing trade and consumption patterns can have marked and variable impacts on the dynamics of land use change. For example, the soy-associated footprint of Brazil has decreased when comparing results from early in our timeseries to the latest data, as has the contribution of cattle meat linked to the footprints of Peru and Venezuela (Figure 6a). The footprint associated with soy and cattle meat destined for China has increased over the timeseries, whilst the opposite is true from the perspective of the USA's footprint (Figure 6b). Figure 6b also reveals the changing role of specific commodities when it comes to international footprints, with a general trend towards a decrease in each destination country's footprint associated with soy, whilst the contributions of maize, rice and sorghum, coffee and cocoa have tended to have a higher footprint later in the timeseries compared with earlier.

Figure 6: The deforestation footprint of commodities from the perspective of downstream countries/regions of consumption, comparing the 2005–2007 period with the 2020–2022 period.

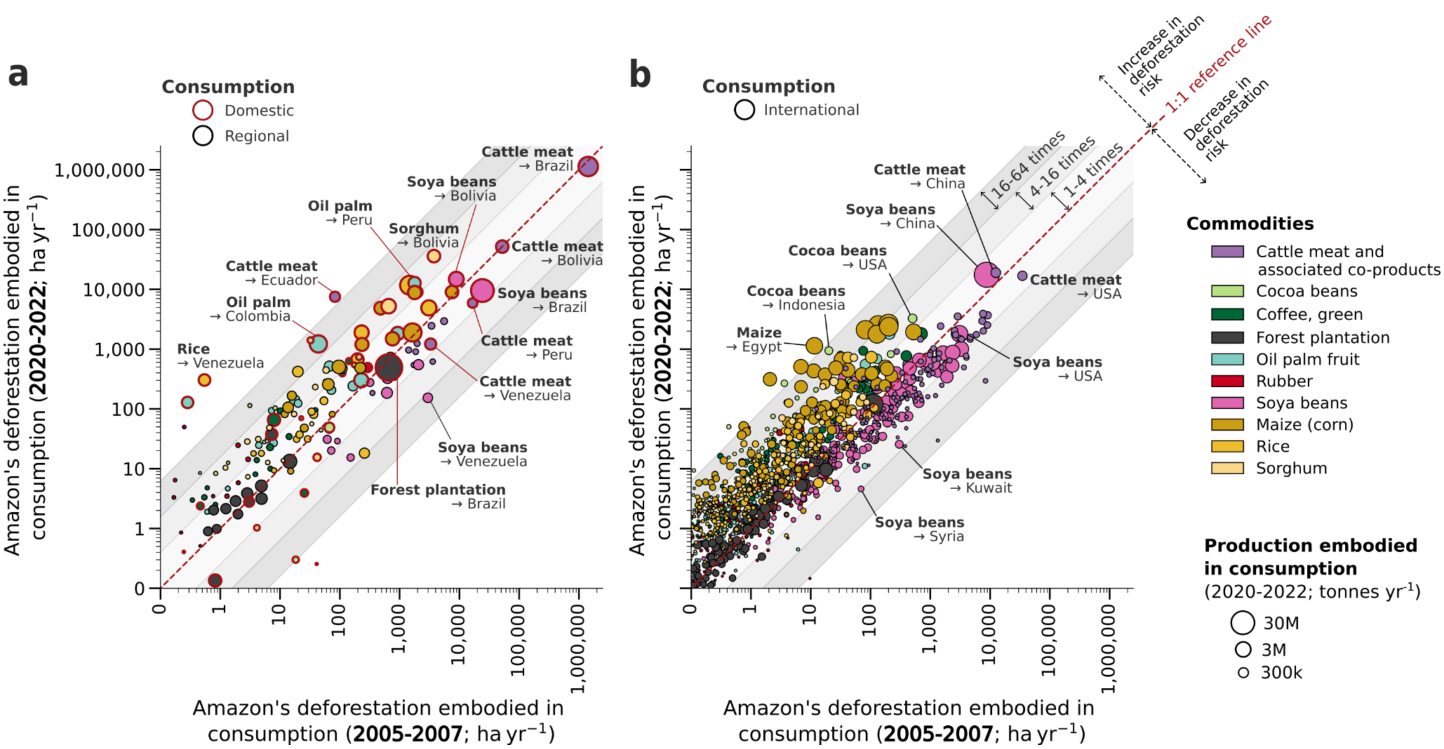
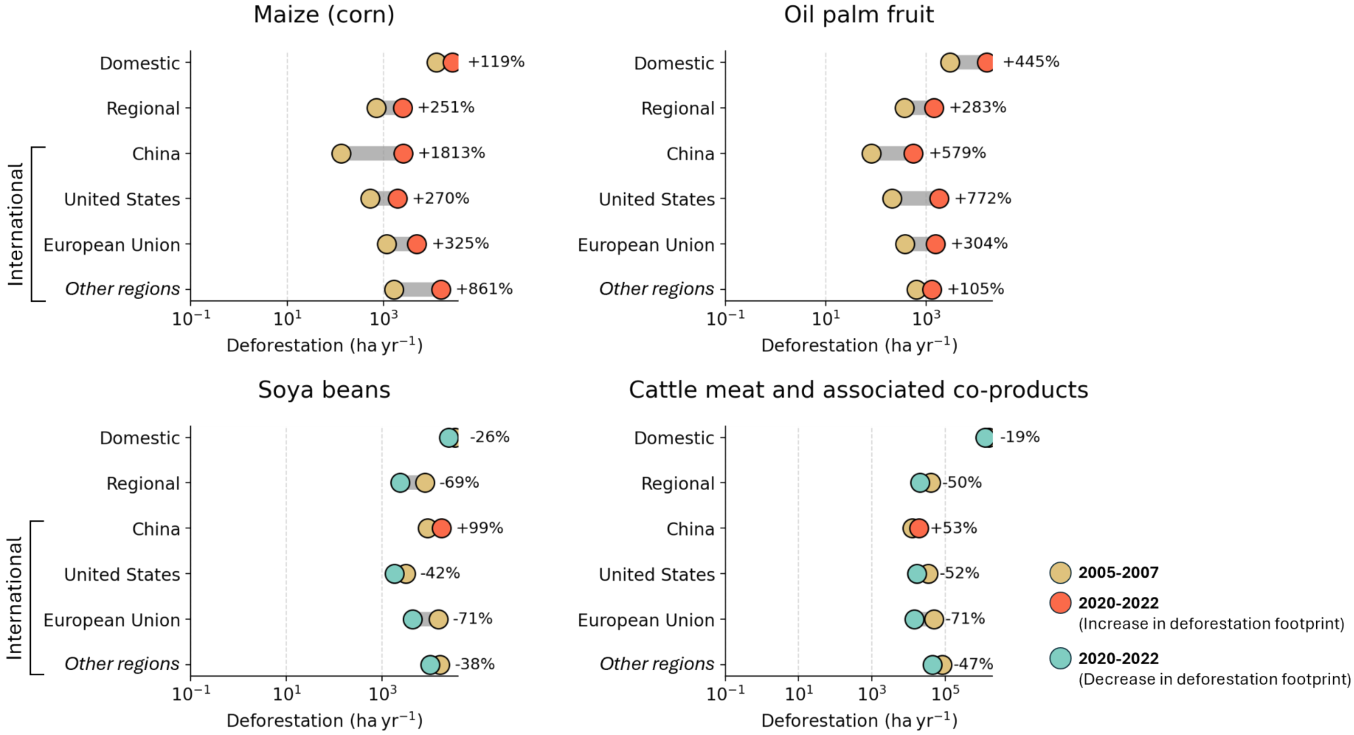


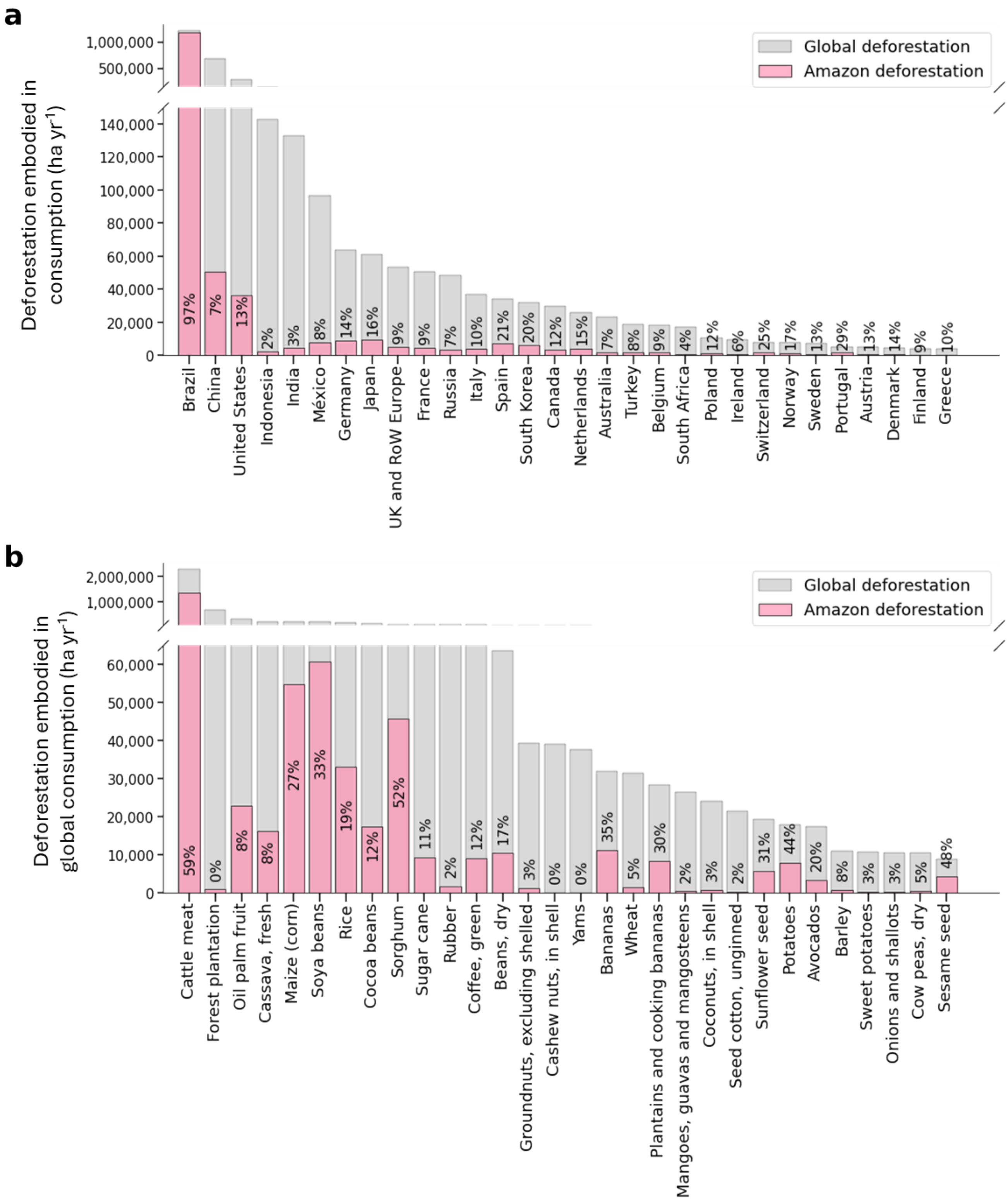
Figure 7 further highlights how destination-specific changes in commodity demand translate into divergent deforestation outcomes. For maize and oil palm, international demand—particularly from China, the United States, the EU, and other countries—has driven sharp increases in deforestation footprints between 2005–2007 and 2020–2022, in some cases by several hundred percent. In contrast, the deforestation footprints associated with soy and cattle meat have generally declined across most destinations, with notable exceptions in China, where both commodities show increases. This divergence underscores that while some supply chains are becoming less land-intensive, others are emerging as increasingly important drivers of land use change, illustrating the dynamic and regionally differentiated nature of deforestation footprints.

Figure 7: Deforestation footprint trends of key agricultural commodities and their consumption destinations, comparing the 2005–2007 period with the 2020–2022 period.



As Figure 8 shows, the Amazon as a whole plays a highly important function in global markets, with more than 20% of the global deforestation footprints of Brazil, Portugal, Switzerland, Spain, and South Korea, and more than 15% of the global footprints of Norway, Japan, and the Netherlands being associated with the Amazon region (Figure 8a). The deforestation per commodity associated with the global commodity markets for cattle (59%), sorghum (52%), sesame seed (48%), potatoes (44%), bananas (35%), soy (33%), plantains (30%), sunflower seed (31%) and maize (27%) are also heavily determined by what goes on in the Amazon region (Figure 8b).

Figure 8: Amazon's contribution to global deforestation in key downstream markets (average 2020–2022).



4. Summary and conclusions

Overall, our analysis demonstrates the fundamental – but regionally distinct and shifting – role that commodity production plays in shaping deforestation in the Amazon region. The Amazon region is a significant source of agricultural production for domestic, regional, and international markets, with cattle and soy being the dominant drivers of deforestation, alongside growing demand for products such as maize, oil palm, rice, sorghum, coffee, and cocoa. This analysis, and the accompanying dashboard (https://www.deforestationfootprint.earth/Amazon), serve to illustrate that by combining the latest spatial and statistical data, we can provide new, landscape-wide insights into the drivers of deforestation, when linked to trade and consumption. This can support targeted, subregional interventions in key hotspots and within key supply chains that are implicated in deforestation in the Amazon.

Our data illustrates the fundamental and ongoing role of pasture expansion as a direct driver of deforestation across the Amazon region, responsible – according to our estimates – for 78% of immediate deforestation activity between 2018 and 2022 and dominating in eastern and central regions while advancing into the Amazon's interior. The vast majority of cattle meat produced on the resulting pasture is destined for domestic markets. The dynamics of pasture expansion, however, are complicated. Pasture expansion is often used as a mechanism to claim land tenure or as a result of speculative land conversion. Some land originally converted to pasture is also eventually destined for conversion to cropland for rotational soy and maize production, with the drivers of these commodities associated with a mix of both domestic and international demand, and with our estimates for soy and maize as drivers of deforestation, thus likely underestimating the true role of these crop commodities in Amazon deforestation activity.

The indication that crops (including staples) are an increasingly important driver of deforestation in the Amazon (especially across western and southern Amazonian subregions) serves to illustrate the importance of monitoring the extent and drivers of land conversion to crop production in sum and across landscapes, and not just reserving analysis for single-commodity impacts to forests. Current threats to the continuation of the Amazon Soy Moratorium offer the potential to further accelerate the role of crops as a major deforestation driver across large portions of the Brazilian Amazon, and further investment in monitoring the proximate and ultimate drivers of deforestation – including via the promotion of transparency of trade and supply chain data by public institutions and by the private sector – is therefore of critical importance for the region.

This more granular analysis for the Amazon region has important implications for key zero-deforestation agendas, particularly those spearheaded from Europe. As illustrated, deforestation in the Amazon region makes a large contribution to the overall global footprint of several importing countries, a fact that should continue to motivate robust transparency mechanisms and requirements for sourcing for these end markets [29,30]. The deforestation and trade analysis presented here is enabled and enhanced by the availability of statistical and geospatial crop information, which is somewhat unique to the Amazon region, and underscores the importance of investing in data provision and developing similar, granular assessments of deforestation drivers in other regions. This includes attention to the Cerrado in Brazil and other critical South American biomes – such as the Atlantic Forest and the Chaco – where land-use change may be displaced if efforts to curb agriculture-driven deforestation focus solely on the Amazon. It also extends to regions such as West and Central Africa, and Southeast Asia, where the risks of agricultural deforestation have increased substantially.

4. Summary and conclusions

Our analysis captures the proximate drivers of deforestation based on immediate land use after forest loss (as quantified by the methods used to attribute geospatial or statistical expansion of crops to productive outputs), but commodity expansion may also often be related to complex interactions of infrastructure development, land speculation and consecutive transition of extensive cattle ranching and 'staple' crops to export-driven 'cash' crops. Agricultural commodity production may also co-exist with other drivers of deforestation, such as climate change, mining and logging. Our analysis also does not differentiate between industrial or more traditional forms of agriculture and therefore is unable to shed light on the presence of lower-impact systems adopting, for example, agro-ecological principles that may operate sustainably within deforestation frontiers. Such dynamics, conversion of landscapes beyond forests, and the supply chain's influence on them, warrant further investigation across the region. This is required both to determine the degree to which estimates provided in footprint studies (such as this one) are robustly linked to realities on the ground, and to help determine how local, regional and international supply chain drivers of deforestation and conversion interplay with other policy measures and/or support interventions across deforestation-risk landscapes.

Data improvements remain critical to developing even more powerful insights, with limitations remaining in knowledge of where crops are being grown and how subnational trades are taking place. Further work to integrate local datasets, and especially to bring together and harmonise regional, geospatial data on forest inventories [30,31] and crop production – including that covering illegal crops such as coca in Colombia [32] – has the potential to improve estimates and reduce reliance on statistical land use change approaches. Overall, the effectiveness of monitoring is impeded by low levels of transparency and a lack of technical and institutional capacities within national statistical agencies. That said, footprint studies – such as those conducted in this analysis – provide critical information on the drivers of deforestation and can help identify 'hotspots' of risk and opportunities for action. The data provided by our analysis can already inform activities such as the risk-based approaches being adopted in downstream supply chain legislation or investments for high-risk regions that must be mindful of the local drivers of land-use change in identifying solutions and avoiding leakage effects. The accompanying Dashboard to this analysis provides a wealth of information on deforestation hotspots and their links to trade and consumption, which decision makers in and beyond the supply chain should explore for the purposes of risk assessment.

Annex: Interpreting results from the DeDuCE deforestation model

Forests and deforestation:

Forests are composed of trees that have been established through natural regeneration. The conversion of these natural forests to other land uses is referred to as deforestation. This definition of forests excludes forest plantations that are intensively managed for wood, fibre, or energy production. Recognising that not all woody vegetation constitutes natural forest, we apply a tree cover density threshold of ≥25% per pixel and use a global forest plantation mask to distinguish natural forests from managed ones. Pixels that do not meet this natural forest criterion are excluded from further analysis (see Singh and Persson [19] for a detailed description).

It is important to note that the Global Forest Change dataset [33] provides tree cover density values only for the year 2000. This is consistent with our focus on evaluating deforestation from 2001–2022. However, it means that the dataset captures only the first recorded loss event and does not account for subsequent forest gain or secondary forest losses. Consequently, losses of secondary forests – those naturally regenerating after the removal of native forests post-2000 – are not represented in our analysis.

Datasets utilised in this analysis:

Spatial datasets

- Tree cover and tree cover loss from Global Forest Change [25]
- Tree cover loss due to fire (Global) [25]
- MapBiomas Collection [21] (South America; in addition to cropland, pasture and forest plantations land cover classes, this dataset includes commodities such as sugarcane, rice, seed cotton, citrus fruits, coffee, and oil palm fruit)
- Soya beans (South America)
- Sugarcane (Brazil)
- Oil palm fruit and coconut (Global)
- RAISG Amazon region boundary [1]
- Subnational regions from GADM

Statistical datasets

- FAOSTAT [19]
- The Brazilian Institute of Geography and Statistics (IBGE) [34]
- The Global Subnational Agricultural Production (GSAP) database [35]

Deforestation attribution:

The DeDuCE model attributes deforestation by overlaying global spatio-temporal data on tree cover loss (from the Global Forest Change dataset (GFC); identifying complete removal of tree cover, i.e. vegetation greater than 5 metres in height, at a 30-m pixel scale) with datasets on crop commodities (e.g. soy), land use (e.g. MapBiomas), dominant drivers of forest loss, among other forest management and disturbances datasets (e.g. fire-induced tree cover loss), to identify deforestation and its drivers using the best available data per pixel.

In instances where deforestation cannot be directly associated with a specific commodity, the model utilises agricultural statistics – at the national and sub-national level – to infer the most likely or potential drivers of forest loss (see Singh and Persson [19] for a detailed description). Here, we utilise the FAOSTAT and Global Subnational Agricultural Production (GSAP) dataset, wherever available, for attributing deforestation in Amazonian countries. The temporal extent of the GSAP dataset is shown in Figure 2 of Ribeiro et al. [29].

When faced with multi-land-use mosaics in MapBiomas [21] that blend croplands, pastures, or forest plantations without clear demarcation, we distribute the area of forest loss within these mosaics in proportion to the extent of each land use relative to the total observed expansion of land use at the national level (since we lack land cover/expansion statistics at the subnational level; see Singh and Persson [19] for a detailed description).

Caveats associated with direct, statistical/proximate and indirect land-use change:

Our analysis breaks new ground in providing information on commodity-driven estimates of deforestation across the Amazon. However, data gaps still necessitate the inclusion of statistical land use change (*sLUC*) approaches to provide a complete picture of deforestation linked to commodity production, and this complicates the conclusions derived from the analysis. As mentioned above, if deforestation pixels can be directly attributed to the expansion of a specific commodity, they are classified as direct land-use change (*sLUC*). When the model uses agricultural production statistics at national or subnational levels to infer the most likely drivers of deforestation, this is referred to as statistical land-use change (*sLUC*). Indirect land-use change refers to deforestation or land conversion that occurs as a secondary consequence of market or production shifts – such as when agricultural expansion in one area displaces other land uses into forested regions.

The DeDuCE model does not explicitly estimate indirect land-use change. However, it is important to note that where agricultural statistics are used for attribution, they indicate the expansion of a crop or other land use within the focal jurisdiction, and this expansion may not always be directly linked to deforestation, as in reality it can also displace other crops into the deforestation frontiers. Therefore, estimates of statistical expansion may be considered an 'upper bound' of sorts for estimates of production-linked deforestation, with higher levels of uncertainty in comparison to direct land-use change attribution based on commodity-specific geospatial information. Continued reliance on national-level statistics, combined with the lack of spatially explicit crop-specific land-use data for the diverse range of crops grown in the region, contributes to this challenge.

Where available, our use of subnational agricultural statistics from IBGE and GSAP helps to reduce these uncertainties and improve the accuracy of commodity-driven deforestation estimates. However, ongoing data limitations mean that it remains intractable to disentangle the impact of broader complex land-use change dynamics. This includes, for example, a lack of inclusion of the impact of illegal commodities, which are not reported in national statistics across the region, and thus are challenging to incorporate into the regional deforestation attribution framework. These limitations should be taken into account when interpreting the results.

Speculative clearing:

Dynamics such as the use of pasture as a tool for speculative land clearing or to claim land ownership further complicate the attribution of deforestation to the production of forest-risk commodities. While the aim of this analysis is to link productive commodity outputs with deforestation, it also accounts, in certain cases, for deforestation associated with speculative or non-productive land-use activities. For crop commodities, recorded statistics on harvested areas are used to quantify expansion. However, when the extent of deforestation linked to crop production exceeds the observed expansion in harvested area, the surplus deforestation is distributed proportionally among all crop commodities based on their respective harvested areas (see Singh and Persson [19] for further details).

For pasture, we simply attribute 95% of pasture-driven deforestation to cattle meat and 5% to leather (see Singh and Persson [19] for further details). This approach does not account for variations in cattle stocking rates or pasture productivity, meaning that deforestation may also be attributed to low-productivity or underutilized pastures.

Forest loss associated with forest fire:

Additionally, any forest loss caused by fires (which may include that linked to speculative land clearing) that is not followed by the establishment of agricultural or forestry land use within three years after the forest loss event is excluded from our attribution to commodity production. This category may include, for example, recent fire-related forest losses in Bolivia that have not yet been associated with a specific post-fire land use (i.e. detected through MapBiomas or other spatial datasets). Thus, here our results should be considered lower-bound estimates, with the potential for additional deforestation to be associated with agriculture and forestry activities more broadly.

Municipalities intersecting with the Amazon region (RAISG) boundary:

Since this study focuses specifically on the Amazon's deforestation footprint, we limit the analysis to the Amazon region as defined by the Amazonian Network of Georeferenced Socio-Environmental Information (RAISG). To assess this, we exclude tree cover loss occurring outside this boundary from the DeDuCE deforestation attribution framework. This exclusion also applies to subnational administrative units that straddle the Amazon region boundary – deforestation is only attributed to the portions falling within the boundary, and portions outside are excluded from attribution. However, for these intersecting municipalities, some uncertainty remains: because agricultural production data cannot be spatially disaggregated within administrative boundaries, there is a risk that crop commodities may be partially attributed to Amazon deforestation even when production occurs outside the region.

Soy-maize multi-cropping deforestation attribution:

In the DeDuCE model, the attribution of deforestation to soy–maize multicrop systems follows a hierarchical approach. Where spatially explicit data on soy cultivation are available, deforestation is attributed exclusively to soy cultivation, even when maize is grown sequentially or within the same pixel. In the case of Brazil, only the first maize harvest reported by IBGE statistics is considered to avoid any potential for double-counting of land use associated with second-season maize.

In regions where spatial data for soy are unavailable – such as Colombia – deforestation attribution between soy and maize is performed proportionally, based on the relative expansion of harvested areas for each crop at the subnational level. This approach has a low to moderate risk of underestimating deforestation associated with soy and maize; however, total deforestation estimates in the region remain unaffected.

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